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An Overview of MOOS-IvP and a Users
Guide to the IvP Helm Autonomy Software

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An Overview of MOOS-IvP and a Brief Users Guide to the IvP Helm Autonomy Software



Rev 4.1



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Abstract

This document describes the IvP Helm - an Open Source behavior-based autonomy application for unmanned vehicles. IvP is short for interval programming - a technique for representing and solving multi-objective optimizations problems. Behaviors in the IvP Helm are reconciled using multi-objective optimization when in competition with each other for influence of the vehicle. The IvP Helm is written as a MOOS application where MOOS is a set of Open Source publish-subscribe autonomy middleware tools. This document describes the configuration and use of the IvP Helm, provides examples of simple missions and information on how to download and build the software from the MOOS-IvP server at www.moosivp.org.

Approved for public release; Distribution is unlimited.



This work is the product of a multi-year collaboration between the Center for Advanced System Technologies (CAST), Code 2501, of the Naval Undersea Warfare Center in Newport Rhode Island and the Department of Mechanical Engineering and the Computer Science and Artificial Intelligence Laboratory (CSAIL) at the Massachusetts Institute of Technology in Cambridge Massachusetts, and the Oxford University Mobile Robotics Group.

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Contents

I	Introduction	10
1	Overview	11
1.1	Purpose and Scope of this Document	11
1.2	Brief Background of MOOS-IvP	11
1.3	Sponsors of MOOS-IvP	11
1.4	The Software	12
1.4.1	Building and Running the Software	12
1.4.2	Operating Systems Supported by MOOS and IvP	13
1.5	Where to Get Further Information	13
1.5.1	Websites and Email Lists	13
1.5.2	Documentation	14
2	Design Considerations of MOOS-IvP	15
2.1	Public Infrastructure - Layered Capabilities	15
2.2	Code Re-Use	16
2.3	The Backseat Driver Design Philosophy	18
2.4	The Publish-Subscribe Middleware Design Philosophy and MOOS	19
2.5	The Behavior-Based Control Design Philosophy and IvP Helm	19
3	A Very Brief Overview of MOOS	22
3.1	Inter-process communication with Publish/Subscribe	22
3.2	Message Content	22
3.3	Mail Handling - Publish/Subscribe - in MOOS	23
3.3.1	Publishing Data	24
3.3.2	Registering for Notifications	24
3.3.3	Reading Mail	24
3.4	Overloaded Functions in MOOS Applications	24
3.4.1	The <code>Iterate()</code> Method	25
3.4.2	The <code>OnNewMail()</code> Method	26
3.4.3	The <code>OnStartup()</code> Method	26
3.5	MOOS Mission Configuration Files	26
3.6	Launching Groups of MOOS Applications with Antler	27
3.7	Scoping and Poking the MOOSDB	27
3.8	A Simple MOOS Application - <code>pXRelay</code>	28
3.8.1	Finding and Launching the <code>pXRelay</code> Example	29
3.8.2	Scoping the <code>pXRelay</code> Example with <code>uXMS</code>	29
3.8.3	Seeding the <code>pXRelay</code> Example with the <code>uPokeDB</code> Tool	29
3.8.4	The <code>pXRelay</code> Example MOOS Configuration File	31
3.8.5	Suggestions for Further Things to Try with this Example	32
3.9	MOOS Applications Available to the Public	33
3.9.1	MOOS Modules from Oxford	33
3.9.2	MOOS Modules from MIT and NUWC	34

4	A First Example with MOOS-IvP - the Alpha Mission	36
4.1	Where to Find, and How to Launch the Alpha Example Mission	36
4.2	A Closer Look at the Behavior File used in the Alpha Example Mission	38
4.3	A Closer Look at the MOOS Applications In the Alpha Example Mission	40
4.3.1	Antler and the Antler Configuration Block	40
4.3.2	The pMarinePID Application and Configuration Block	41
4.3.3	The iMarineSim Application and Configuration Block	41
4.3.4	The pNodeReporter Application and Configuration Block	42
4.3.5	The pMarineViewer Application and Configuration Block	42
II	The IvP Helm and Behaviors	43
5	The IvP Helm as a MOOS Application	44
5.1	Overview	44
5.2	Helm Engagement	45
5.3	Helm All-Stop Events and Status	47
5.4	Parameters for the pHelmIvP MOOS Configuration Block	48
5.5	Launching the IvP Helm and Output to the Terminal Window	51
5.6	Publications and Subscriptions for IvP Helm	52
5.6.1	Variables published by the IvP Helm	53
5.6.2	Variables Subscribed for by the IvP Helm	55
5.7	Automated Filtering of Successive Duplicate Helm Publications	55
5.7.1	Motivation for the Duplication Filter	55
5.7.2	Implementation and Usage of the Duplication Filter	56
5.7.3	Clearing the Duplication Filter	57
6	IvP Helm Autonomy	58
6.1	Overview	58
6.1.1	The Influence of Brooks, Stallman and Dantzig on the IvP Helm	58
6.1.2	Traditional and Non-traditional Aspects of the IvP Behavior-Based Helm	58
6.1.3	Two Layers of Building Autonomy in the IvP Helm	59
6.2	Inside the IvP Helm - A Look at the Helm Iterate Loop	60
6.2.1	Step 1 - Reading Mail and Populating the Info Buffer	60
6.2.2	Step 2 - Evaluation of Mode Declarations	61
6.2.3	Step 3 - Behavior Participation	61
6.2.4	Step 4 - Behavior Reconciliation	61
6.2.5	Step 5 - Publishing the Results to the MOOSDB	61
6.3	Mission Behavior Files	62
6.3.1	Variable Initialization Syntax	62
6.3.2	Behavior Configuration Syntax	62
6.3.3	Hierarchical Mode Declaration Syntax	63
6.4	Hierarchical Mode Declarations	63
6.4.1	Background	63
6.4.2	Behavior Configuration <i>Without</i> Hierarchical Mode Declarations	64

6.4.3	Syntax of Hierarchical Mode Declarations - The Bravo Mission	65
6.4.4	A More Complex Example of Hierarchical Mode Declarations	66
6.4.5	Monitoring the Mission Mode at Run Time	67
6.5	Behavior Participation in the IvP Helm	68
6.5.1	Behavior Run Conditions	68
6.5.2	Behavior Run Conditions and Mode Declarations	69
6.5.3	Behavior Run States	69
6.5.4	Behavior Flags and Behavior Messages	70
6.5.5	Monitoring Behavior Run States and Messages During Mission Execution	71
6.6	Behavior Reconciliation in the IvP Helm - Multi-Objective Optimization	72
6.6.1	IvP Functions	72
6.6.2	The IvP Build Toolbox	72
6.6.3	The IvP Solver and Behavior Priority Weights	75
6.6.4	Monitoring the IvP Solver During Mission Execution	76
7	Properties of Helm Behaviors	77
7.1	Brief Overview	77
7.2	Parameters Common to All IvP Behaviors	78
7.2.1	A Summary of the Full Set of General Behavior Parameters	78
7.2.2	Altering Behavior Parameters Dynamically with the <code>UPDATES</code> Parameter	80
7.2.3	Limiting Behavior Duration with the <code>DURATION</code> Parameter	81
7.2.4	The <code>PERPETUAL</code> Parameter	82
7.2.5	Detection of Stale Variables with the <code>NOSTARVE</code> Parameter	82
7.3	Overloading the <code>setParam()</code> Function in New Behaviors	83
7.4	Behavior Functions Invoked by the Helm	83
7.4.1	Helm-Invoked Immutable Functions	85
7.4.2	Helm-Invoked Overloaded Functions	85
7.5	Local Behavior Utility Functions	86
7.5.1	Summary of Implementor-Invoked Utility Functions	86
7.5.2	The Information Buffer	87
7.5.3	Requesting the Inclusion of a Variable in the Information Buffer	88
7.5.4	Accessing Variable Information from the Information Buffer	88
7.6	Overloading the <code>onRunState()</code> and <code>onIdleState()</code> Functions	89
7.7	Dynamic Behavior Spawning	89
7.7.1	Behavior Specifications Viewed as Templates	90
7.7.2	Behavior Completion and Removal from the Helm	90
7.7.3	Example Missions with Dynamic Behavior Spawning	91
7.7.4	Examining the Helm's Life Event History	91
8	Behaviors of the IvP Helm	93
8.1	BHV_Waypoint	95
8.1.1	Brief Overview of Configuration Parameters and Variables Published	95
8.1.2	Specifying Waypoints - the <code>points</code> , <code>order</code> , and <code>repeat</code> Parameters	97
8.1.3	The <code>capture_radius</code> and <code>nonmonotonic_radius</code> Parameters	97
8.1.4	Track-line Following using the <code>lead</code> Parameter	98

8.1.5	Variables Published by the BHV_Waypoint Behavior	99
8.1.6	Further Clarification on the <code>repeat</code> vs. <code>perpetual</code> parameter	100
8.2	BHV_OpRegion	102
8.2.1	Brief Overview of Configuration Parameters and Variables Published	102
8.2.2	Safety Checking Applied to an Operation Region	103
8.2.3	Safety Limits on Operation Time, Vehicle Depth, and Vehicle Altitude	103
8.2.4	Variables Published by the BHV_OpRegion Behavior	104
8.3	BHV_Loiter	106
8.3.1	Brief Overview of Configuration Parameters and Variables Published	106
8.3.2	How Things Work	107
8.4	BHV_PeriodicSpeed	110
8.4.1	Brief Overview of Configuration Parameters and Variables Published	110
8.4.2	Parameters of the BHV_PeriodicSpeed Behavior	110
8.4.3	State Transition Policy and Initial Condition Parameters	111
8.4.4	Variables Published by the BHV_PeriodicSpeed Behavior	111
8.5	BHV_PeriodicSurface	112
8.6	BHV_ConstantDepth	114
8.7	BHV_ConstantHeading	115
8.8	BHV_ConstantSpeed	116
8.9	BHV_GoToDepth	117
8.10	BHV_MemoryTurnLimit	119
8.11	BHV_StationKeep	121
8.11.1	Overview	121
8.11.2	Brief Summary of the BHV_StationKeep Behavior Parameters	121
8.11.3	Setting the Station-Keep Point and Radial-Speed Relationships	122
8.11.4	Passive Low-Energy Station Keeping Mode	123
8.11.5	Station Keeping On Demand	125
8.12	BHV_Timer	126
8.12.1	Brief Overview of Configuration Parameters and Variables Published	126
9	Contact Related Behaviors of the IvP Helm	127
9.1	Properties Common to All Contact Related Behaviors	127
9.1.1	Common Behavior Configuration Parameters	128
9.1.2	Closest Point of Approach Calculations	129
9.2	The AvoidCollision Behavior	132
9.2.1	Brief Overview of Configuration Parameters and Variables Published	132
9.3	BHV_CutRange	135
9.3.1	Brief Overview of Configuration Parameters and Variables Published	135
9.3.2	Specifying the Priority Policy - the <code>pwt*_dist</code> Parameters	136
9.4	BHV_Shadow	137
9.5	BHV_Trail	138
9.5.1	Brief Overview of Configuration Parameters and Variables Published	138
9.5.2	Specifying the Priority Policy - the <code>pwt*_dist</code> Parameters	139
10	Extended Example Missions with the IvP Helm	141

10.1 Preliminaries	141
10.1.1 Using pAntler to Launch Missions	141
10.1.2 Using the nsplug Utility for Configuring Mission and Behavior Files	141
10.1.3 Shell Scripts	143
10.2 Mission S3: The Charlie Mission	144
10.2.1 Topic #1: Hierarchical Mode Declarations in the Charlie Mission	144
10.2.2 Topic #2: The Loiter Behavior	146
10.2.3 Topic #3: The StationKeep Behavior	148
10.3 Mission S4: The Delta Mission	152
10.3.1 Topic #1: Configuring the Helm for Operation at Depth	153
10.3.2 Topic #2: The ConstantDepth Behavior	154
10.3.3 Topic #3: The PeriodicSurface Behavior	154
10.3.4 Topic #4: The Waypoint Behavior with Survey Patterns	155
10.3.5 Topic #4: Using pMarineViewer with Geo-referenced Mouse Clicks	156
10.3.6 Suggestions for Further Experimenting with the Delta Mission	156
10.4 Mission S5: The Echo Mission	160
10.4.1 Topic #1: The BearingLine Behavior	160
10.4.2 Topic #2 Dynamic Behavior Spawning	161
10.4.3 Topic #3: Sending Updates to the Original and Spawmed Behaviors	163
10.5 Mission M1: The Multi-Loiter Mission	166
10.6 Mission M2: The Berta Mission	167
10.6.1 Topic #1: The AvoidCollision Behavior and Dynamic Behavior Spawning	167
10.6.2 Topic #2: Contact Management with pBasicContactMgr	169
III Autonomy Utilities	172
11 The uHelmScope Utility: Scoping on the IvP Helm	173
11.1 Brief Overview	173
11.2 Console Output of uHelmScope	173
11.2.1 The General Helm Overview Section of the uHelmScope Output	174
11.2.2 The MOOSDB-Scope Section of the uHelmScope Output	175
11.2.3 The Behavior-Posts Section of the uHelmScope Output	175
11.3 Stepping Forward and Backward Through Saved Scope History	176
11.4 Console Key Mapping and Command Line Usage Summaries	176
11.5 IvPHelm MOOS Variable Output Supporting uHelmScope Reports	177
11.6 Configuration Parameters for uHelmScope	178
11.7 Publications and Subscriptions for uHelmScope	179
12 Geometry Utilities	180
12.1 Brief Overview	180
12.2 Points	180
12.2.1 String Representations for Points	180
12.2.2 Optional Point Parameters	180
12.3 Polygons	181

12.3.1	String Representations for Polygons	181
12.3.2	A Polygon String Representation using the Radial Format	181
12.3.3	A Polygon String Representation using the Ellipse Format	182
12.3.4	Optional Polygon Parameters	183
12.4	SegLists and their String Representations	183
12.4.1	Methods for Specifying Seglists	183
12.4.2	A SegList String Representation using the Lawnmower Format	183
13	The pMarineViewer Utility: A GUI for Mission Control	185
13.1	Brief Overview	185
13.2	Description of the pMarineViewer GUI Interface	186
13.3	Pull-Down Menu Options	187
13.3.1	The “BackView” Pull-Down Menu	187
13.3.2	The “GeoAttributes” Pull-Down Menu	189
13.3.3	The “Vehicles” Pull-Down Menu	190
13.3.4	The “MOOS-Scope” Pull-Down Menu	191
13.3.5	The Optional ”Action” Pull-Down Menu	191
13.3.6	The Optional “Mouse-Context” Pull-Down Menu	192
13.3.7	The Optional “Reference-Point” Pull-Down Menu	194
13.4	Displayable Vehicle Shapes, Markers, Drop Points, and other Geometric Objects	194
13.4.1	Displayable Vehicle Shapes	195
13.4.2	Displayable Marker Shapes	196
13.4.3	Displayable Drop Points	197
13.4.4	Displayable Geometric Objects	198
13.5	Support for Command-and-Control Usage	199
13.5.1	Poking the MOOSDB with Geo Positions	199
13.5.2	Configuring GUI Buttons for Command and Control	199
13.6	Configuration Parameters for pMarineViewer	200
13.7	More about Geo Display Background Images	204
13.8	Publications and Subscriptions for pMarineViewer	206
13.8.1	Variables published by the pMarineViewer application	206
13.8.2	Variables subscribed for by pMarineViewer application	207
14	The uTimerScript Utility: Scripting Events to the MOOSDB	208
14.1	Overview of the uTimerScript Interface and Configuration Options	208
14.1.1	Brief Summary of the uTimerScript Configuration Parameters	208
14.1.2	MOOS Variables Posted by uTimerScript	209
14.1.3	MOOS Variables Subscribed for by uTimerScript	209
14.1.4	Command Line Usage of uTimerScript	209
14.2	Basic Usage of the uTimerScript Utility	210
14.2.1	Configuring the Event List	210
14.2.2	Resetting the Script	211
14.3	Script Flow Control	211
14.3.1	Pausing the Timer Script	212
14.3.2	Conditional Pausing of the Timer Script and Atomic Scripts	212

14.3.3	Fast-Forwarding the Timer Script	212
14.4	Macro Usage in Event Postings	213
14.4.1	Built-In Macros Available	213
14.4.2	User Configured Macros with Random Variables	214
14.4.3	Support for Simple Arithmetic Expressions with Macros	214
14.5	Random Time Warps and Initial Delays	214
14.5.1	Random Time Warping	215
14.5.2	Random Initial Start Delays	215
14.6	More on uTimerScript Output to the MOOSDB and Console	215
14.6.1	Status Messages Posted to the MOOSDB by uTimerScript	215
14.6.2	Console Output Generated by uTimerScript	216
14.7	Examples	217
14.7.1	A Script Used as Proxy for an On-Board GPS Unit	217
14.7.2	A Script as a Proxy for Simulating Random Wind Gusts	219
15	The pBasicContactMgr Utility: Managing Platform Contacts	221
15.1	Overview of the pBasicContactMgr Interface and Configuration Options	221
15.1.1	Brief Summary of the pBasicContactMgr Configuration Parameters	222
15.1.2	MOOS Variables Posted by pBasicContactMgr	222
15.1.3	MOOS Variables Subscribed for by pBasicContactMgr	222
15.1.4	Command Line Usage of pBasicContactMgr	223
15.2	Basic Usage of the pBasicContactMgr Utility	223
15.2.1	Contact Alert Messages	223
15.2.2	Contact Alert Triggers	224
15.2.3	Contact Alert Record Keeping	225
15.2.4	Contact Resolution	226
15.3	Usage of the pBasicContactMgr with the IvP Helm	226
15.4	Console Output Generated by pBasicContactMgr	226
IV	Appendices	228
A	Use of Logic Expressions	229
B	Behavior Summaries	231
C	Colors	248

Part I

Introduction

1 Overview

1.1 Purpose and Scope of this Document

The purpose of this document is to provide an overview of the IvP Helm in terms of design considerations, architecture and usage. This document contains references to example missions distributed with the MOOS-IvP software bundle at www.moos-ivp.org. The example and material herein should serve as a “getting-started” guide as well as users manual for users looking to go beyond simple autonomy missions. *THIS DOCUMENT REPRESENTS WORK IN PROGRESS. IT IS STILL CONSIDERED TO BE IN DRAFT FORM AND HAS KNOWN OMISSIONS. THE READER IS ENCOURAGED TO EMAIL THE AUTHORS FEEDBACK AND LOOK FOR LATER VERSIONS.*

1.2 Brief Background of MOOS-IvP

MOOS was written by Paul Newman in 2001 to support operations with autonomous marine vehicles in the MIT Ocean Engineering and the MIT Sea Grant programs. At the time Newman was a post-doc working with John Leonard and has since joined the faculty of the Mobile Robotics Group at Oxford University. MOOS continues to be developed and maintained by Newman at Oxford and the most current version can be found at his website. The MOOS software available in the MOOS-IvP project includes a snapshot of the MOOS code distributed from Oxford. The IvP Helm was developed in 2004 for autonomous control on unmanned marine surface craft, and later underwater platforms. It was written by Mike Benjamin as a post-doc working with John Leonard, and as a research scientist for the Naval Undersea Warfare Center in Newport Rhode Island. The IvP Helm is a single MOOS process that uses multi-objective optimization to implement behavior coordination.

Acronyms

MOOS stands for “Mission Oriented Operating Suite” and its original use was for the Bluefin Odyssey III vehicle owned by MIT. IvP stands for “Interval Programming” which is a mathematical programming model for multi-objective optimization. In the IvP model each objective function is a piecewise linear construct where each piece is an *interval* in N-Space. The IvP model and algorithms are included in the IvP Helm software as the method for representing and reconciling the output of helm behaviors. The term interval programming was inspired by the mathematical programming models of linear programming (LP) and integer programming (IP). The pseudo-acronym IvP was chosen simply in this spirit and to avoid acronym clashing.

1.3 Sponsors of MOOS-IvP

Original development of MOOS and IvP were more or less infrastructure by-products of other sponsored research in (mostly marine) robotics. Those sponsors were primarily The Office of Naval Research (ONR), as well as the National Oceanic and Atmospheric Administration (NOAA). MOOS and IvP are currently funded by Code 31 at ONR, Dr. Don Wagner and Dr. Behzad Kamgar-Parsi. MOOS is additionally supported in the U.K. by EPSRC. Early development of IvP benefited from the support of the In-house Laboratory Independent Research (ILIR) program at the Naval Undersea Warfare Center in Newport RI. The ILIR program is funded by ONR.

1.4 The Software

The MOOS-IvP autonomy software is available at the following URL:

```
http://www.moos-ivp.org
```

Follow the links to *Software*. Instructions are provided for downloading the software from an SVN server with anonymous read-only access.

1.4.1 Building and Running the Software

This document is written to Release 4.1 which is equivalent to Revision 2847 of the MOOS-IvP SVN development tree. This revision represents the state of development as of August 18th, 2010. After checking out the tree from the SVN server as prescribed at this link, the top level directory should have the following structure:

```
moos-ivp/  
  MOOS/  
    MOOS-2300-Dec0309/  
      README.txt  
      README-LINUX.txt  
      README-OS-X.txt  
      README-WINDOWS.txt  
      README.txt  
      build-moos.sh  
      build-ivp.sh  
      configure-ivp.sh  
  ivp/  
  lib/  
  scripts/
```

Note there is a MOOS directory and an IvP sub-directory. The MOOS directory is a symbolic link to a particular MOOS revision checked out from the Oxford server. In the example above this is Revision 2300 on the Oxford SVN server. This directory is left completely untouched other than giving it the local name MOOS-2208. The use of a symbolic link is done to simplify the process of bringing in a new snapshot from the Oxford server.

The build instructions are maintained in the README files and are probably more up to date than this document can hope to remain. In short building the software amounts to two steps - building MOOS and building IvP. Building MOOS is done by executing the build-moos.sh script:

```
> cd moos-ivp  
> ./build-moos.sh
```

Alternatively one can go directly into the MOOS directory and configure options with `ccmake` and build with `cmake`. The script is included to facilitate configuration of options to suit local use. Likewise the IvP directory can be built by executing the `build-ivp.sh` script. The MOOS tree must be built before building IvP. Once both trees have been built, the user's shell executable path must be augmented to include the two directories containing the new executables:

```
moos-ivp/MOOS/MOOSBin
moos-ivp/bin
```

At this point the software should be ready to run and a good way to confirm this is to run the example simulated mission in the missions directory:

```
> cd moos-ivp/ivp/missions/alpha/
> pAntler alpha.moos
```

Running the above should bring up a GUI with a simulated vehicle rendered. Clicking the DEPLOY button should start the vehicle on its mission. If this is not the case, some help and email contact links can be found at www.moos-ivp.org/support/, or emailing issues@moos-ivp.org.

1.4.2 Operating Systems Supported by MOOS and IvP

The MOOS software distributed by Oxford is well supported on Linux, Windows and Mac OS X. The software distributed by MIT includes additional MOOS utility applications and the IvP Helm and related behaviors. These modules are support on Linux and Mac OS X and the software compiles and runs on Windows but Windows support is limited.

1.5 Where to Get Further Information

1.5.1 Websites and Email Lists

There are two websites - the MOOS website maintained by Oxford University, and the MOOS-IvP website maintained by MIT. At the time of this writing they are at the following URLs:

```
http://www.robots.ox.ac.uk/~pnewman/TheMOOS/
http://www.moos-ivp.org
```

What is the difference in content between the two websites? As discussed previously, MOOS-IvP, as a set of software, refers to the software maintained and distributed from Oxford *plus* additional MOOS applications including the IvP Helm and library of behaviors. The software bundle released at moos-ivp.org does include the MOOS software from Oxford - usually a particular released version. For the absolute latest in the core MOOS software and documentation on Oxford MOOS modules, the Oxford website is your source. For the latest on the core IvP Helm, behaviors, and MOOS tools distributed by MIT, the moos-ivp.org website is the source.

There are two mailing lists open to the public. The first list is for MOOS users, and the second is for MOOS-IvP users. If the topic is related to one of the MOOS modules distributed from the Oxford website, the proper email list is the "moosusers" mailing list. You can join the "moosusers" mailing list at the following URL:

```
https://lists.csail.mit.edu/mailman/listinfo/moosusers,
```

For topics related to the IvP Helm or modules distributed on the moos-ivp.org website that are not part of the Oxford MOOS distribution (see the software page on moos-ivp.org for help in drawing the distinction), the "moosivp" mailing list is appropriate. You can join the "moosivp" mailing list at the following URL:

```
https://lists.csail.mit.edu/mailman/listinfo/moosivp,
```

1.5.2 Documentation

Documentation on MOOS can be found on the Oxford University website:

<http://www.robots.ox.ac.uk/~pnewman/MOOSDocumentation/index.htm>

This includes documentation on the MOOS architecture, programming new MOOS applications as well as documentation on several bread-and-butter applications such as `pAntler`, `pLogger`, `uMS`, `pMOOSBridge`, `iRemote`, `iMatlab`, `pScheduler` and more. Documentation on the IvP Helm, behaviors and autonomy related MOOS applications not from Oxford can be found on the www.moos-ivp.org website under the Documentation link. Below is a summary of documents:

List of available MOOS-IvP related documentation

- *An Overview of MOOS-IvP and a Brief Users Guide to the IvP Helm Autonomy Software* (this document) - This is the primary document describing the IvP Helm regarding how it works, the motivation for its design, how it is used and configured, and example configurations and results from simulation.
- *MOOS-IvP Autonomy Tools Users Manual* - A users manual for ten MOOS applications, and five offline tools for post-mission analysis collectively referred to as the Alog Toolbox. The MOOS applications are: `pNodeReporter`, `uTimerScript`, `uHelmScope`, `uPokeDB`, `pBasicContactMgr`, `uXMS`, `uTermCommand`, `pMarineViewer`, `pEchoVar`, and `uProcessWatch`. These applications are common supplementary tools for running an autonomy system in simulation and on the water. MIT CSAIL Technical Report TR-2010-039.
- *A Tour of MOOS-IvP Autonomy Software Modules* - This document acts as a catalog of existing modules (Both MOOS applications and IvP Behaviors). For each module, it relates (a) where it can be downloaded, (b) what the module does, (c) who it was written by, (d) rough estimate on size and complexity, and (e) what modules it may depend on for its build. MIT CSAIL Technical Report TR-2009-006.
- *Extending a MOOS-IvP Autonomy System and Users Guide to the IvPBuild Toolbox* - This document is a users manual for those wishing to write their own IvP Helm behaviors and MOOS modules. It describes the `IvPBehavior` and `CMOOSApp` superclass. It also describes the `IvPBuild` Toolbox containing a number of tools for building IvP Functions, the primary output of behaviors. It provides an example template directory with example IvP Helm behavior and an example MOOS application along with an example CMake build structure for linking against the standard software MOOS-IvP software bundle. MIT CSAIL Technical Report TR-2009-037.

2 Design Considerations of MOOS-IvP

The primary motivation in the design of MOOS-IvP is to build highly capable autonomous systems. Part of this picture includes doing so at a reduced short and long-term cost and a reduced time line. By “design” we mean both the choice in architectures and algorithms as well as the choice to make key modules for infrastructure, basic autonomy and advanced tools available to the public under an Open Source license. The MOOS-IvP software design is based on three architecture philosophies, (a) the backseat driver paradigm, (b) publish and subscribe autonomy middleware, and (c) behavior based autonomy. The common thread is the ability to separate the development of software for an overall system into distinct modules coordinated by infrastructure software made available to the public domain.

2.1 Public Infrastructure - Layered Capabilities

The central architecture idea of both MOOS and IvP is the separation of overall capability into separate and distinct modules. The unique contributions of MOOS and IvP are the methods used to *coordinate* those modules. A second central idea is the decision to make algorithms and software modules for infrastructure, basic autonomy and advanced tools available to the public under an Open Source license. The idea is pictured in Figure 1. There are three things in this picture - (a) modules that actually perform a function (the wedges), (b) modules that coordinate other modules (the center of the wheel), and (c) standard wrapper software use by each module to allow it to be coordinated (the spokes).

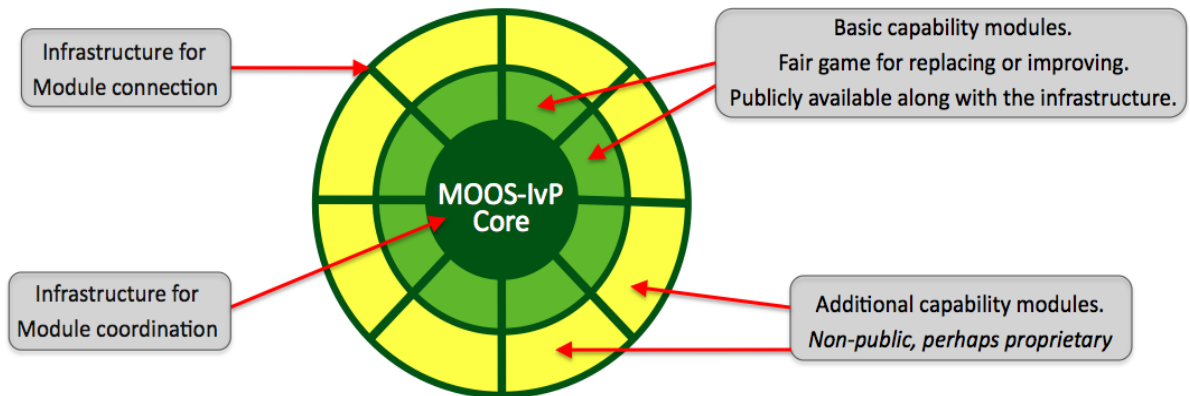


Figure 1: **Public Infrastructure - Layered Capabilities:** The center of the wheel represents MOOS-IvP Core. For MOOS this means the MOOSDB and the message passing and scheduling algorithms. For IvP this means the IvP helm behavior management and the multi-objective optimization solver. The wedges on the wheel represent individual modules - either MOOS processes or IvP behaviors. The spokes of the wheel represent the idea that each module inherits from a superclass to grab functionality key to plugging into the core. Each wedge or module contains a wrapper defined by the superclass that augments the function of the individual module. The darker wedges indicate publicly available modules and the lighter ones are modules added by users to augment the public set to comprise a particular fielded autonomy system.

The darker wedges in Figure 1 represent application modules (not infrastructure) that provide basic functionality and are publicly available. However, they do not hold any special immutable status. They can be replaced with a better version, or, since the source code is available, the

code of the existing module can be changed or augmented to provide a better or different version (hopefully with a different name - see the section on branching below). Later sections provide an overview of about 40 or so particular modules that are currently available. By modules we mean MOOS applications and IvP behaviors and the above comments hold in either case. The white wedges in Figure 1 represent the imaginable unimplemented modules or functionality. A particular fielded MOOS-IvP autonomy system typically is comprised of (a) the MOOS-IvP core modules, (b) *some* of the publicly available MOOS applications and IvP behaviors, and (c) additional perhaps non-public MOOS applications and IvP behaviors provided by one or more 3rd party developers.

The objective of the public-infrastructure/layered-capabilities idea is to strike an important balance - the balance between effective code re-use and the need for users to retain privacy regarding how they choose to augment the public codebase with modules of their own to realize a particular autonomy system. The benefits of code re-use are an important motivation in fundamental architecture decisions in both MOOS and IvP. The modules that comprise the public MOOS-IvP codebase described in this document represent over twenty work-years of development effort. Furthermore, certain core components of the codebase have had hundreds if not thousands of hours of usage on a dozen or so fielded platform types in a variety of situations. The issue of code re-use is discussed next.

2.2 Code Re-Use

Code re-use is critical, and starts with the ability to have a system comprised of separate but coordinated modules. The key technical hurdle is to achieve module separation without invoking a substantial hit on performance. In short, MOOS middleware is a way of coordinating separate processes running on a single computer or over several networked computers. IvP is a way of coordinating several autonomy behaviors running within a single MOOS process.

Factors Contributing to Code Re-use:

- *Freedom from proprietary issues.* Software serving as infrastructure shared by all components (MOOS processes and IvP behaviors) are available under an Open Source license. In addition many mature MOOS and IvP modules providing commonly needed capabilities are also publicly available. Proprietary or non-publicly released code may certainly co-exist with non-proprietary public code to comprise a larger autonomy system. Such a system would retain a strategic edge over competitors if desired, but have a subset of components common with other users.
- *Module independence.* Maintaining or augmenting a system comprised of a set of distinct modules can begin to break down if modules are not independent with simple easy-to-augment interfaces. Compile dependencies between modules need to be minimized or eliminated. The maintenance of core software libraries and application code should be decoupled completely from the issues of 3rd party additional code.
- *Simple well-documented interfaces.* The effort required to add modules to the code base should be minimized. Documentation is needed for both (a) using the publicly available applications and libraries, and (b) guiding users in adding their own modules.
- *Freedom to innovate.* The infrastructure does not put undue restrictions on how basic problems can be solved. The infrastructure remains agnostic to techniques and algorithms used

in the modules. No module is sacred and any module may be replaced.

Benefits of Code Re-Use:

- *Diversity of contributors.* Increasingly, an autonomy system contains many components that touch many areas of expertise. This would be true even for a vanilla use of a vehicle, but is compounded when considering the variety of sensors and missions and ways of exploiting sensors in achieving mission objectives. A system that allows for wide code re-use is also a system that allows module contributions from a wide set of developers or experts. This has a substantial impact on the issues mentioned below of lower cost, higher quality and reliability, and reduced development time line.
- *Lower cost.* One immediate benefit of code re-use is the avoidance of repeatedly re-inventing modules. A group can build capabilities incrementally and experts are free to concentrate on their area and develop only the modules that reflect their skill set and interests. Perhaps more important, code re-use gives the systems integrator *choices* in building a complete system from individual modules. Having choices leads to increased leverage in bargaining for favorable licensing terms or even non-proprietary terms for a new module. Favorable licensing terms arranged at the outset can lead to substantially lower long-term costs for future code maintenance or augmentation of software.
- *Higher performance capability.* Code re-use enhances performance capability in two ways. First, since experts are free to be experts without re-inventing the modules outside their expertise and provided by others, their own work is more likely to be more focused and efficient. They are likely to achieve a higher capability for a given a finite investment and given finite performance time. Second, since code re-use gives a systems integrator *choices*, this creates a meritocracy based on optimal performance-cost ratio of candidate software modules. The under-capable, more expensive module is less likely to diminish the overall autonomy capability if an alternative module is developed to offer a competitive choice. Survival of the fittest.
- *Higher performance reliability.* An important part of system reliability is testing. The more testing time and the greater diversity of testing scenarios the better. And of course the more time spent testing on physical vehicles versus simulation the better. By making core components of a codebase public and permitting re-use by a community of users, that community provides back an enormous service by simply using the software and complaining when or if something goes wrong. Certain core components of the MOOS-IvP codebase have had hundreds if not thousands of hours of usage on a dozen or so platform types in a variety of situations. And many more hours in simulation. Testing doesn't replace good coding practice or formal methods for testing and verifying correctness, but it complements those two aspects and is enhanced by code re-use.
- *Reduced development time line.* Code re-use means less code is being re-developed which leads to quicker overall system development. More subtly, since code re-use can provide a systems integrator choices and competition on individual modules, development time can be reduced as a consequent. An integrator may simply accept the module developed the quickest, or the competition itself may speed up development. If choices and competition result in

more favorable license agreements between the integrator and developer, this in itself may streamline agreements for code maintenance and augmentation in the long term. Finally, as discussed above, if code re-use leads to an element of community-driven bug testing, this will also quicken the pace in the evolution toward a mature and reliable autonomy system.

2.3 The Backseat Driver Design Philosophy

The key idea in the backseat driver paradigm is the separation between *vehicle control* and *vehicle autonomy*. The vehicle control system runs on a platform’s main vehicle computer and the autonomy system runs on a separate payload computer. This separation is also referred to as the *mission controller - vehicle controller* interface. A primary benefit is the decoupling of the platform autonomy system from the actual vehicle hardware. The vehicle manufacturer provides a navigation and control system capable of streaming vehicle position and trajectory information to the main vehicle computer, and accepting a stream of autonomy decisions such as heading, speed and depth in return. Exactly how the vehicle navigates and implements control is largely unspecified to the autonomy system running in the payload. The relationship is depicted in Figure 2.

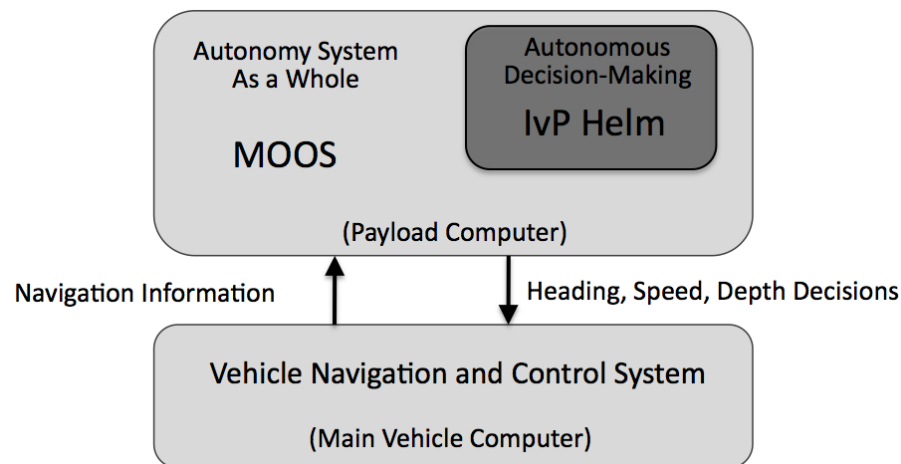


Figure 2: **The backseat driver paradigm:** The key idea is the separation of vehicle autonomy from vehicle control. The autonomy system provides heading, speed and depth commands to the vehicle control system. The vehicle control system executes the control and passes navigation information, e.g., position, heading and speed, to the autonomy system. The backseat paradigm is agnostic regarding how the autonomy system implemented, but in this figure the MOOS-IvP autonomy architecture is depicted.

The autonomy system on the payload computer consists of a set of distinct processes communicating through a publish-subscribe database called the MOOSDB (Mission Oriented Operating Suite - Database). One such process is an interface to the main vehicle computer, and another key process is the IvP Helm implementing the behavior-based autonomy system. The MOOS community is referred to as the “larger autonomy” system, or the “autonomy system as a whole” since MOOS itself is middleware, and actual autonomous decision making, sensor processing, contact management etc., are implemented as individual MOOS processes.

2.4 The Publish-Subscribe Middleware Design Philosophy and MOOS

MOOS provides a middleware capability based on the publish-subscribe architecture and protocol. Each process communicates with each other through a single database process in a star topology (Figure 3). The interface of a particular process is described by what messages it produces (publications) and what messages it consumes (subscriptions). Each message is a simple variable-value pair where the values are limited to either string or numerical values such as (STATE, ‘DEPLOY’), or (NAV_SPEED, 2.2). Limiting the message type reduces the compile dependencies between modules, and facilitates debugging since all messages are human readable.

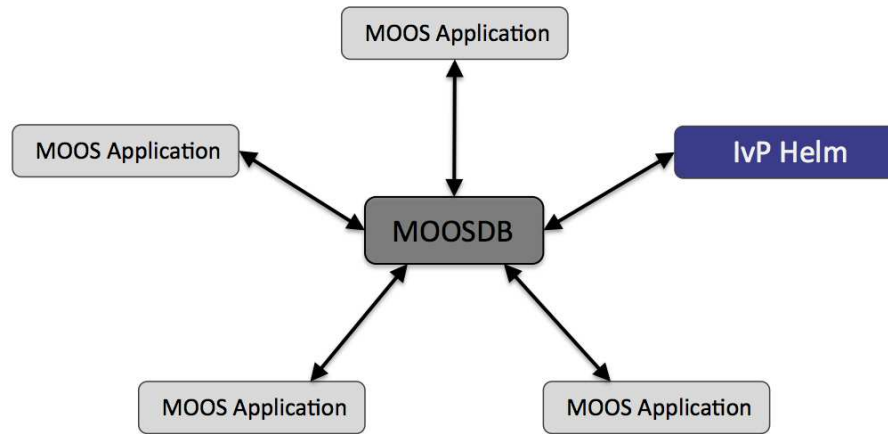


Figure 3: **A MOOS community**: is a collection of MOOS applications typically running on a single machine each with a separate process ID. Each process communicates through a single MOOS database process (the MOOSDB) in a publish-subscribe manner. Each process may be executing its inner-loop at a frequency independent from one another and set by the user. Processes may be all run on the same computer or distributed across a network.

The key idea with respect to facilitating code re-use is that applications are largely independent, defined only by their interface, and any application is easily replaceable with an improved version with a matching interface. Since MOOS Core and many common applications are publicly available along with source code under an Open Source GPL license, a user may develop an improved module by altering existing source code and introduce a new version under a different name. The term MOOS Core refers to (a) the MOOSDB application, and (b) the MOOS Application superclass that each individual MOOS application inherits from to allow connectivity to a running MOOSDB. Holding the MOOS Core part of the codebase constant between MOOS developers enables the plug-and-play nature of applications.

2.5 The Behavior-Based Control Design Philosophy and IvP Helm

The IvP Helm runs as a single MOOS application and uses a behavior-based architecture for implementing autonomy. Behaviors are distinct software modules that can be described as self-contained mini expert systems dedicated to a particular aspect of overall vehicle autonomy. The helm implementation and each behavior implementation exposes an interface for configuration by the user for a particular set of missions. This configuration often contains particulars such as a

certain set of waypoints, search area, vehicle speed, and so on. It also contains a specification of state spaces that determine which behaviors are active under what situations, and how states are transitioned. When multiple behaviors are active and competing for influence of the vehicle, the IvP solver is used to reconcile the behaviors (Figure 4).

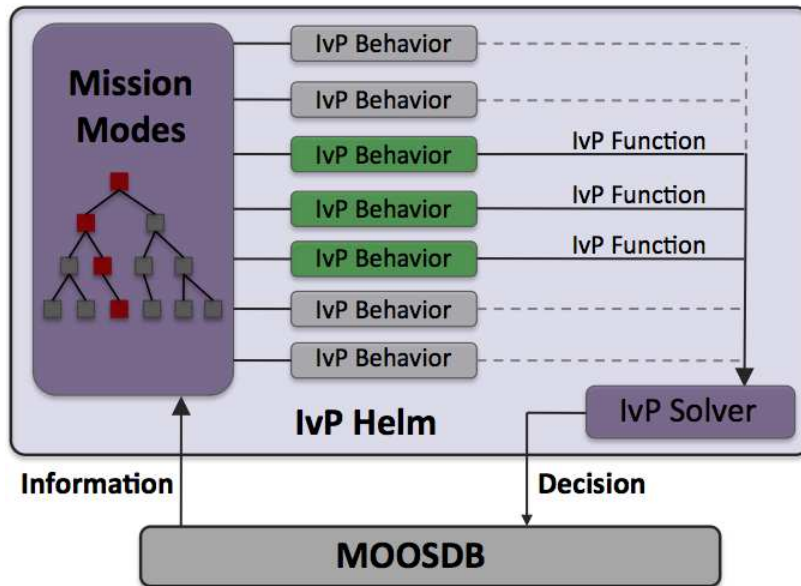


Figure 4: **The IvP Helm:** The helm is a single MOOS application running as the process pHelmIvP. It is a behavior-based architecture where the primary output of a behavior on each iteration is an IvP objective function. The IvP solver performs multi-objective optimization on the set of functions to find the single best vehicle action, which is then published to the MOOSDB. The functions are built and the set is solved on *each* iteration of the helm - typically one to four times per second. Only a subset of behaviors are active at any given time depending on the vehicle situation, and the state space configuration provided by the user.

The solver performs this coordination by soliciting an objective function, i.e., utility function, from each behavior defined over the vehicle decision space, e.g., possible settings for heading, speed and depth. In the IvP Helm, the objective functions are of a certain type - piecewise linearly defined - and are called IvP Functions. The solver algorithms exploit this construct to find a rapid solution to the optimization problem comprised of the weighted sum of contributing functions.

The concept of a behavior-based architecture is often attributed to [9]. Since then various solutions to the issue of action selection, i.e., the issue of coordinating competing behaviors, have been put forth and implemented in physical systems. The simplest approach is to prioritize behaviors in a way that the highest priority behavior locks out all others as in the Subsumption Architecture in [9]. Another approach is referred to as the potential fields, or vector summation approach (See [1], [12]) which considers the average action between multiple behaviors to be a reasonable compromise. These action-selection approaches have been used with reasonable effectiveness on a variety of platforms, including indoor robots, e.g., [1], [2], [16], [17], land vehicles, e.g., [18], and marine vehicles, e.g., [8], [10], [13], [19], [20]. However, action-selection via the identification of a single highest priority behavior and via vector summation have well known shortcomings later described in [16], [17] and [18] in which the authors advocated for the use of multi-objective opti-

mization as a more suitable, although more computationally expensive, method for action selection. The IvP model is a method for implementing multi-objective function based action-selection that is computationally viable in the IvP Helm implementation.

3 A Very Brief Overview of MOOS

MOOS is often described as autonomy “middleware” which can be argued is shorthand for the glue that connects a collection of applications where the “real” work is going on. MOOS does indeed connect a collection of applications, of which the IvP Helm is one. However, each application inherits a generic MOOS interface whose implementation provides a powerful, easy-to-use means of communicating with other applications and controlling the relative frequency at which the application executes its primary set of functions. Due to its combination of ease-of-use, general extendability and reliability, it has been used in the classroom by students with no prior experience, as well on many extended field exercises with substantial robotic resources at stake. To frame the later discussion of the IvP Helm, the basic issues regarding MOOS applications are introduced here. For further information on MOOS, see [15].

3.1 Inter-process communication with Publish/Subscribe

MOOS has a star-like topology. This is depicted in Figure 3 on page 19. Each application within a MOOS community (a MOOSApp) has a connection to a single MOOS Database (called MOOSDB) that lies at the heart of the software suite. All communication happens via this central server application. The network has the following properties:

- No Peer to Peer communication.
- All communication between the client and server is instigated by the client, i.e., the MOOSDB never makes a unsolicited attempt to contact a MOOSApp.
- Each client has a unique name.
- A given client need have no knowledge of what other clients exist.
- A client has no way of transmitting data to a given client - it can only be sent to the MOOSDB.
- The network can be distributed over any number of machines running any combination of supported operating systems.

This centralized topology is obviously vulnerable to bottle-necking at the server regardless of how well written the server is. However the advantages of such a design are perhaps greater than its disadvantages. Firstly the network remains simple regardless of the number of participating clients. The server has complete knowledge of all active connections and can take responsibility for the allocation of communication resources. The clients operate independently with inter-connections. This prevents rogue clients (badly written or hung) from directly interfering with other clients.

3.2 Message Content

The communications API in MOOS allows data to be transmitted between the MOOSDB and a client. The meaning of that data is dependent on the role of the client. However the form of that data is constrained by MOOS. Somewhat unusually MOOS only allows for data to be sent in string or double form. Data is packed into messages (CMOOSMsg class) which contains other salient information shown in Table 1.

Variable	Meaning
Name	The name of the data
String Value	Data in string format
Double Value	Numeric double float data
Source	Name of client that sent this data to the MOOSDB
Time	Time at which the data was written
Data Type	Type of data (STRING or DOUBLE)
Message Type	Type of Message (usually NOTIFICATION)
Source Community	The community to which the source process belongs

Table 1: The contents of MOOS message

The fact that data is commonly sent in string format is often seen as a strange and inefficient aspect of MOOS. For example the string "Type=EST,Name=AUV,Pos=[3x1]3.4,6.3,-0.23" might describe the position estimate of a vehicle called "AUV" as a 3x1 column vector. Typically string data in MOOS is a concatenation of comma separated "name = value" pairs. It is true that using custom binary data formats does decrease the number of bytes sent. However binary data is unreadable to humans and requires structure declarations to decode it and header file dependencies are to be avoided where possible. The communications efficiency argument is not as compelling as one may initially think. The CPU cost invoked in sending a TCP/IP packet is largely independent of size up to about one thousand bytes. So it is as costly to send two bytes as it is one thousand. In this light there is basically no penalty in using strings. There is however a additional cost incurred in parsing string data which is far in excess of that incurred when simply casting binary data. Irrespective of this, experience has shown that the benefits of using strings far outweighs the difficulties. In particular:

- Strings are human readable.
- All data becomes the same type.
- Logging files are human readable (they can be compressed for storage).
- Replaying a log file is simply a case of reading strings from a file and "throwing" them back at the MOOSDB in time order.
- The contents and internal order of strings transmitted by an application can be changed without the need to recompile consumers (subscribers to that data) - users simply would not understand new data fields but they would not crash.

Of course, scalar data need not be transmitted in string format - for example the depth of a sub-sea vehicle. In this case the data would be sent while setting the data type to "MOOS_DOUBLE" and writing the numeric value in the double data field of the message.

3.3 Mail Handling - Publish/Subscribe - in MOOS

Each MOOS application is a client having a connection to the MOOSDB. This connection is made on the client side and the client manages a private thread that coordinates the communication with

the MOOSDB. This thread completely hides the intricacies and timings of the communications from the rest of the application and provides a small, well dened set of methods to handle data transfer. By having this thread automatically available to each MOOS application, the application can:

1. Publish data - issue a notification on named data.
2. Register for notifications on named data.
3. Collect notifications on named data - reading mail.

3.3.1 Publishing Data

Data is published as a pair - a variable and value - that constitute the heart of a MOOS message describe in Table 1. The client invokes the `Notify(VarName, VarValue)` command where appropriate in the client code. The above command is implemented both for string values and double values, and the rest of the fields described in Table 1 are filled in automatically. Each notification results in another entry in the client's "outbox", which is emptied the next time the MOOSDB accepts an incoming call from the client.

3.3.2 Registering for Notifications

Assume that a list of names of data published has been provided by the author of a particular MOOS application. For example, a application that interfaces to a GPS sensor may publish data called `GPS_X` and `GPS_Y`. A different application may register its interest in this data by subscribing or registering for it. An application can register for notifications using a single method `Register` specifying both the name of the data and the maximum rate at which the client would like to be informed that the data has been changed. The latter parameter is specified in terms of the minimum possible time between notifications for a named variable. For example setting it to zero would result in the client receiving each and every change notification issued on that variable.

3.3.3 Reading Mail

A client can enquire at any time whether it has received any new notifications from the MOOSDB by invoking the `Fetch` method. The function fills in a list of notification messages with the fields given in Table 1. Note that a single call to `Fetch` may result in being presented with several notifications corresponding to the same named data. This implies that several changes were made to the data since the last client-server conversation. However, the time difference between these similar messages will never be less than that specified in the `Register` function described above. In typical applications the `Fetch` command is called on the client's behalf just prior to the `Iterate` method, and the messages are handled in the user overloaded `OnNewMail` method. These methods are described next.

3.4 Overloaded Functions in MOOS Applications

MOOS provides a base class called `CMOOSApp` which simplifies the writing of a new MOOS application as a derived subclass. Beneath the hood of the `CMOOSApp` class is a loop which repetitively calls

a function called `Iterate()` which by default does nothing. One of the jobs as a writer of a new MOOS-enabled application is to flesh this function out with the code that makes the application do what we want. Behind the scenes this uber-loop in `CMOOSApp` is also checking to see if new data has been delivered to the application. If it has, another virtual function, `OnNewMail()`, is called if this is the spot to write code to process the newly delivered data.

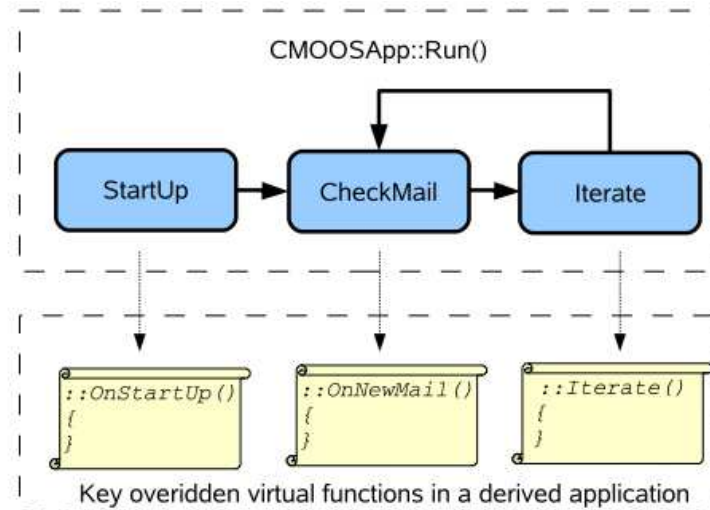


Figure 5: **Key virtual functions of the MOOS application base class:** The flow of execution once `Run()` has been called on a class derived from `CMOOSApp`. The scrolls indicate where users of the functionality of `CMOOSApp` will be writing new code that implements whatever it is that is wanted from the new applications.

The roles of the three virtual functions in Figure 5 are discussed below. The `pHelivP` application does indeed inherit from `CMOOSApp` and overload these three functions. The base class contains other virtual functions (`OnConnectToServer()` and `OnDisconnectFromServer()`) not discussed here but discussed in [15].

3.4.1 The `Iterate()` Method

By overriding the `CMOOSApp::Iterate()` function in a new derived class, the author creates a function from which the work that the application is tasked with doing can be orchestrated. In the `pHelivP` application, this method will consider the next best vehicle decision, typically in the form of deciding values for the vehicle heading, speed and depth. The rate at which `Iterate()` is called by the `SetAppFreq()` method or by specifying the `AppTick` parameter in a mission file (see Section 3.5 for more on configuring an application from a file). Note that the requested frequency specifies the maximum frequency at which `Iterate()` will be called - it does not guarantee that it will be called at the requested rate. For example if you write code in `Iterate()` that takes 1 second to complete there is no way that this method can be called at more than 1Hz. If you want to call `Iterate()` as fast as is possible simply request a frequency of zero - but you may want to reconsider why you need such a greedy application.

3.4.2 The `OnNewMail()` Method

Just before `Iterate()` is called, the `CMOOSApp` base class determines whether new mail is present, i.e., whether some other process has posted data for which the client has previously registered, as described above. If new mail is waiting, the `varCMOOSApp` base class calls the `OnNewMail()` virtual function, typically overloaded by the application. The mail arrives in the form of a list of `CMOOSMsg` objects (see Table 1). The programmer is free to iterate over this collection examining who sent the data, what it pertains to, how old it is, whether or not it is string or numerical data and to act on or process the data accordingly.

3.4.3 The `OnStartup()` Method

This function is called just before the application enters into its own forever-loop depicted in Figure 5. This is the application that implements the application's initialization code, and in particular reads configuration parameters (including those that modify the default behaviour of the `CMOOSApp` base class) from a file. The next section (3.5) addresses the issue of configuring a MOOS application from a file.

3.5 MOOS Mission Configuration Files

Every MOOS process can read configuration parameters from a mission file which by convention has a `.moos` extension. Traditionally MOOS processes share the same mission file to the maximum extent possible. For example, it is customary for there to be one common mission file for all MOOS processes running on a given machine. Every MOOS process has information contained in a configuration block within a `*.moos` file. The block begins with the statement

```
ProcessConfig = ProcessName
```

where `ProcessName` is the unique name the application will use when connecting to the MOOSDB. The configuration block is delimited by braces. Within the braces there is a collection of parameter statements, one per line. Each statement is written as:

```
ParameterName = Value
```

where `Value` can be any string or numeric value. All applications deriving from `CMOOSApp` inherit several important configuration options. The most important options for `CMOOSApp` derived applications are `CommsTick` and `AppTick`. The latter configures how often the communications thread talks to the MOOSDB and the former how often (approximately) `Iterate()` will be called. An example configuration block can be found in Listing 8 on page 50.

Parameters may also be defined at the “global” level, i.e., not in any particular process' configuration block. Three parameters that are mandatory and typically found at the top of all `*.moos` files are: `ServerHost` naming the IP address associated with the MOOSDB server being launched with this file, `ServerPort` naming the port number over which the MOOSDB server is communicating with clients, and `Community` naming the community comprising the server and clients. An example is shown in lines 1-3 in Listing 4-A.

3.6 Launching Groups of MOOS Applications with Antler

Antler provides a simple and compact way to start a MOOS mission comprised of several MOOS processes, a.k.a., a MOOS “community”. For example if the desired mission file is `alpha.moos` then executing the following from a terminal shell:

```
> pAntler alpha.moos
```

will launch the required processes for the mission. It reads from its configuration block (which is declared as `ProcessConfig=ANTLER`) a list of process names that will constitute the MOOS community. Each process to be launched is specified with a line with the general syntax

```
Run = procname [ @ LaunchConfiguration ] [ MOOSName ]
```

where `LaunchConfiguration` is an optional comma-separated list of `parameter=value` pairs which collectively control how the process `procname` (for example `pHelmIvP`, or `pLogger` or `MOOSDB`) is launched. Exactly what parameters can be specified is outside the scope of this discussion. Antler looks through its entire configuration block and launches one process for every line which begins with the `RUN=` left-hand side. When all processes have been launched Antler waits for all of them to exit and then quits itself.

There are many more aspects of Antler not discussed here but can be found in the Antler documentation at the Oxford website (see Section 1.5). These include hooks for altering the console appearance for each launched process, controlling the search path for specifying how executables are located on the host file system, passing parameters to launched processes, running multiple instances of a particular process, and using Antler to launch multiple distinct communities on a network.

3.7 Scoping and Poking the MOOSDB

An important tool for writing and debugging MOOS applications (and IvP Helm behaviors) is the ability for the user to interact with an active MOOS community and see the current values of particular MOOS variables (scoping the DB) and to alter one or more variables with a desired value (poking the DB). Below are listed tools for scoping and poking respectively. More information on each can be found on the Oxford or MIT websites, or in in some instances, other parts of this document.

Tools for scoping the MOOSDB:

- `uMS` - A GUI-based tool written in FLTK and maintained and distributed from the Oxford website.
- `uXMS` - A terminal-based tool maintained and distributed from the MIT website
- `uHelmScope` - A terminal-based tool specialized for displaying information about a running instance of the helm, but it also contains a general-purpose scoping utility similar to `uXMS`. Distributed from the MIT website.
- `MOOSDB http` - The newer releases of MOOS allow the `MOOSDB` to be configured to run an http server on the current `MOOSDB` variable-value pairs, viewable through a web browser.

Tools for poking the MOOSDB:

- `uMS` - The GUI-based tool for scoping, listed above, also provides a means for poking. Distributed from the Oxford website.
- `uPokeDB` - A light-weight command-line tool for poking one or more variable-value pairs, with the option of scoping on the before and after values of the poked variable before exiting. Distributed from the MIT website.
- `pMarineViewer` - A GUI-based tool primarily used for rendering the paths of vehicles in 2D space on a Geo display, but also can be configured to poke the DB with variable-value pairs connected to buttons on the display. Distributed from the MIT website.
- `uTermCommand` - A terminal-based tool for poking the DB with pre-defined variable-value pairs. The user can configure the tool to associate aliases (as short as a single character) to quickly poke the DB. Distributed from the MIT website.
- `iRemote` - A terminal-based tool for remote control of a robotic platform running MOOS. It can be configured to associate a pre-defined variable-value poke with any un-mapped key on the keyboard. Distributed from the Oxford website.

The above list is almost certainly not a complete list for scoping and poking a MOOSDB, but it's a decent start.

3.8 A Simple MOOS Application - `pXRelay`

The bundle of applications distributed from www.moos-ivp.org contains a very simple MOOS application called `pXRelay`. The `pXRelay` application registers for a single “input” MOOS variable and publishes a single “output” MOOS variable. It makes a single publication on the output variable for each mail message received on the input variable. The value published is simply a counter representing the number of times the variable has been published. By running two (differently named) versions of `pXRelay` with complementary input/output variables, the two processes will perpetuate some basic publish/subscribe handshaking. This application is distributed primarily as a simple example of a MOOS application that allows for some illustration of the following topics introduced up to this point:

- Finding and launching with `pAntler` example code distributed with the MOOS-IvP software bundle.
- An example mission configuration file.
- Scoping variables on a running MOOSDB with the `uXMS` tool.
- Poking the MOOSDB with variable-value pairs using the `uPokeDB` tool.
- Illustrating the `OnStartUp()`, `OnNewMail()`, and `Iterate()` overloaded functions of the `CMOOSApp` base class.

Besides touching on these topics, the collection of files in the `pXRelay` source code sub-directory is not a bad template from which to build your own modules.

3.8.1 Finding and Launching the pXRelay Example

The pXRelay example mission should be in the same directory tree containing the source code. See Section 1.4 on page 12. There is a single mission file, xrelay.moos:

```
moos-ivp/
  MOOS/
    ivp/
      missions/
        xrelay/
          xrelay.moos    <---- The MOOS file
```

To run this mission from a terminal window, simply change directories and launch:

```
> cd moos-ivp/ivp/missions/xrelay
> pAntler xrelay.moos
```

After pAntler has launched each process, there should be four open terminal windows, one for each pXRelay process, one for uXMS, and one for the MOOSDB itself.

3.8.2 Scoping the pXRelay Example with uXMS

Among the four windows launched in the example, the window to watch is the uXMS window, which should have output similar to the following (minus the line numbers):

Listing 1 - Example uXMS output after the pXRelay example is launched.

0	VarName	(S)ource	(T)ime	(C)ommunity	VarValue	
1	-----	-----	-----	-----	-----	(73)
2	APPLES	n/a	n/a	n/a	n/a	
3	PEARS	n/a	n/a	n/a	n/a	
4	APPLES_ITER_HZ	pXRelay_APPLES	14.93	xrelay	24.93561	
5	PEARS_ITER_HZ	pXRelay_PEARs	14.94	xrelay	24.93683	
6	APPLES_POST_HZ	n/a	n/a	n/a	n/a	
7	PEARS_POST_HZ	n/a	n/a	n/a	n/a	

Initially the only thing that is changing in this window is the integer at the end of line 1 representing the number of updates written to the terminal. Here uXMS is configured to scope on the six variables shown in the VarName column. Column 2 shows which process last posted on the variable, column 3 shows when the last posting occurred, column 4 shows the community name from which the post originated, and column 5 shows the current value of the variable. The "n/a" entries indicate that a process has yet to write to the given variable. For further info on the workings of uXMS see [4], or type 'h' to see the help menu.

There are two pXRelay processes running - one under the alias pXRelay_APPLES publishing the variable APPLES as its output variable, APPLES_ITER_HZ indicating the frequency in which the Iterate() function is executed, and APPLES_POST_HZ indicating the frequency at which the output variable is posted. There is likewise a pXRelay_PEARs process and the corresponding output variables.

3.8.3 Seeding the pXRelay Example with the uPokeDB Tool

Upon launching the pXRelay example, the only variables actively changing are the *_ITER_HZ variables (lines 4-5 in Listing 1) which confirm that the Iterate() loop in each process is indeed being

executed. The output for the other variables in Listing 1 reflect the fact that the two processes have not yet begun handshaking. This can be kicked off by poking the APPLES (or PEARS) variable, which is the input variable for pXRelay_PEARs, by typing the following:

```
> cd moos-ivp/ivp/missions/xrelay
> uPokeDB xrelay.moos APPLES=1
```

The uPokeDB tool will publish to the MOOSDB the given variable-value pair APPLES=1. It also takes as an argument the mission file, xrelay.moos, to read information on where the MOOSDB is running in terms of machine name and port number. The output should look similar to the following:

Listing 2 - Example uPokeDB output after poking the MOOSDB with APPLES=1.

```
0 PRIOR to Poking the MOOSDB
1  VarName          (S)ource      (T)ime      VarValue
2  -----          -
3  APPLES
4
5
6 AFTER Poking the MOOSDB
7  VarName          (S)ource      (T)ime      VarValue
8  -----          -
9  APPLES           uPokeDB       40.19       1.00000"
```

The output of uPokeDB first shows the value of the variable prior to the poke, and then the value afterwards. Further information on the uPokeDB tool can be found in [4]. Once the MOOSDB has been poked as above, the pXRelay_PEARs application will receive this mail and, in return, will write to its output variable PEARs, which in turn will be read by pXRelay_APPLES and the two processes will continue thereafter to write and read their input and output variables. This progression can be observed in the uXMS terminal, which may look something like that shown in Listing 3:

Listing 3 - Example uXMS output after the pXRelay example is seeded.

```
0  VarName          (S)ource      (T)ime      (C)ommunity  VarValue
1  -----          -
2  APPLES           pXRelay_APPLES 44.78      xrelay       151
3  PEARS            pXRelay_PEARs  44.74      xrelay       151
4  APPLES_ITER_HZ   pXRelay_APPLES 44.7        xrelay       24.90495
5  PEARS_ITER_HZ    pXRelay_PEARs  44.7        xrelay       24.90427
6  APPLES_POST_HZ   pXRelay_APPLES 44.79      xrelay       8.36411
7  PEARS_POST_HZ    pXRelay_PEARs  44.74      xrelay       8.36406
```

Upon each write to the MOOSDB the value of the variable is incremented by 1, and the integer progression can be monitored in the last column on lines 2-3. The APPLES_POST_HZ and PEARS_POST_HZ variables represent the frequency at which the process makes a post to the MOOSDB. This of course is different than (but bounded above by) the frequency of the Iterate() loop since a post is made within the Iterate() loop only if mail had been received prior to the outset of the loop. In a world with no latency, one might expect the “post” frequency to be exactly half of the “iterate” frequency. We would expect the frequency reported on lines 6-7 to be no greater than 12.5, and in this case values of about 8.4 are observed instead.

3.8.4 The pXRelay Example MOOS Configuration File

The mission file used for the pXRelay example, `xrelay.moos` is discussed here. This file is provided as part of the MOOS-IvP software bundle under the “missions” directory as discussed above in Section 3.8.1. It is discussed here in three parts in Listings 4-A through 4-C below.

The part of the `xrelay.moos` file provides three mandatory pieces of information needed by the MOOSDB process for launching. The MOOSDB is a server and on line 1 is the IP address for the machine, and line 2 indicates the port number where clients can expect to find the MOOSDB once it has been launched. Since each MOOSDB and the set of connected clients form a MOOS “community”, the community name is provided on line 3. Note the `xrelay` community name in the `xrelay.moos` file and the community name in column 4 of the `uXMS` output in Listing 1 above.

Listing 4-A - The `xrelay.moos` mission file for the pXRelay example.

```

1  ServerHost = localhost
2  ServerPort = 9000
3  Community = xrelay
4
5  //-----
6  // Antler configuration block
7  ProcessConfig = ANTLER
8  {
9      MSBetweenLaunches = 200
10
11     Run = MOOSDB @ NewConsole = true
12     Run = pXRelay @ NewConsole = true ~ pXRelay_PEARs
13     Run = pXRelay @ NewConsole = true ~ pXRelay_APPLES
14     Run = uXMS @ NewConsole = true
15 }
```

The configuration block in lines 7-15 of `xrelay.moos` is read by the `pAntler` for launching the processes or clients of the MOOS community. Line 9 specifies how much time, in milliseconds, between the launching of processes. Lines 11-14 name the four MOOS applications launched in this example. On these lines, the component “`NewConsole = true`” determines whether a new console window will be opened for each process. Try changing them to `false` - only the `uXMS` window really needs to be open. The others merely provide a visual confirmation that a process has been launched. The “`~ pXRelay_PEARs`” component of lines 12 and 13 tell `pAntler` to launch these applications with the given alias. This is required here since each MOOS client needs to have a unique name, and in this example two instances of the `pXRelay` process are being launched.

In lines 17-39 in Listing 4-B below, the two `pXRelay` applications are configured. Note that the argument to `ProcessConfig` on lines 20 and 32 is the alias for `pXRelay` specified in the Antler configuration block on lines 12 and 13. Each `pXRelay` process is configured such that its incoming and outgoing MOOS variables complement one another on lines 25-26 and 37-38. Note the `AppTick` parameter (see Section 3.4.1) is set to 25 in both configuration blocks, and compare with the observed frequency of the `Iterate()` function reported in the variables `APPLES_ITER_HZ` and `PEARs_ITER_HZ` in Listing 1. MOOS has done a pretty faithful job in this example of honoring the requested frequency of the `Iterate()` loop in each application.

Listing 4-B - The `xrelay.moos` mission file - configuring the pXRelay processes.

```

17 //-----
18 // pXRelay config block
```



```

19
20 ProcessConfig = pXRelay_APPLES
21 {
22     AppTick      = 25
23     CommsTick    = 25
24
25     OUTGOING_VAR = APPLES
26     INCOMING_VAR = PEARS
27 }
28
29 //-----
30 // pXRelay config block
31
32 ProcessConfig = pXRelay_PEARs
33 {
34     AppTick      = 25
35     CommsTick    = 25
36
37     INCOMING_VAR = APPLES
38     OUTGOING_VAR = PEARS
39 }

```

In the last portion of the `xrelay.moos` file, shown in Listing 4-C below, the `uXMS` process is configured. In this example, `uXMS` is configured to scope on the six variables specified on lines 54-59 to give the output shown in Listings 1 and 3. By setting the `PAUSED` parameter on line 49 to `false`, the output of `uXMS` is continuously and automatically updated - in this case four times per second due to the rate of 4Hz specified in lines 46-47. The `DISPLAY_*` parameters in lines 50-52 ensure that the output in columns 2-4 of the `uXMS` output is expanded. See [4] for further ways to configure the `uXMS` tool.

Listing 4-C - The `xrelay.moos` mission file for the `pXRelay` example - configuring `uXMS`.

```

41 //-----
42 // uXMS config block
43
44 ProcessConfig = uXMS
45 {
46     AppTick      = 4
47     CommsTick    = 4
48
49     PAUSED       = false
50     DISPLAY_SOURCE = true
51     DISPLAY_TIME  = true
52     DISPLAY_COMMUNITY = true
53
54     VAR = APPLES
55     VAR = PEARS
56     VAR = APPLES_ITER_HZ
57     VAR = PEARS_ITER_HZ
58     VAR = APPLES_POST_HZ
59     VAR = PEARS_POST_HZ
60 }

```

3.8.5 Suggestions for Further Things to Try with this Example

- Take a look at the `OnStartup()` method in the `XRelay.cpp` class in the `pXRelay` module in the software bundle to see how the handling of parameters in the `xrelay.moos` configuration file are implemented, and the subscription for a MOOS variable.

- Take a look at the `OnNewMail()` method in the `XRelay.cpp` class in the `pXRelay` module in the software bundle to see how incoming mail is parsed and handled.
- Take a look at the `Iterate()` method in the `XRelay.cpp` class in the `pXRelay` module in the software bundle to see an example of a MOOS process that acts upon incoming mail and conditionally posts to the MOOSDB
- Try changing the `AppTick` parameter in *one* of the `pXRelay` configuration blocks in the `xrelay.moos` file, re-start, and note the resulting change in the iteration and post frequencies in the `uXMS` output.
- Try changing the `CommsTick` parameter in *one* of the `pXRelay` configuration blocks in the `xrelay.moos` file to something much lower than the `AppTick` parameter, re-start, and note the resulting change in the iteration and post frequencies in the `uXMS` output.

3.9 MOOS Applications Available to the Public

Below are very brief descriptions of MOOS applications in the public domain. This is by no means a complete list. It does not include applications outside MIT, Oxford and NUWC, and it is not even a complete list of applications from those organizations. For a more in-depth tour of MOOS applications, see [5].

3.9.1 MOOS Modules from Oxford

- `pAntler`: A tool for launching a collection of MOOS processes given a mission file. See [15], [14]. Also, see Section 4.3.1.
- `pMOOSBridge`: A tool that allows messages to pass between communities and allows for the renaming of messages as they are shuffled between communities. See [15], [14].
- `pLogger`: A logger for recording the activities of a MOOS session. It can be configured to record a fraction of, or all publications of any number of MOOS variables. See [5], [14].
- `pScheduler`: A simple tool for generating and responding to messages sent to the MOOSDB by processes in a MOOS community. See [5], [14].
- `uMS`: A GUI-Based MOOS scope for monitoring one or more MOOSDBs. See [5], [14].
- `uPlayback`: An FLTK-based, cross platform GUI application that can load in log files and replay them into a MOOS community as though the originators of the data were really running and issuing notifications. See [5], [14].
- `iMatlab`: An application that allows matlab to join a MOOS community - even if only for listening in and rendering sensor data. It allows connection to the MOOSDB and access to local serial ports. See [5], [14].
- `iRemote`: A terminal-based tool for remote control of a robotic platform running MOOS. It can be configured to associate a pre-defined variable-value poke with any un-mapped key on the keyboard. See [5], [14].

- **uMVS**: A multi-vehicle AUV simulator, capable of simulating any number of vehicles and acoustic ranging between them and acoustic transponders. The vehicle simulation incorporates a full 6 D.O.F vehicle model replete with vehicle dynamics, center of buoyancy / center of gravity geometry, and velocity dependent drag. The acoustic simulation is also fairly smart. It simulates acoustic packets propagating as spherical shells through the water column. See [5], [14].

3.9.2 MOOS Modules from MIT and NUWC

- **pHelmIvP**: The IvP Helm, and primary focus of this document.
- **pNodeReporter**: The `pNodeReporter` application garners vehicle navigation information such as position, speed, heading, yaw and depth, along with high-level helm information such as its operation mode, and publishes a summary variable, `NODE_REPORT_LOCAL`, which is consumed by viewer applications such as `pMarineViewer`, and as input to other vehicles participating in cooperative tasks.
- **uHelmScope**: A terminal-based tool specialized for displaying information about a running instance of the helm, but it also contains a general-purpose scoping utility similar to `uXMS`. See [4], [7]. Also, see Section 11.
- **uPokeDB**: A light-weight command-line tool for poking one or more variable-value pairs, with the option of scoping on the before and after values of the poked variable before exiting. See [4], [7]. Also, see Sections 3.7 and 3.8.3.
- **pMarineViewer**: A GUI-based tool primarily used for rendering the paths of vehicles in 2D space on a Geo display, but also can be configured to poke the DB with variable-value pairs connected to buttons on the display. See [4], [7]. Also, see Section 13.
- **uXMS**: A terminal based tool for live scoping on a MOOSDB process. See [4], [7]. Also, see Sections 3.7 and 3.8.2..
- **iMarineSim**: A very simple single-vehicle simulator that updates vehicle state based on present actuator values. Runs locally in the MOOS community associated with the simulated vehicle, so, unlike `uMVS`, there is one `iMarineSim` process running per each vehicle.
- **pEchoVar**: A lightweight process that runs without user interaction for “echoing” specified variable-value pairs posted with a follow-on post having different variable name.
- **pMarinePID**: An application providing simple PID control for vehicle speed-thrust, heading-rudder, and depth-pitch.
- **uFunctionVis**: A application for live rendering of objective functions produced by the IvP Helm behaviors. See [7].
- **uProcessWatch**: An application for monitoring the presence (connection) of a set of MOOS processes to a running MOOSDB. Status is summarized by a single published variable. See [4], [7].

- `uTermCommand`: A terminal-based tool for poking the DB with pre-defined variable-value pairs. The user can configure the tool to associate aliases (as short as a single character) to quickly poke the DB. See [4], [7].
- `uTimerScript`: A MOOS application that will poke the MOOSDB with pre-defined variable-value pairs in a script that may repeat. Not unlike `pScheduler`, but it can do some additional things such as jump forward or pause in the script based on MOOS notifications. It may also schedule its events to occur at a random point in a fixed time interval. See [4], [7].

4 A First Example with MOOS-IvP - the Alpha Mission

In this section a simple mission is described using the IvP Helm. This example is designed to run in simulation on a single desktop/laptop machine. The mission configuration files for this example are distributed with the source code. Information on how to find these files and launch this mission are described below in Section 4.1. In this example the vehicle simply traverses a set of pre-defined given waypoints and returns back to the launch position. The user may re-call the vehicle prematurely before completing the waypoints, and may subsequently command the vehicle to resume the waypoints at any time. By this example the objective is to touch the following issues:

- Launching a mission with a given mission (.moos) file and behavior (.bhv) file.
- Configuration of MOOS processes, including the IvP Helm, with a .moos file.
- Configuration of the IvP Helm (mission planning) with a .bhv file.
- Implementation of simple command and control with the IvP Helm.
- Interaction between MOOS processes and the helm during normal mission operation.

4.1 Where to Find, and How to Launch the Alpha Example Mission

The example mission should be in the same directory tree containing the source code (See Section 1.4). There are two files - a MOOS file, also mission file or .moos file, and a behavior file or .bhv file:

```
moos-ivp/  
  MOOS/  
    ivp/  
      missions/  
        alpha/  
          alpha.moos    <---- The MOOS file  
          alpha.bhv     <---- The Behavior file
```

To run this mission from a terminal window, simply change directories and launch:

```
> cd moos-ivp/ivp/missions/alpha  
> pAntler alpha.moos
```

After pAntler has launched each process, the pMarineViewer window should be open and look similar to that shown in Figure 6. After clicking the DEPLOY button in the lower right corner the vehicle should start to traverse the shown set of waypoints.

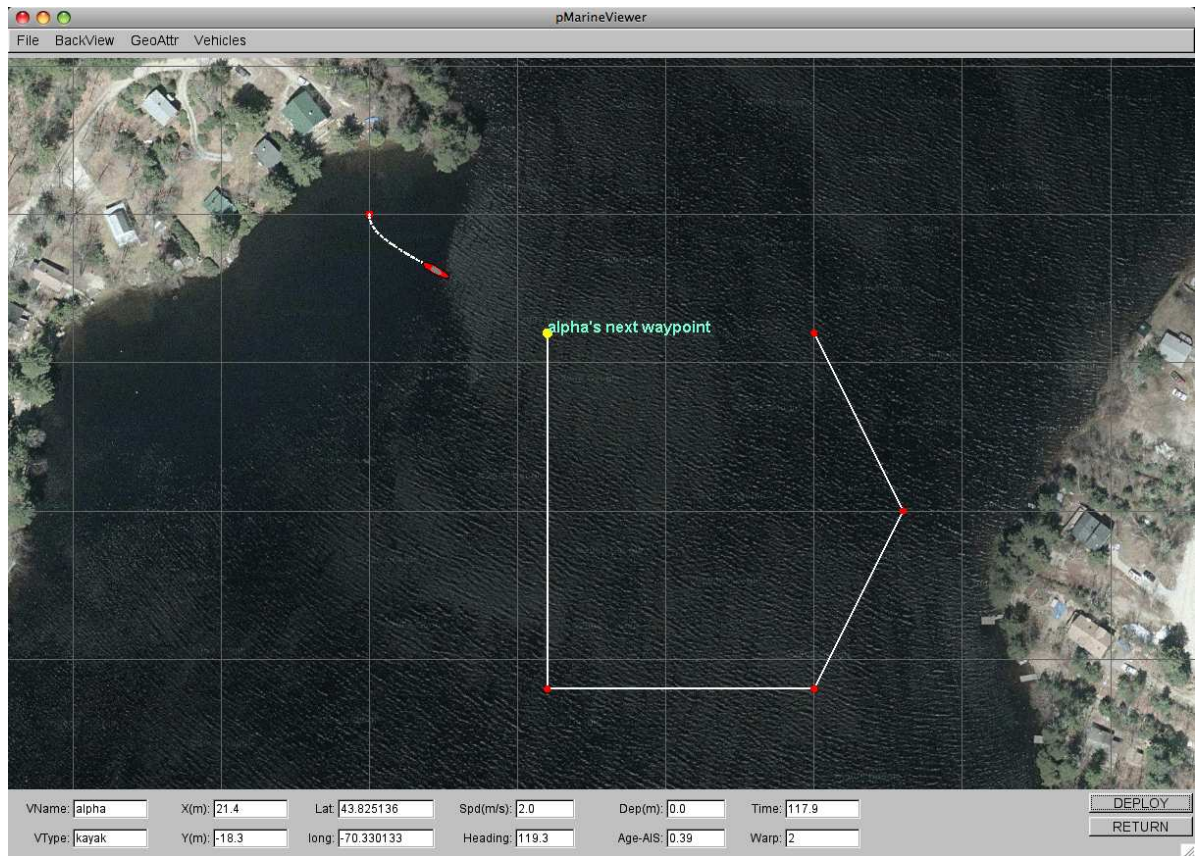


Figure 6: **The Alpha Example Mission - In the Surveying Mode**: A single vehicle is dispatched to traverse a set of waypoints and, upon completion, traverse to the waypoint (0,0) which is the launch point.

This mission will complete on its own with the vehicle returning to the launch point. Alternatively, by hitting the RETURN button at any time before the points have been traverse, the vehicle will change course immediately to return to the launch point, as shown in Figure 7. When the vehicle is returning as in the figure, it can be re-deployed by hitting the DEPLOY button again.

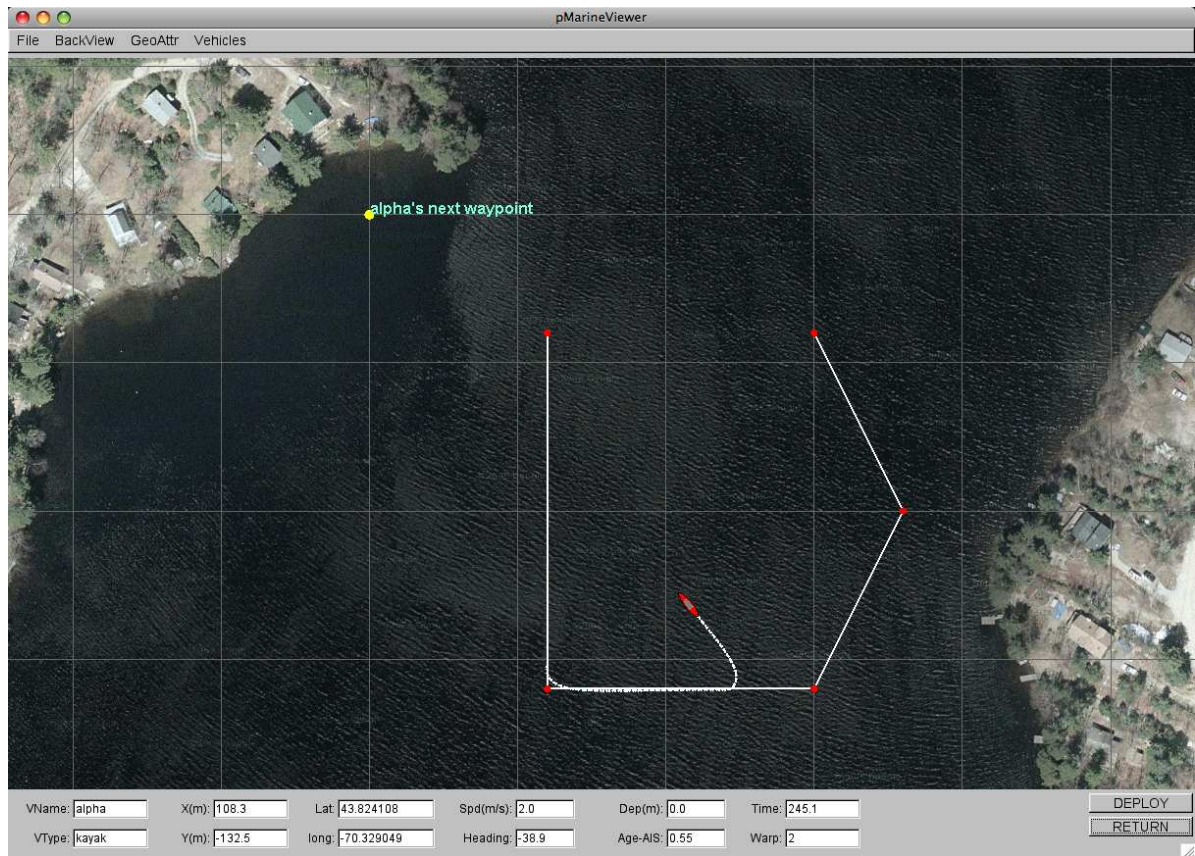


Figure 7: **The Alpha Example Mission - In the Returning Mode**: The vehicle can be commanded to return prior to the completion of its waypoints by the user clicking the RETURN button on the viewer.

The vehicle in this example is configured with two basic waypoint behaviors. Their configuration with respect to the points traversed and when each behavior is actively influencing the vehicle, is discussed next.

4.2 A Closer Look at the Behavior File used in the Alpha Example Mission

The mission configuration of the helm behaviors is provided in a *behavior file*, and the complete behavior file for the example mission is shown in Listing 5. Behaviors are configured in blocks of parameter-value pairs - for example lines 6-17 configure the waypoint behavior with the five waypoints shown in the previous two figures. This is discussed in more detail in Section 6.3.

Listing 5: The behavior file for the Alpha example.

```

0 initialize   DEPLOY = false
1 initialize   RETURN = false
2
3 //-----
4 Behavior = BHV_Waypoint
5 {
6   name      = waypt_survey
7   pwt       = 100

```

```

 8   condition = RETURN = false
 9   condition = DEPLOY = true
10   endflag   = RETURN = true
11   perpetual = true
12
13       lead = 8
14   lead_damper = 1
15       speed = 2.0 // meters per second
16       radius = 4.0
17   nm_radius = 10.0
18       points = 60,-40:60,-160:150,-160:180,-100:150,-40
19       repeat = 1
20 }
21
22 //-----
23 Behavior = BHV_Waypoint
24 {
25     name      = waypt_return
26     pwt       = 100
27     condition = RETURN = true
28     condition = DEPLOY = true
29     perpetual = true
30     endflag   = RETURN = false
31     endflag   = DEPLOY = false
32
33     speed = 2.0
34     radius = 2.0
35     nm_radius = 8.0
36     point = 0,0
37 }

```

The parameters for each behavior are separated into two groups. Parameters such as `name`, `priority`, `condition` and `endflag` are parameters defined generally for all IvP behaviors. Parameters such as `speed`, `radius`, and `points` are defined specifically for the Waypoint behavior. A convention used in `.bhv` files is to group the general behavior parameters separately at the top of the configuration block.

In this mission, the vehicle follows two sets of waypoints in succession by configuring two instances of a basic waypoint behavior. The second waypoint behavior (lines 23-37) contains only a single waypoint representing the vehicle launch point (0,0). It's often convenient to have the vehicle return home when the mission is completed - in this case when the first waypoint behavior has reached its last waypoint. Although it's possible to simply add (0,0) as the last waypoint of the first waypoint behavior, it is useful to keep it separate to facilitate recalling the vehicle pre-maturely at any point after deployment.

Behavior conditions (lines 8-9, 27-28), and endflags (line 10, lines 30-31) are primary tools for coordinating separate behaviors into a particular mission. Behaviors will not participate unless each of its conditions are met. The conditions are based on current values of the MOOS variables involved in the condition. For example, both behaviors will remain idle unless the variable `DEPLOY` is set to `true`. This variable is set initially to be `false` by the initialization on line 0, and is toggled by the `DEPLOY` button on the `pMarineViewer` GUI shown in Figures 6 and 7. The `pMarineViewer` MOOS application is one option for a command and control interface to the helm. The MOOS variables in the behavior conditions in Listing 5 do not care which process was responsible for setting the value. Endflags are used by behaviors to post a MOOS variable and value when a behavior has reached a completion. The notion of completion is different for each behavior and some behaviors have no notion of completion, but in the case of the waypoint behavior, completion is declared when the

last waypoint is reached. In this way, behaviors can be configured to run in a sequence, as in this example, where the returning waypoint behavior will have a necessary condition (line 27) met when the surveying behavior posts its endflag on line 10.

4.3 A Closer Look at the MOOS Applications In the Alpha Example Mission

Running the example mission involves five other MOOS applications in addition to the IvP helm. In this section we take a closer look at what those applications do and how they are configured. The full MOOS file, `alpha.moos`, used to run this mission is given in full in the appendix. An overview of the situation is shown in Figure 8.

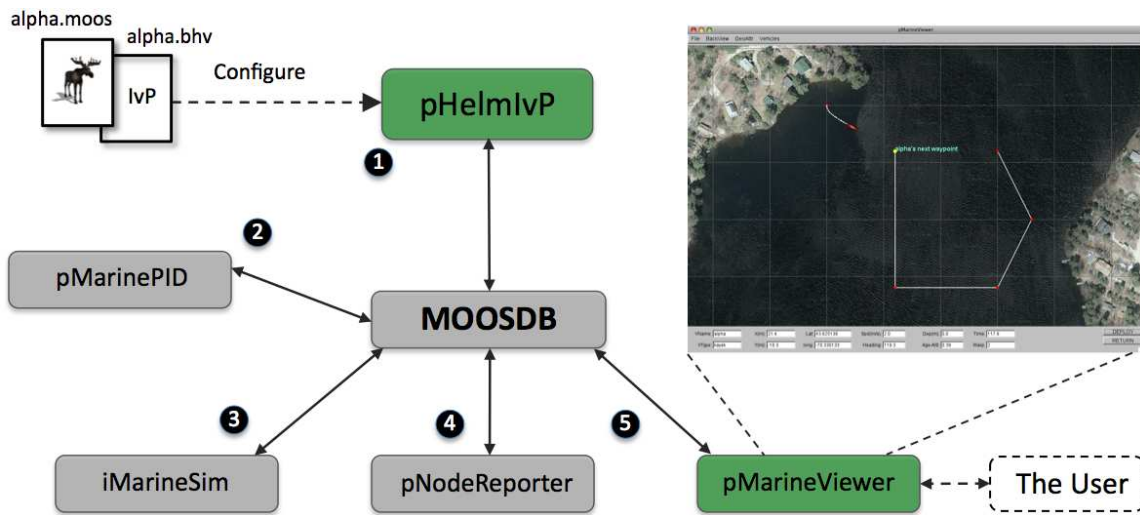


Figure 8: **The MOOS processes in the example “alpha” mission:** In (1) The helm produces a desired heading and speed. In (2) the PID controller subscribes for the desired heading and speed and publishes actuation values. In (3) the simulator grabs the actuator values and the current vehicle pose and publishes a set of MOOS variables representing the new vehicle pose. In (4) all navigation output is wrapped into a single node-report string to be consumed by the helm and the GUI viewer. In (5) the pMarineViewer grabs the node-report and renders a new vehicle position. The user can interact with the viewer to write limited command and control variables to the MOOSDB.

4.3.1 Antler and the Antler Configuration Block

The `pAntler` tool is used to orchestrate the launching of all the MOOS processes participating in this example. From the command line, `pAntler` is run with a single argument the `.moos` file. As it launches processes, it hands each process a pointer to this same MOOS file. The Antler configuration block in this example looks like:

Listing 6 - An example Antler configuration block for the Alpha mission.

```

0 ProcessConfig = ANTLER
1 {
2   MSBetweenLaunches = 200
3
4   Run = MOOSDB           @ NewConsole = false

```

```

5   Run = iMarineSim      @ NewConsole = false
6   Run = pNodeReporter  @ NewConsole = false
7   Run = pMarinePID     @ NewConsole = false
8   Run = pMarineViewer  @ NewConsole = false
9   Run = pHelmIvP       @ NewConsole = false
10  }

```

The first parameter on line 2 specifies how much time should be left between the launching of each process. Lines 4-9 specify which processes to launch. The MOOSDB is typically launched first. The `NewConsole` switch on each line determines whether a new console window should be opened with each process. Try switching one or more of these to `true` as an experiment.

4.3.2 The pMarinePID Application and Configuration Block

The `pMarinePID` application implements a simple PID controller which produces values suitable for actuator control based on inputs from the helm. The full configuration for this block can be found in the appendix. In simulation the output is consumed by the vehicle simulator rather than the vehicle actuators.

In short: The `pMarinePID` application typically gets its info from `pHelmIvP`; produces info consumed by `iMarineSim` or actuator MOOS processes when not running in simulation.

Subscribes to: `DESIRED_HEADING`, `DESIRED_SPEED`.

Publishes to: `DESIRED_RUDDER`, `DESIRED_THRUST`.

4.3.3 The iMarineSim Application and Configuration Block

The `iMarineSim` application is a very simple vehicle simulator that considers the current vehicle pose and actuator commands and produces a new vehicle pose. It can be initialized with a given pose as shown in the configuration block used in this example, shown in Listing 7:

Listing 7 - An example iMarineSim configuration block for the Alpha mission.

```

0   ProcessConfig = iMarineSim
1   {
2     AppTick    = 10
3     CommsTick  = 10
4
5     START_X    = 0
6     START_Y    = 0
7     START_SPEED = 0
8     START_HEADING = 180
9     PREFIX     = NAV
10  }

```

In short: The `iMarineSim` application typically gets its info from `pMarinePID`; produces info consumed by `pNodeReporter` and itself on the next iteration of `iMarineSim`.

Subscribes to: `DESIRED_RUDDER`, `DESIRED_THRUST`, `NAV_X`, `NAV_Y`, `NAV_SPEED`, `NAV_HEADING`.

Publishes to: `NAV_X`, `NAV_Y`, `NAV_HEADING`, `NAV_SPEED`.

4.3.4 The pNodeReporter Application and Configuration Block

An Automated Information System (AIS) is commonplace on many larger marine vessels and is comprised of a transponder and receiver that broadcasts one's own vehicle ID and pose to other nearby vessels equipped with an AIS receiver. It periodically collects all latest pose elements, e.g., latitude and longitude position and latest measured heading and speed, and wraps it up into a single update to be broadcast. This MOOS process collects pose information by subscribing to the MOOSDB for NAV_X, NAV_Y, NAV_HEADING, NAV_SPEED, and NAV_DEPTH and wraps it up into a single MOOS variable called NODE_REPORT_LOCAL. This variable in turn can be subscribed to another MOOS process connected to an actual serial device acting as an AIS transponder. For our purposes, this variable is also subscribed to by pMarineViewer for rendering a vehicle pose sequence.

In short: The pNodeReporter application typically gets its info from iMarineSim or otherwise on-board navigation systems such as GPS or compass; produces info consumed by pMarineViewer and instances of pHelmvP running in other vehicles or simulated vehicles.

Subscribes to: NAV_X, NAV_Y, NAV_SPEED, NAV_HEADING.

Publishes to: NODE_REPORT_LOCAL

4.3.5 The pMarineViewer Application and Configuration Block

The pMarineViewer is a MOOS process that subscribes to the MOOS variable NODE_REPORT_LOCAL and NODE_REPORT which contains a vehicle ID, pose and timestamp. It renders the updated vehicle(s) position. It is a multi-threaded process to allow both communication with MOOS and let the user pan and zoom and otherwise interact with the GUI. It is non-essential for vehicle operation, but essential for visually confirming that all is going as planned.

In short: The pMarineViewer application typically gets its info from pNodeReporter and pHelmvP; produces info consumed by pHelmvP when configured to have command and control hooks (as in this example).

Subscribes to: NODE_REPORT, NODE_REPORT_LOCAL, VIEW_POINT, VIEW_SEGLIST, VIEW_POLYGON, VIEW_MARKER.

Publishes to: Depends on configuration, but in this example: DEPLOY, RETURN.

Part II

The IvP Helm and Behaviors

5 The IvP Helm as a MOOS Application

In this section the helm is discussed in terms of its identity as a MOOS application - its MOOS configuration parameters, its `Iterate()` loop, its output to the console, and its output in terms of publications to other applications running in the MOOS community. The helm *engagement status* and *all-stop status* are also introduced since they are the highest level descriptions regarding helm activity.

5.1 Overview

The IvP Helm is implemented as the MOOS module called `pHelmIvP`. On the surface it is similar to any other MOOS application - it runs as a single process that connects to a running MOOSDB process interfacing solely by a publish-subscribe interface, as depicted in Figure 9. It is configured from a behavior file, or `.bvh` file, in addition to the MOOS file used to configure other MOOS applications. The helm primarily publishes a steady stream of information that drives the platform, typically regarding the desired heading, speed or depth. It may also publish information conveying aspects of the autonomy state that may be useful for monitoring, debugging or triggering other algorithms either within the helm or in other MOOS processes. The helm can be configured to generate decisions over virtually any user-defined decision space.

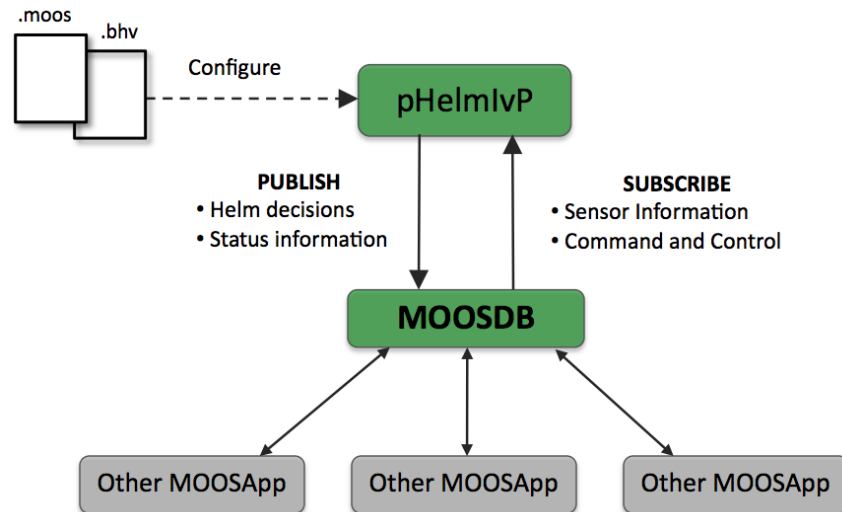


Figure 9: **The `pHelmIvP` MOOS application:** The IvP Helm is implemented as the MOOS application `pHelmIvP`. The helm is configured with two files - the mission file and behavior file. Once launched it connects to the MOOSDB along with other MOOS applications performing other functions. Information flowing into the helm include both sensor information and command and control inputs. The helm produces commands for maneuvering the vehicle along with other status information produced by active behaviors.

The helm subscribes for sensor information or any other information it needs to make decisions. This information includes navigation information regarding the platform's current position and trajectory, information regarding the position or state of other vehicles, or environmental in-

formation. The information it subscribes for is prescribed by the behaviors themselves, configured in the `.bhv` file. In addition to sensor information, the helm also receives some level of command and control information. For example, in some marine vehicle configurations, one of the “Other MOOSApp” modules in the figure is a driver for an acoustic modem over which command and control information may be relayed.

The helm has a couple informative high-level state descriptions, the *engagement mode* and the *all-stop status*, that may be compared to the operation of an automobile. Launching the `pHelmIvP` MOOS process is analagous to turning on the car’s engine. Putting the helm in the engaged mode is like shifting the car from “Park” to “Drive”. And the all-stop status refers whether or not the car is breaking to a stop. The analogy is summarized below.

IvP Helm	Automobile
Helm: Running / Not Running	Engine: On / Off
Engagement: Engaged / Disengaged	Gear: Drive / Park
All-Stop: Clear / Not Clear	Pedals: Gas / Break

Figure 10: **The Helm/Automobile Analogy:** The helm and its high-level state descriptions, the *engagement mode* and *all-stop status*, have analogies with the operation of an automobile.

5.2 Helm Engagement

The highest level interface with the helm concerns simply whether it is *engaged* or *disengaged*. In the engaged mode, the helm is likely in the process of executing a mission. In the disengaged mode, the helm is standing by, likely because it is being asked to stand by, but also because the helm may have noticed something wrong (generated an all-stop) and subsequently disengaged on its own and is waiting for re-engagement. In this section we discuss (a) how the engagement is changed, (b) what it is going on in the helm when it is disengaged, (c) how the helm engagement state is initialized at start-up. At any point in time after the helm is launched, the helm will post the MOOS variable `IVPHELM_ENGAGED` with either the value "ENGAGED" or "DISENGAGED". This is posted on each iteration and registering for this mail is the manner recommended by which other MOOS applications monitor the helm’s heart beat.

Helm Engagement Transitions

The helm engagement state can be transitioned by writing to the MOOS variable `MOOS_MANUAL_OVERRIDE`. As Figure 11 depicts, a value of `false`, which is case insensitive, puts the helm in the `ENGAGED` state. A value of `true` puts it into the `DISENGAGED` state. When the helm transitions from `ENGAGED` to `DISENGAGED` it makes *one* more publication to the helm decision variables, each with a value zero.

This is referred to as the production of an *all-stop posting*, discussed in more detail in a later section.

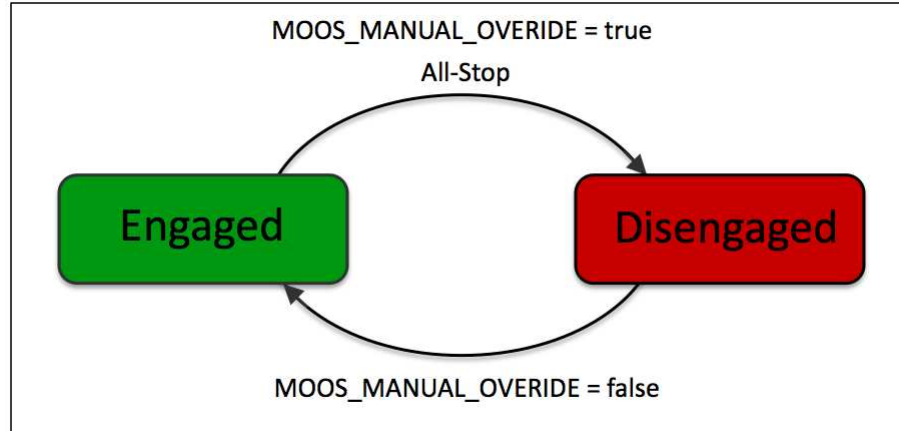


Figure 11: **The Engagement Mode of the IvP Helm:** The helm is either `ENGAGED` or `DISENGAGED`, depending on both how the helm is initialized and mail received by the helm after start-up on the variable `MOOS_MANUAL_OVERRIDE`. The helm may also disengage itself if an all-stop event has been detected.

The variable `MOOS_MANUAL_OVERRIDE` contains the mis-spelling of “override”. However, it is a variable that has some legacy presence in other MOOS applications such as `iRemote`. To avoid a situation where there is an attempt to override the helm, but the request is ignored because of a (proper) spelling, the helm will also respect transition requests on the properly spelled variable `MOOS_MANUAL_OVERRIDE`. This has the drawback however that these two variables could conceivably have different values in the MOOSDB. This is not a problem but could be confusing for someone trying to infer the engagement state by opening a scope on the MOOSDB, on either the wrong variable or the two disagreeing variables. In this case the helm engagement state would be aligned with the variable with the most recent publication time stamp. In any event, the best way to monitor the helm engagement state is to scope on the MOOS variable `IVPHELM_ENGAGEMENT`, published by the helm itself, or use the `uHelmScope` tool.

The helm may also automatically transition itself from the `ENGAGED` to the `DISENGAGED` state (but never the other way around), by posting and all-stop event. All-stop events and the helm are discussed separately in Section 5.3. All-stop events are generated by the helm upon finding that one or more possible error conditions have been detected during the normal execution of its helm iteration. If the helm disengages due to an all-stop, it can be re-engaged by another MOOS client posting `MOOS_MANUAL_OVERRIDE=false`, but this is no guarantee that the helm wouldn’t just disengage again immediately if the same condition persists that caused the all-stop event.

What Is and Isn’t Happening when the Helm is Disengaged

When the helm is in the `DISENGAGED` state, the MOOS application loop depicted in Figure 5 on page 25 carries on. The `OnNewMail()` continues to be called and new mail is read and dealt with exactly as it would if the helm were in the `ENGAGED` state. The `Iterate()` loop, however, is truncated to

virtually a no-op, with the only action being the output of a heartbeat character to the console if the helm is configured to do so (Section 5.5). No behavior code is called whatsoever. The helm iteration counter, a key index in the `uHelmScope` output, is also suspended despite the fact that technically the `Iterate()` loop continues to be called.

Initializing the Helm Engagement State at Process Launch Time

The helm, by default, is configured to be initially in the `DISENGAGED` state upon start-up. By setting the parameter `START_ENGAGED=true` in the mission file configuration block, the helm will indeed be in the `ENGAGED` state upon start-up. This feature was found to have practical use in UUV operations to allow for rebooting of the autonomy computer to automatically launch the helm, engaged and ready to accept field commands. This feature should be used with caution, and it may be phased out in a later software release.

5.3 Helm All-Stop Events and Status

An *all-stop event* is something that brings the vehicle to a full-stop, with typically zero-speed, zero-depth commanded. The *all-stop status* is simply a string describing *why* the vehicle is at an all-stop. Sometimes an all-stop indicates a problem, e.g., missing critical sensor information. Sometimes a vehicle may just stop as part of the mission, e.g., coming to the surface for a GPS fix. The all-stop status message can be used to discern the two types of situations. In the automobile analogy, an all-stop is equivalent to hitting the car's breaks with the intent to stop completely. An all-stop event will result in the following:

- Zero-values will be posted for all decision variables, `DESIRED_SPEED=0`, `DESIRED_DEPTH=0`, etc.
- The helm will possibly transition into the `DISENGAGED` state (putting the car in "park" by analogy). By default the helm is configured to remain in the `ENGAGED` state upon an all-stop, but if configured instead with `DISENGAGED_ON_ALLSTOP=true`, the helm will indeed disengage upon an all-stop.
- The reason for the all-stop will be posted to MOOS variable `IVPHELM_ALLSTOP`. The value of this variable will be `"clear"` if there are no all-stop events that have occurred since the helm has entered the `ENGAGED` state.

The reasons for all-stop may be:

- No behaviors are active. The helm has absolutely no opinion about any of its decision variables. In this case, the following would be posted: `IVPHELM_ALLSTOP="NoIvPFunctions"`.
- Some behaviors are active, but decisions are missing on one or more mandatory decision variables. In this case, the following would be posted: `IVPHELM_ALLSTOP="MissingDecVars"`.
- When the vehicle is disengaged due to manual override, the following would be posted: `IVPHELM_ALLSTOP="ManualOverride"`.
- One of the behaviors has determined an all-stop is warranted for some reason. For example, a waypoint behavior that cannot determine own-platform's current position would declare an all-stop. In this case, the following would be posted: `IVPHELM_ALLSTOP="BehaviorError"`.

To gain further insight on an all-stop caused by a behavior error, the nature of the error is expressed in a separate posting to the MOOS `BHV_ERROR` variable. It's possible that more than one behavior error occurred in the helm iteration where the all-stop event occurred, in which case there would be multiple postings to the `BHV_ERROR` variable. When the vehicle is engaged and operating free of an all-stop, the all-stop status is reflected by `IVPHELM_ALLSTOP="clear"`.

Experiment 1: Noting engagement and all-stop status in the Alpha mission.

Issues Explored: (1) The relationship between the `MOOS_MANUAL_OVERRIDE` variable and the helm engagement state and all-stop status. (2) How to visually confirm this relationship.

- Try running the Alpha mission again from Section 4. Note that when the simulation is first launched, before the `DEPLOY` button is hit in the `pMarineViewer` window, the label next to the vehicle says "alpha (DISENGAGED) (ManualOverride)"
- Try opening a `uXMS` scope to scope on a few key variables:

```
$ uXMS alpha.moos MOOS_MANUAL_OVERRIDE IVPHELM_ENGAGED IVPHELM_ALLSTOP
```

 Note that `MOOS_MANUAL_OVERRIDE = "true"`, `IVPHELM_ENGAGED = "DISENGAGED"`, and `IVPHELM_ALLSTOP = "ManualOverride"`.
- Deploy the vehicle by hitting the `DEPLOY` button in the `pMarineViewer` window. Note the changes in both the vehicle label in the GUI, and the values of the variables in the `uXMS` scope. Note that when the all-stop status string is set to "clear", the label in the `pMarineViewer` window just doesn't show it. An absent all-stop status message implies the all-stop status is "clear".

5.4 Parameters for the `pHelmIvP` MOOS Configuration Block

The following configuration parameters are defined for the `IvP Helm`. The parameter names are case insensitive.

Parameter	Mandatory	Description
<code>ALLOW_DISENGAGE</code>	NO	If false (default is true) helm cannot be disengaged.
<code>BEHAVIORS</code>	NO	The name and location of the behavior configuration file.
<code>COMMUNITY</code>	YES	Global MOOS parameter. Determines ownship name.
<code>DISENGAGE_ON_ALLSTOP</code>	NO	If true (default is false) helm will disengage on all-stop.
<code>DOMAIN</code>	YES	The decision space for the <code>IvP Solver</code> .
<code>OK_SKEW</code>	NO	Tolerance on the age of incoming mail before rejected as being too old.
<code>OTHER_OVERRIDE_VAR</code>	NO	Names an additional MOOS Variable acting as <code>MOOS_MANUAL_OVERRIDE</code> .
<code>START_ENGAGED</code>	NO	Determines whether or not the helm is in override mode at start-up.
<code>VERBOSE</code>	NO	Determines verbosity of terminal output - <code>quiet</code> , <code>terse</code> , or <code>verbose</code> .

Table 2: Configuration parameters for the `pHelmIvP` block in a typical MOOS mission configuration file.

The ALLOW_DISENGAGED Parameter

Optional. By setting this parameter to `false`, the helm cannot be manually overridden (disengaged) once it has been engaged. This can be dangerous and should be carefully considered, and thus the default is `true`. This option was implemented based on experiences with launching UUV autonomy missions and preventing an inadvertent disengagement due to a remote login to the vehicle. There was a tendency for some users to use `iRemote` upon remote login to interact with MOOS, and `iRemote` posts `MOOS_MANUAL_OVERRIDE=true` upon launch and connection to the MOOSDB.

The BEHAVIORS Parameter

Optional (sort of). The parameter names the behavior file, i.e., `*.bhv` file, on the local file system from which the helm behaviors are read. More than one file may be specified on separate lines, and the helm will read in all files almost as if they were one single file. This is an optional parameter because a file could alternatively be specified on the command line. A behavior file must be specified via one means or the other. If a behavior file is specified *both* on the command line and in the `pHelmIvP` configuration block with this parameter, they will both be used to configure the helm behaviors.

The COMMUNITY Parameter

The `COMMUNITY` parameter is defined at the “global” level outside of any MOOS process’ configuration block. See Section 3.5. The helm reads this parameter and uses its value as the name associated with “ownership”. It is a mandatory parameter.

The DISENGAGED_ON_ALLSTOP Parameter

Optional. By setting this parameter to `true`, the helm will disengage when an all-stop event occurs. The default setting is `false`.

The DOMAIN Parameter

Mandatory. This parameter prescribes the decision space of the helm. It consists of one line per decision variable. Each line contains a colon-separated list of four fields. Field one is the domain variable name, field two is the lower bound value, field three is the higher bound value, and field four is the number of points in the domain. For example `DOMAIN = speed:0:3:16` shown in Listing 8 indicates a domain variable called “speed”, with a lower and upper bound 0 and 3 meters/second respectively. Since there are 16 points, the speed choices are 0, 0.2, 0.4, ..., 2.8, 3.0. The helm requires that a decision be made on all listed variables on each iteration of the control loop. If a variable is used by some behaviors but is not necessarily involved in all decisions, it can be declared as optional. For example `DOMAIN=speed:0:3:16:optional`.

The OK_SKEW Parameter

Optional. This parameter sets the allowable skew tolerated by the helm for receiving incoming mail messages. If a clock skew is detected greater than this value, the message will be ignored. A check for skews can be disabled by setting `OK_SKEW = ANY`. The default value is 60 seconds.

The OTHER_OVERRIDE_VAR Parameter

Optional. This parameter names a MOOS variable the helm will regard as being synonymous with the two default variables accepted for manual override, `MOOS_MANUAL_OVERRIDE`, and the legacy misspelling of this variable, `MOOS_MANUAL_OVERRIDE`.

The START_ENGAGED Parameter

Optional. This parameter is set to either `true` or `false`. The default is `false` as the helm normally starts in the `Disengaged` state and needs to receive MOOS mail on the variable `MOOS_MANUAL_OVERRIDE` with the value of this variable set to `true`. When `START_ENGAGED` is set to `true`, the helm is in the `Engaged` state upon start-up. The issue of helm engagement was discussed in more detail in Section 5.2.

The VERBOSE Parameter

Optional. This parameter affects how much information is written to the terminal on each iteration of the helm. The possible values are *verbose*, *terse*, or *quiet*. The *verbose* setting will write a brief helm report to the terminal on each iteration. With the *terse* setting minimal output will be produced, a '*' character when not producing helm commands, and a '\$' character when active and healthy. With the *quiet* setting, no output at all will be written to the terminal. The default value is *terse*. This setting can be changed after the helm is started by changing the value of `HELM_VERBOSE` in the MOOSDB.

An Example pHelmIvP MOOS Configuration Block

Below is an example configuration block for the IvP Helm.

Listing 8 - An example pHelmIvP configuration block.

```

0 //----- pHelmIvP configuration block -----
1 ProcessConfig = pHelmIvP
2 {
3   AppTick      = 4    // Defined for all MOOS processes
4   CommsTick    = 4    // Defined for all MOOS processes
5
6   Domain       = course:0:359:360
7   Domain       = speed:0:3:16
8   Domain       = depth:0:500:101
9
10  Behaviors    = foobar.bhv
11  VERBOSE      = terse
12  OK_SKEW     = ANY
13
14  START_ENGAGED      = false
15  ALLOW_DISENGAGED   = true
16  DISENGAGE_ON_ALLSTOP = false
17 }
```

The `APPTICK` and `COMMSTICK` parameters are defined for all MOOS processes (see [15]) and specify the frequency in which the helm process iterates and communicates with the MOOSDB. The `COMMUNITY` parameter is not included in the configuration block because it is specified at the global level in the mission file.

to the IvP Helm and the particular user usage. Behaviors used by the helm are either static or dynamic. Static behaviors are compiled in to the pHelmIvP executable. Dynamic behaviors are brought in at run time via shared libraries compiled separately. The helm looks for an environment variable IVP_BEHAVIOR_DIRS for a colon-separated list of directories to search for shared libraries. If this variable is not set, or if one or more of the directories are not legitimate directories, an error message will indicate so between what is otherwise line 16 and 18 in Listing 9. This kind of error may not actually be problematic if the behaviors specified in the behavior file can all be otherwise successfully found.

For each specified behavior file, the information shown in lines 20-26 is generated to the terminal. For each behavior configuration in a given .bhv file, a single line is output as in lines 22-25 indicating that the behavior type is recognized and it is configured properly. A single unrecognized behavior or improper configuration will result in (a) an error message indicating the offending line number and file name, (b) the output of the actual offending line, and (c) immediate disconnection of the process from the MOOSDB and exit. (Tip: If the helm is launched with Antler an error during start-up will result in the closing of the pHelmIvP console window which makes it hard to catch useful error output for debugging. In this case, the helm should just be launched outside of Antler in its own terminal window.)

The output on line 31 of Listing 9, a series of dollar sign characters, indicates for each character, the completion of a single helm iteration - a heartbeat output. This is the output when the VERBOSE parameter is set to the default setting of terse. When set to quiet no output is generated at all. When set to verbose, a short multi-line report is generated for each iteration. An example is shown below in Listing 10:

Listing 10 - An example helm iteration report generated by an active helm.

```

0 Iteration: 161 *****
1 Helm Summary -----
2 loiter_a did NOT produce an obj-function
3 loiter_b produces obj-function - time:0.00 pcs: 9.00000 pwt: 100.00000
4 waypt_return did NOT produce an obj-function
5 loiter_timer did NOT produce an obj-function
6 Number of Objective Functions: 1
7 DESIRED_SPEED: 2.10
8 DESIRED_COURSE: 145.00
9 (End) Iteration: 161 *****

```

On each iteration the Helm Summary indicates which behaviors produced objective functions (lines 2-5), and for those that did, it indicates the CPU time needed to generate the function, the number of pieces in the piecewise linear IvP function, and its priority weight. Following this, the decision rendered for current iteration is output with one line per decision variable (lines 7-8). This is a very thin summary of what is going on within the helm and it should be noted that the uHelmScope tool is a much better suited for monitoring helm activity and debugging. This tool is described later in Section 11.

5.6 Publications and Subscriptions for IvP Helm

The IvP Helm, like any MOOS process, can be specified in terms of its interface to the MOOSDB, i.e., what variables it publishes and what variables it subscribes for. It is impossible to provide

a complete specification here since the helm is comprised of behaviors, and the means to include any number of third party behaviors. Each behavior is able to post variable-value pairs, published to the MOOSDB by the helm on behalf of the behavior at the end of the iteration. Likewise, each behavior may declare to the helm any number of MOOS variables it would like the helm to register for on its behalf. Barring these variables, published and subscribed for by the helm on behalf of individual behaviors, this section addresses the remaining portion of the helm's publish - subscribe interface.

5.6.1 Variables published by the IvP Helm

Variables published by the IvP Helm are summarized in Table 3 below. The column indicating frequency is in respect to each helm iteration. A more detailed description of each variable follows the table.

#	Variable	Freq	Description
1	IVPHELM_SUMMARY	Each	Summary of many statistics of the current helm iteration, current mode.
2	IVPHELM_POSTINGS	Each	Recap of all variable-value behavior posting for the current iteration.
3	IVPHELM_STATEVARS	Rare	List of variables involved in behavior preconditions.
4	IVPHELM_MODESET	Once	Description of Helm Hierarchical Mode Declarations.
5	IVPHELM_ENGAGED	Each	Status of the Helm Engagement State ("ENGAGED" or "DISENGAGED").
6	IVPHELM_ALLSTOP	Rare	Reason for a helm all-stop or ("clear" if no all-stop present).
7	HELM_IPF_COUNT	Each	IvP Functions involved in the decision of the most recent iteration.
8	CREATE_CPU	Each	Total time needed to create IvP Functions in the most recent iteration.
9	LOOP_CPU	Each	Total time in the <code>Iterate()</code> loop of the most recent iteration.
10	PLOGGER_CMD	Once	A hook to the <code>pLogger</code> to record the behavior file(s).
11	DESIRED_*	Most	The result of the Helm in its configured decision space.
12	BHV_IPF	Most	String form of IvP functions produced by behaviors.
13	BHV_WARNING	Rare	Warning messages generated by helm behaviors.
14	BHV_ERROR	Rare	Error messages generated by helm behaviors.

Table 3: Variables published by the IvP Helm.

- **IVPHELM_SUMMARY:** Produced on each iteration of the helm for consumption by the `uHelmScope` application. It contains information on the current helm iteration regarding the number of IvP functions created, create time, solve time, which behaviors are active, running, idle, and the decision ultimately produced during the iteration.
- **IVPHELM_POSTINGS:** Produced on each iteration of the helm for consumption by the `uHelmScope` application. It provides a recap of all variable-value postings made by all behaviors on the current iteration.

- **IVPHELM.STATEVARS**: Produced periodically by the helm for consumption by the `uHelmScope` application. It contains a comma-separated list of MOOS variables involved in preconditions of any behavior, i.e., variables affecting behavior run states.
- **IVPHELM.DOMAIN**: Produced once by the helm at start-up for consumption by the `uHelmScope` application. It contains the specification of the IvP Domain in use by the helm.
- **IVPHELM.MODESET**: Produced once by the helm at start-up for consumption by the `uHelmScope` application (see Section 11.) It contains the specification of the Hierarchical Mode Declarations, if any, in use by the helm.
- **IVPHELM.ENGAGED**: Written by the helm on each iteration of the `pHelmIvP` MOOS application, regardless of whether the helm is in the engaged state or not. (see Section 5.2). It is either "ENGAGED" or "DISENGAGED". This is the recommended MOOS variable for regarding as a "heartbeat" indicator of the helm.
- **HELM.IPF_COUNT**: Produced on each iteration of the helm. It contains the number of IvP functions involved in the solver on the current iteration.
- **CREATE_CPU**: The CPU time in seconds used in total by all behaviors on the current iteration for constructing IvP functions.
- **LOOP_CPU**: The CPU time in seconds used by the IvP solver in the current helm iteration.
- **BHV_IPF**: The helm will publish this variable for each active behavior in the current iteration. It contains a string representation of the IvP function produced by the behavior. It is used for visualization by the `uFunctionVis` application, and for logging and later playback and analysis.
- **PLOGGER_CMD**: This variable is published with the below value to ensure that the `pLogger` application logs the `.bhv` file along with the other data log files and the `.moos` file.

```
"COPY_FILE_REQUEST = filename.bhv"
```

- **DESIRED.***: Each of the decision variables in the `IvPDomain` provided in the helm configuration will have a separate posting prefixed by `DESIRED_` as in `DESIRED_SPEED`. One exception is that the variable `course` will be converted to `heading` for legacy reasons.
- **BHV_WARNING**: Although this variable may never be posted, it is the default MOOS variable used when a behavior posts a warning. A warning may be harmless but deserves consideration.
- **BHV_ERROR**: Although this variable may never be posted, it is the default MOOS variable used when a behavior posts what it considers a fatal error - one that the helm will interpret as a request to generate the equivalent of `ALL-STOP`.

In addition to the above variables, the helm will post any variable-value pair on behalf of a behavior that makes the request. These include `endflags`, `runflags`, `idleflag`, `activeflags` and `inactiveflags`.

5.6.2 Variables Subscribed for by the IvP Helm

Variables subscribed for by the IvP Helm are summarized in Table 4 below. A more detailed description of each variable follows the table.

#	Variable	Description
1	MOOS_MANUAL_OVERRIDE	Allows for transition of the helm Engagement State.
2	MOOS_MANUAL_OVERRIDE	Allows for transition of the helm Engagement State.
3	HELM_MAP_CLEAR	Resets the helm map that filters successive duplicate publications.

Table 4: Variables subscribed for by the IvP Helm.

- **MOOS_MANUAL_OVERRIDE**: When set to `true`, usually by a third-party application such as `iRemote`, or from a command-and-control communication, the helm may relinquish control. If the helm was configured with `ACTIVE_START = true`, it will not relinquish control (this may be changed).
- **HELM_VERBOSE**: Affects the console output produced by the helm. Legal values are `verbose`, `terse`, or `quiet`. See Section 5.5.
- **HELM_MAP_CLEAR**: When received, the helm clears an internal map that is used to suppress repeated duplicate postings. See Section 5.7.

In addition to the above variables, the helm will subscribe for any variable-value pair on behalf of a behavior that makes the request. This includes, but is not limited to, variables involved in the `CONDITION` and `UPDATES` parameters available generally for all behaviors.

5.7 Automated Filtering of Successive Duplicate Helm Publications

The helm implements a “duplication filter” to drastically reduce the amount of mail posted by the helm on behalf of behaviors. This filter has been noted to reduce the overall log file size seen during in-water exercises by 60-80%. Reductions at this level noticeably facilitate the use of post-mission analysis tools and data archiving. For the most part this filter is operating behind the scenes for the typical helm user. However, knowledge of it is indeed relevant for users wishing to implement their own behaviors, and we discuss it here to explain a bit what is behind the variable `HELM_MAP_CLEAR` to which the helm subscribes, and listed above in Section 5.6.2.

5.7.1 Motivation for the Duplication Filter

The primary motivation of implementing the duplication filter is to reduce the amount of unnecessary mail posted by the helm on behalf behaviors, and thereby greatly reduce the size of log files and facilitate the post-mission handling of data. By unnecessary we mean successive variable-value pairs that match exactly in both fields. For sure, there are cases when a behavior developer may not want this filter, and there are simple ways to bypass the filter for any post. But in most cases, successive duplicate posts are just redundant and unnecessary. For example, a waypoint behavior named

“SURVEY” will post, on each helm iteration, the variables PWT_BHV_SURVEY and STATE_BHV_SURVEY indicating the behavior’s priority and run-state. These variable values often remain unchanged for many successive iterations, and really only need to be posted upon a change.

The `uHelmScope` tool depends on a number of status variables published by the helm to provide content for the scope. These variables are the `IVPHELM_*` variables listed in Table 3. This includes the variable `IVPHELM_POSTINGS` which is a summary of *all* variable-value postings made by *all* behaviors on the current iteration. This provides the content for the Behavior-Posts section of the `uHelmScope` output, described in Section 11.2.3 on page 175. This string can be long, and the point here is that each unnecessary successive duplicate post by a behavior actually shows up in the log file twice! They can also clutter the output in the `uHelmScope` window, but main detriment motivating the filter is the reduction of log file bloat.

5.7.2 Implementation and Usage of the Duplication Filter

The helm keeps two maps (STL maps in C++), one for string data and one for numerical data:

```
KEY --> StringValue
KEY --> DoubleValue
```

The two maps correspond to the two types of message types in MOOS (see Section 3.2 on page 22). The `KEY` is typically the MOOS variable name. Inside a behavior implementation, the following four functions are available:

```
void postMessage(string varname, string value, string key="");
void postMessage(string varname, double value, string key="");
void postBoolMessage(string varname, bool value, string key="");
void postIntMessage(string varname, double value, string key="");
```

These functions are available in all behavior implementations because they are defined in the `IvPBehavior` superclass, of which all behaviors are subclasses. Before the helm posts a message to the `MOOSDB` the filter is applied by a simple check to its map to determine if there is a value match on the given key. If a match is made, the post will not be made to the `MOOSDB` on the behavior’s behalf. The `postIntMessage()` function is merely a convenience version of the `postMessage()` function that rounds the variable value to the nearest integer to further reduce posts when combined with the filter. The `postBoolMessage()` ultimately posts a string value `"true"` or `"false"`.

The default value of the `key` parameter is the empty string, and in most cases this parameter can be omitted without disabling the duplication filter. This is because the `KEY` used by the caller is only part of the key actually used by the duplication filter. The actual key is the concatenation of (a) the behavior name, (b) the variable name, and (c) the key passed by the caller. Thus the default value, the empty string, still results in a decent key being used by the filter. The key is augmented by the behavior name because often there is more than one behavior posting messages on same variable. The optional key parameter is used for two reasons. First, it can be used to further distinguish posts within a behavior on the same variable name. Second, when the key value has the special value `"repeatable"`, then no key is used and the duplication filter is disabled for that variable posting.

5.7.3 Clearing the Duplication Filter

Occasionally a user, or another MOOS application in the same community as the helm, may want to “clear” the map used by the helm to implement its duplication filter. This can be done by writing to variable `HELM_MAP_CLEAR`, with any value. This may be necessary for the following reason. Suppose a GUI application subscribes for the variable `VIEW_SEGLIST` which contains a list of line segments for rendering. If the viewer application is launched *after* the variable is published, the application will only receive the most recent mail on the variable `VIEW_SEGLIST`. There may be publications to this variable, made prior to the most recent publication, that are relevant to the GUI application at launch time. Those publications for the variable `VIEW_SEGLIST` may not be the most recent from the perspective of the `MOOSDB`, but they may be the most recent from the perspective of a particular behavior in the helm. By clearing the filter, it gives each behavior the chance to once again have all of its variable-value posts made to the `MOOSDB`. In the `pMarineViewer` application, a publication to `HELM_MAP_CLEAR` is made upon start-up. Clearing the filter will only clear the way for the next post for a given variable. It will not result in the publishing to the `MOOSDB` of the contents of the maps used by the filter.

6 IvP Helm Autonomy

6.1 Overview

An autonomous helm is primarily an engine for decision making. The IvP Helm uses a behavior-based architecture to organize its decision making and is distinctive in the manner in which it resolves competition between competing behaviors - it performs multi-objective optimization on their collective output using a mathematical programming model called interval programming. Here the IvP Helm architecture is described and the means for configuring it given a set of behaviors and a set of mission objectives.

6.1.1 The Influence of Brooks, Stallman and Dantzig on the IvP Helm

The notion of a behavior-based architecture for implementing autonomy on a robot or unmanned vehicle is most often attributed to Rodney Brooks' Subsumption Architecture, [9]. A key principle at the heart of Brooks' architecture and arguably the primary reason its appeal has endured, is the notion that autonomy systems can be built *incrementally*. Notably, Brooks' original publication pre-dated the arrival of Open Source software and the Free Software Foundation founded by Richard Stallman. Open Source software is not a pre-requisite for building autonomy systems incrementally, but it has the capability of greatly accelerating that objective. The development of complex autonomy systems stands to significantly benefit if the set of developers at the table is large and diverse. Even more so if they can be from different organizations with perhaps even the loosest of overlap in interest regarding how to use the collective end product.

As discussed in Section 2.5, a key issue in behavior-based autonomy has been the issue of action selection, and the IvP Helm is distinct in this regard with the use of multi-objective optimization and interval programming. The algorithm behind interval programming, as well as the term itself, was motivated by the mathematical programming model, linear programming, developed by George Dantzig, [11]. The key idea in linear programming is the choice of the particular mathematical construct that comprises an instance of a linear programming problem - it has enough expressive flexibility to represent a huge class of practical problems, *and* the constructs can be effectively exploited by the simplex method to converge quickly even on very large problem instances. The constructs used in interval programming to represent behavior output (piecewise linear functions) were likewise chosen to have enough expressive flexibility to handle any current and future behavior, and due to the opportunity to develop solution algorithms that exploit the piecewise linear constructs.

6.1.2 Traditional and Non-traditional Aspects of the IvP Behavior-Based Helm

The IvP Helm indeed takes its motivation from early notions of the behavior-based architecture, but is also quite different in many regards. The notion of behavior independence to temper the growth of complexity in progressively larger systems is still a principle closely followed in the IvP Helm. Behaviors may certainly influence one another from one iteration to the next, as we'll see in discussions in this section. This was also evident in the Alpha example mission in Section 4 where the completion of the Survey behavior triggered the Return behavior. But within a single iteration, the output generated by a single behavior is not affected at all by what is generated by other behaviors in the same iteration. The only inter-behavior "communication" realized within an

iteration comes when the IvP solver reconciles the output of multiple behaviors. The independence of behaviors not only helps a single developer manage the growth of complexity, but it also limits the dependency between developers. A behavior author need not worry that a change in the implementation of another behavior by another author requires subsequent recoding of one's own behavior(s).

Certain aspects of behaviors in the IvP Helm may also be a departure from some notions traditionally associated (fairly or not) with behavior-based architectures:

- Behaviors have state. IvP behaviors are instances of a class with a fairly simple interface to the helm. Inside they may be arbitrarily complex, keep histories of observed sensor data, and may contain algorithms that could be considered “reactive” or “plan-based”.
- Behaviors influence each other between iterations. The primary output of behaviors is their objective function, ranking the utility of candidate actions. IvP behaviors may also generate variable-value posts to the MOOSDB observable by behaviors on the next helm iteration. In this way they can explicitly influence other behaviors by triggering or suppressing their activation or even affecting the parameter configuration of other behaviors.
- Behaviors may accept externally generated plans. The input to a behavior can be anything represented by a MOOS variable, and perhaps generated by other MOOS processes outside the helm. It is allowable to have one or more planning engines running on the vehicle generating output consumed by one or more behaviors.
- Several instances of the same behavior. Behaviors generally accept a set of configuration parameters that allow them to be configured for quite different tasks or roles in the same helm and mission. Different waypoint behaviors, for example, can be configured for different components of a transit mission. Or different collision avoidance behaviors can be instantiated for different contacts.
- Behaviors can be run in a configurable sequence. Due to the `condition` and `endflag` parameters defined for all behaviors, a sequence of behaviors can be readily configured into a larger mission plan.
- Behaviors rate actions over a coupled decision space. IvP functions generated by behaviors are defined over the Cartesian product of the set of vehicle decision variables. This is distinct from the de-coupled decision making style proposed in [16] and [18] - early advocates of multi-objective optimization in behavior-based action selection.

6.1.3 Two Layers of Building Autonomy in the IvP Helm

The autonomy in play on a vehicle during a particular mission is the product of two distinct efforts - (1) the development of vehicle behaviors and their algorithms, and (2) mission planning via the configuration of behaviors and mode declarations. The former involves the writing of new source code, and the latter involves the editing of mission behavior files, such as the simple example for the Alpha example mission in Listing 5 on page 38.

6.2 Inside the IvP Helm - A Look at the Helm Iterate Loop

Like other MOOS applications, the IvP Helm implements an `Iterate()` loop within which the basic function of the helm is executed. Components of the `Iterate()` loop, with respect to the behavior-based architecture, are described in this section. The basic flow, in five steps, is depicted in Figure 12. Description of the five components follow.

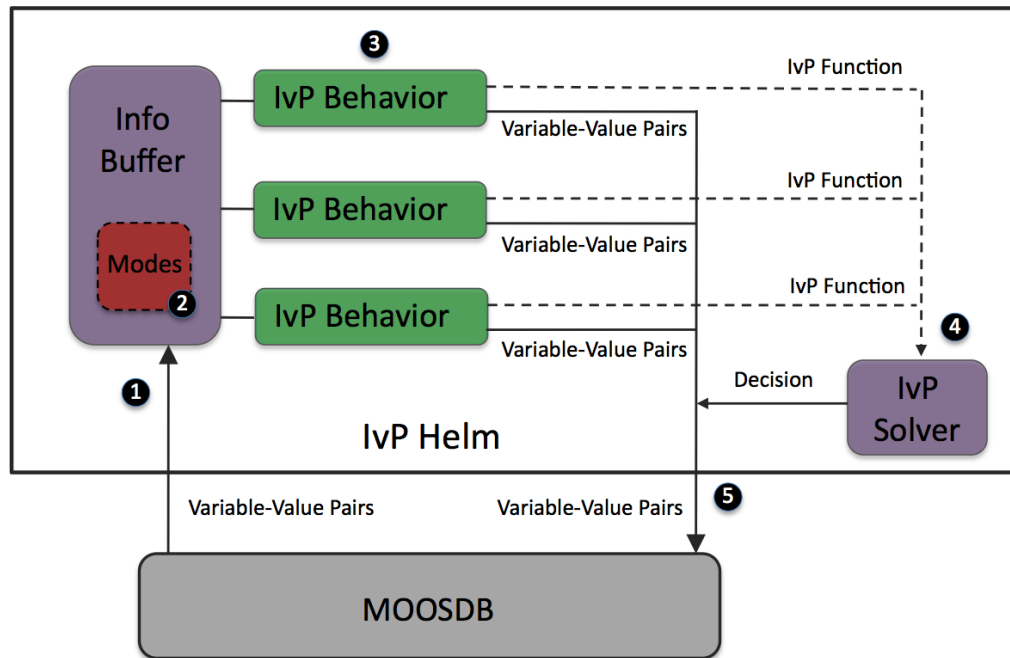


Figure 12: **The pHelmIvP Iterate Loop:** (1) Mail is read from the MOOSDB. It is parsed and stored in a local buffer to be available to the behaviors, (2) If there were any mode declarations in the mission behavior file they are evaluated at this step. (3) Each behavior is queried for its contribution and may produce an IvP function and a list of variable-value pairs to be posted to the MOOSDB at the end of the iteration, (4) the objective functions are resolved to produce an action, expressible as a set of variable-value pairs, (5) all variable-value pairs are published to the MOOSDB for other MOOS processes to consume.

6.2.1 Step 1 - Reading Mail and Populating the Info Buffer

The first step of a helm iteration occurs outside the `Iterate()` loop. As depicted in Figure 5 on page 25, a MOOS application will read its mail by executing its `OnNewMail()` function just prior to executing its `Iterate()` loop if there is any mail in its in-box. The helm parses mail to maintain its own information buffer which is also a mapping of variables to values. This is done primarily for simplicity - to ensure that each behavior is acting on the same world state as represented by the info buffer. Each behavior has a pointer to the buffer and is able to query the current value of any variable in the buffer, or get a list of variable-value changes since the previous iteration.

6.2.2 Step 2 - Evaluation of Mode Declarations

Once the information buffer is updated with all incoming mail, the helm evaluates any mode declarations specified in the behavior file. Mode declarations are discussed in Section 6.4. In short, a mode is represented by a string variable that is reset on each iteration based on the evaluation of a set of logic expressions involving other variables in the buffer. The variable representing the mode declaration is then available to the behavior on the current iteration when it, for example, evaluates its `condition` parameters. A condition for behavior participating in the current iteration could therefore read something like `condition = (MODE==SURVEYING)`. The exact value of the variable `MODE` is set during this step of the `Iterate()` loop.

6.2.3 Step 3 - Behavior Participation

In the third step much of the work of the helm is realized by giving each behavior a chance to participate. Each behavior is queried sequentially - the helm contains no separate threads in this regard. The order in which behaviors is queried does not affect the output. This step contains two distinct parts for each behavior - (1) Determination of whether the behavior will participate, and (2) production of output if it is indeed participating on this iteration. Each behavior may produce two types of information as the Figure 12 indicates. The first is an objective function (or “utility” function) in the form of an IvP function. The second kind of behavior output is a list of variable-value pairs to be posted by the helm to the MOOSDB at the end of the `Iterate()` loop. A behavior may produce both kinds of information, neither, or one or the other, on any given iteration.

6.2.4 Step 4 - Behavior Reconciliation

In the fourth step depicted in Figure 12, the IvP functions are collected by the IvP solver to produce a single decision over the helm’s decision space. Each function is an IvP function - an objective function that maps each element of the helm’s decision space to a utility value. In this case the functions are of a particular form - piecewise linearly defined. That is, each piece is an *interval* of the decision space with an associated linear function. Each function also has an associated weight and the solver performs multi-objective optimization over the weighted sum of functions (in effect a single objective optimization at that point). The output is a single optimal point in the decision space. For each decision variable the helm produces another variable-value pair, such as `DESIRED_SPEED = 2.4` for publication to the MOOSDB.

6.2.5 Step 5 - Publishing the Results to the MOOSDB

In the last step, the helm simply publishes all variable-value pairs to the MOOSDB, some of which were produced directly by the behaviors, and some of which were generated as output from the IvP Solver. The helm employs the duplication filter described in Section 5.7, only on the variable-value pairs generated directly from the behaviors, and not the variable-value pairs generated by the IvP solver that represent a decision in the helm’s domain. For example, even if the decision about a vehicle’s depth, represented by the variable `DESIRED_DEPTH` produced by the helm were unchanged for 5 minutes of operation, it would be published on each iteration of the helm. To do otherwise could give the impression to consumers of the variable that the variable is “stale”, which could trigger an unwanted override of the helm out of concern for safety.

6.3 Mission Behavior Files

The helm is configured for a particular mission primarily through one or more mission behavior files, typically with a `*.bhv` suffix. Behavior files have three types of entries, usually but not necessarily kept in three distinct parts - (1) variable initializations, (2) behavior configurations, and (3) hierarchical mode declarations. These three parts are discussed below. The example `alpha.bhv` file in Listing 5 on page 38 did not contain hierarchical mode declarations, but does contain examples of variable initializations and behavior configurations.

6.3.1 Variable Initialization Syntax

The syntax for variable initialization is fairly straight-forward:

```
initialize <variable> = <value>
...
initialize <variable> = <value>
```

One initialization per line. The keyword `initialize` is case insensitive. The `<variable>` is indeed case sensitive since it will be published to the MOOSDB and MOOS variables are case sensitive when registered for by a client. The variable `<value>` may or may not be case sensitive depending on whether or not a client registering for the variable regards the case. Considering again the helm `Iterate()` loop depicted in Figure 12 on page 60, variable initializations are applied to the helm's information buffer prior to the very first helm iteration, but are posted to the MOOSDB at the end of the first helm iteration.

6.3.2 Behavior Configuration Syntax

The bulk of the helm configuration is done with individual behavior parameter blocks which have the following form:

```
Behavior = <behavior-type>
{
  <parameter> = <value>
  ...
  <parameter> = <value>
}
```

The first line is a declaration of the behavior type. The keyword `Behavior` is not case sensitive, but the `<behavior-type>` is. This is followed by an open brace on a separate line. Each subsequent line sets a particular parameter of the behavior to a given value. The behavior configuration concludes with a close brace on a separate line. The issue of case sensitivity for the `<parameter>` and `<value>` entries is a matter determined by the individual behavior implementation.

As a convention (not enforced in any way) general behavior parameters, defined at the IvP Behavior superclass level, are grouped together and listed before parameters that apply to a specific behavior. For example, in the Alpha example in Listing 5 on page 38, the general behavior parameters are listed on lines 8-12 and 22-25, but the parameters specific to the waypoint behavior, `speed`, `radius`, and `points`, follow in a separate block. Generally it is not mandatory to provide

a parameter-value pair for each parameter defined for a behavior, given that meaningful defaults are in place within the behavior implementation. Some parameters are indeed mandatory however. Documentation for the individual behavior should be consulted. Multiple instances of a behavior type are allowed, as in the Alpha example where there are two waypoint behaviors - one for traversing a set of points, and one for returning to a vehicle recovery point. Each behavior should have its own unique value provided in the `name` parameter.

6.3.3 Hierarchical Mode Declaration Syntax

Hierarchical Mode Declarations are covered in depth in Section 6.4, but the syntax is briefly discussed here. A behavior file contains a set of declaration blocks of the form:

```
Set <mode-variable-name> = <mode-value>
{
  <mode-variable-name> = <parent-value>
  <condition>
  . . .
  <condition>
} <else-value>
```

A tree will be formed where each node in the tree is described from the above type of declaration. The keyword `Set` is case insensitive. The `<mode-variable-name>`, `<parent-value>` and `<else-value>` are case sensitive. The `<condition>` entries are treated exactly as with the `CONDITION` parameter for behaviors, see Section 6.5.1.

As indicated in Figure 12, the value of each mode variable is reset at the outset of the `Iterate()` loop, after the information buffer is updated with incoming mail. A mode variable is set by progressing through each declaration block, and determining whether the conditions are met. Thus the ordering of the declaration blocks is significant - the specification of parent should be made prior to that of a child. Examples are further discussion can be found below in Section 6.4.

6.4 Hierarchical Mode Declarations

Hierarchical mode declarations (HMDs) are an optional feature of the IvP Helm for organizing the behavior activations according to declared mission modes. Modes and sub-modes can be declared, in line with a mission planner's own concept of mission evolution, and behaviors can be associated with the declared modes. In more complex missions, it can facilitate mission planning (in terms of less time and better detection of human errors), and it can facilitate the understanding of exactly what is happening in the helm - during the mission execution and in post-analysis.

6.4.1 Background

A trend of unmanned vehicle usage can be characterized as being increasingly less of the shorter, scripted variety to be increasingly more of the longer, adaptive mission variety. A typical mission in our own lab five years ago would contain a certain set of tasks, typically waypoints and ultimately a rendezvous point for recovering the vehicle. Data acquired during deployment was off-loaded and analyzed later in the laboratory. What has changed? The simultaneous maturation of acoustic communications, on-board sensor processing, and longer vehicle battery life has dramatically

changed the nature of mission configurations. The vehicle is expected to adapt to both the phenomena it senses and processes on board, as well as adapt its operation given field-control commands received via acoustic, radio or satellite communications. Multi-vehicle collaborative missions are also increasingly viable due to lower vehicle costs and mature comms capabilities. In such cases a vehicle is not only adapting to sensed phenomena and field commands, but also to information from collaborating vehicles.

Our missions have evolved from having a finite set of fixed tasks to be composed instead of a set of modes, an initial mode when launched, an understanding of what brings us from one mode to another, and what behaviors are in play in each mode. Modes may be entered and exited any number of times, in exact sequences unknown at launch time, depending on what they sense and how they are commanded in the field.

6.4.2 Behavior Configuration *Without Hierarchical Mode Declarations*

Behaviors can be configured for a mission without the use of hierarchical mode declarations - support for HMDs is a relatively recent addition to the helm. HMDs are a tool for organizing which behaviors are idle or participating in which circumstances. Consider the alpha example mission in Section 4, and the behavior file in Listing 5. By examination of the behavior file, and experimenting a bit with the viewer during simulation, the vehicle apparently is always in one of three modes - (a) idle, (b) surveying the waypoints, or (c) returning to the launch point. This is achieved by the `condition` parameters for the two behaviors. There are only two variables involved in the behavior conditions, `DEPLOY` and `RETURN`. If restricted to Boolean values, the below table confirms the observation that there are only three possible modes.

DEPLOY	RETURN	Mode
<code>true</code>	<code>true</code>	Returning
<code>true</code>	<code>false</code>	Surveying
<code>false</code>	<code>true</code>	Idle
<code>false</code>	<code>false</code>	Idle

Table 5: Possible modes implied by the condition parameters in the alpha mission in Listing 5.

There are a couple drawbacks with this however. First, the modes are to be inferred from the behavior conditions and this is not trivial in missions with larger behavior files. Mapping the behavior conditions to a mode is useful both in mission planning and mission monitoring. In the alpha mission, in order to understand at any given moment what mode the vehicle is in, the two variables need to be monitored, and the above table internalized. The second drawback is the increased likelihood of error, in the form of unintentionally being in two modes at the same time, or being in an undefined mode. For example, line 11 in Listing 5 really should read `RETURN != true`, and not `RETURN = false`. Since there is no Boolean type for MOOS variables, this variable could be set to "False" and the condition as it reads on line 11 in Listing 5 would not be satisfied, and the vehicle would be in the idle state, despite the fact that `DEPLOY` may be set to `true`. These problems are alleviated by the use of hierarchical mode declarations.

6.4.3 Syntax of Hierarchical Mode Declarations - The Bravo Mission

An example is provided showing of the use of hierarchical mode declarations by extending the Alpha mission described in Section 4. This example mission is dubbed the “Bravo” mission in the directory `s2.bravo` alongside the Alpha mission `s1.alpha` in the MOOS-IvP distribution (Section 4.1). It is also given fully in Listing 11 on the next page. The *implicit* modes of the Alpha mission, described in Table 5, are explicitly declared in the Bravo behavior file to form the following hierarchy:

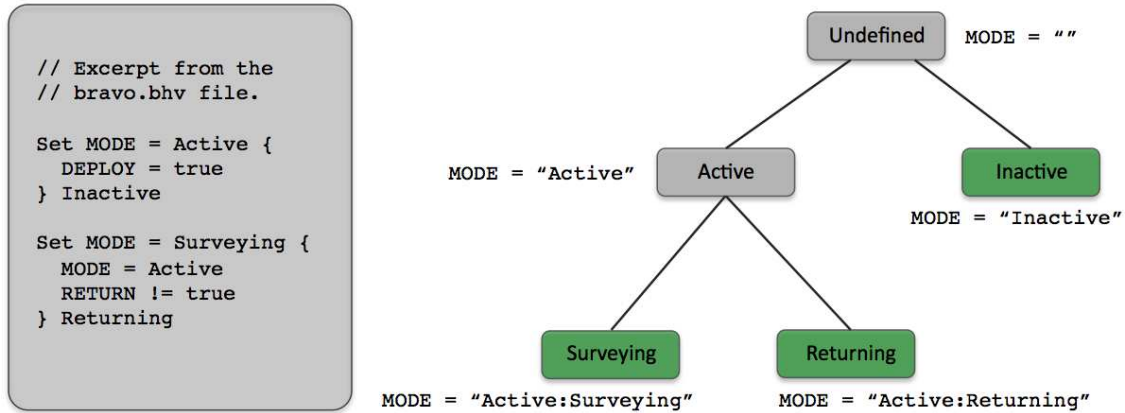


Figure 13: **Hierarchical modes for the Bravo mission:** The vehicle will always be in one of the modes represented by a leaf node. A behavior may be associated with any node in the tree. If a behavior is associated with an internal node, it is also associated with all its children.

The hierarchy in Figure 13 is formed by the mode declaration constructs on the left-hand side, taken as an excerpt from the `bravo.bhv` file. After the mode declarations are read when the helm is initially launched, the hierarchy remains static thereafter. The hierarchy is associated with a particular MOOS variable, in this case the variable `MODE`. Although the hierarchy remains static, the mode is re-evaluated at the outset of each helm iteration based on the conditions associated with nodes in the hierarchy. The mode evaluation is represented as a string in the variable `MODE`. As shown in Figure 13 the variable is the concatenation of the names of all the nodes. The mode evaluation begins sequentially through each of the blocks. At the outset the value of the variable `MODE` is reset to the empty string. After the first block in Figure 13 `MODE` will be set to either "Active" or "Inactive". When the second block is evaluated, the condition "`MODE=Active`" is evaluate based on how `MODE` was set in the first block. For this reason, mode declarations of children need to be listed after the declarations of parents in the behavior file.

Once the mode is evaluated, at the outset of the helm iteration, it is available for use in the conditions of the behaviors, as in lines 20 and 23 in Listing 11. Note the "`==`" relation in lines 18 and 36. This is a string-matching relation that matches when one side matches exactly one of the components in the other side’s colon-separated list of strings. Thus "`Active`" `==` "`Active:Returning`", and "`Returning`" `==` "`Active:Returning`". This is to allow a behavior to be easily associated with an internal node regardless of its children. For example if a collision-avoidance behavior were to be added to this mission, it could be associated with the "Active" mode rather than explicitly naming all the sub-modes of the "Active" mode.

Listing 11: The Bravo Mission - Use of Hierarchical Mode Declarations.

```

0 initialize   DEPLOY = false
1 initialize   RETURN = false
2
3 //----- Declaration of Hierarchical Modes
4 set MODE = ACTIVE {
5   DEPLOY = true
6 } INACTIVE
7
8 set MODE = SURVEYING {
9   MODE = ACTIVE
10  RETURN != true
11 } RETURNING
12
13 //-----
14 Behavior = BHV_Waypoint
15 {
16   name      = waypt_survey
17   pwt       = 100
18   condition = MODE == SURVEYING
19   endflag   = RETURN = true
20   perpetual = true
21
22     lead = 8
23   lead_damper = 1
24     speed = 2.0 // meters per second
25     radius = 4.0
26   nm_radius = 10.0
27     points = 60,-40:60,-160:150,-160:180,-100:150,-40
28     repeat = 1
29 }
30
31 //-----
32 Behavior = BHV_Waypoint
33 {
34   name      = waypt_return
35   pwt       = 100
36   condition = MODE == RETURNING
37   perpetual = true
38   endflag   = RETURN = false
39   endflag   = DEPLOY = false
40
41     speed = 2.0
42     radius = 2.0
43   nm_radius = 8.0
44     point = 0,0
45 }

```

6.4.4 A More Complex Example of Hierarchical Mode Declarations

The Bravo example given above, while having the benefit of being a working example distributed with the codebase, is not complex. In this section a modestly complex, although fictional, hierarchy is provided to highlight some issues with the syntax. The hierarchy with the corresponding mode declarations are shown in Figure 14. The declarations are given in the order of layers of the tree ensuring that parents are declared prior to children. As with the Bravo example in Figure 13, the nodes that represent realizable modes are depicted in the darker (green) color.

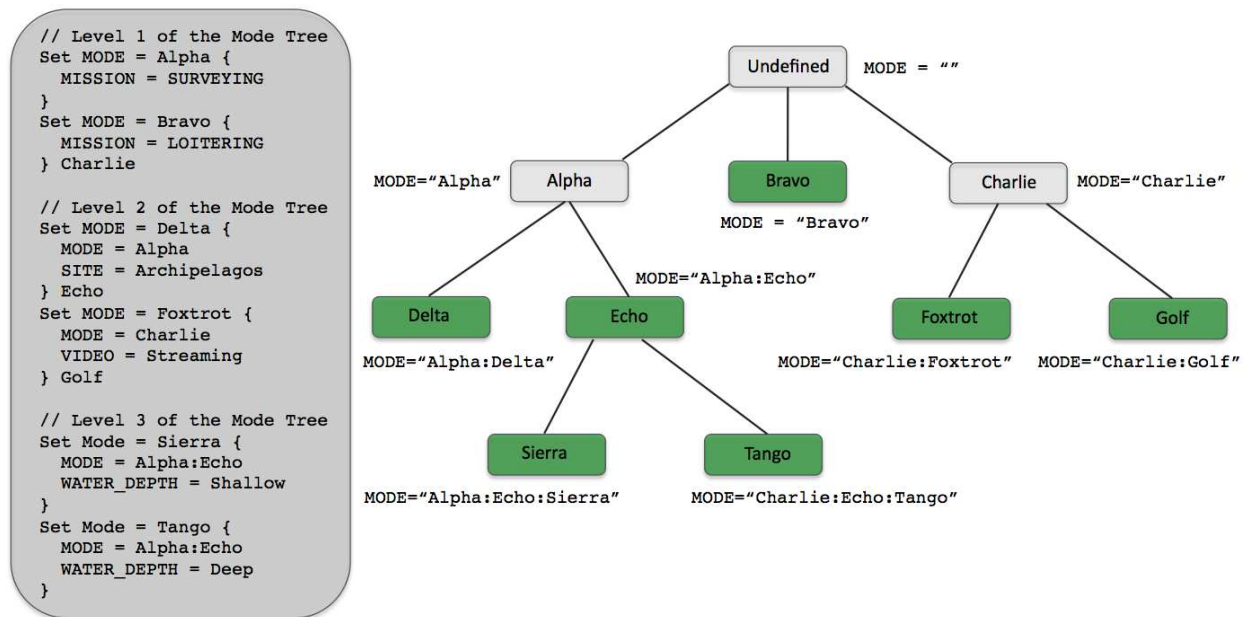


Figure 14: **Example Hierarchical Mode Declaration:** The hierarchy on the right is constructed from the set of mode declarations on the left (with fictional conditions). Darker nodes represent modes that are realizable through some combination of conditions.

The "Alpha" mode for example is not realizable since it has the children "Delta" and "Echo", with the latter being set as the <else-value> if the conditions of the former are not met. The "Bravo" mode is realizable since it has no children. The "Echo" mode is realizable despite having children because the "Tango" mode is not the <else-value> of the "Sierra" mode declaration. For example, if the following three conditions hold, (a) "MISSION=SURVEYING", (b) "SITE!=Archipelagos", and (c) "WATER_DEPTH=Medium", then the value of the variable MODE would be set to "Alpha:Echo". Finally, note that the condition in the "Sierra" declaration, "MODE=Alpha:Echo", is specified fully, i.e., "MODE=Echo" would not achieve the desired result.

6.4.5 Monitoring the Mission Mode at Run Time

The mission mode can be monitored at run time in a couple ways. First, since the mode variable is posted as a MOOS variable, any MOOS scope tool will work, e.g., uXMS, uMS, uHelmScope. Using uHelmScope, the mission variable can be monitored as part of the basic MOOSDB scoping capability (see Section 11.2.2), but it is also displayed on its own, in the fourth line of the main output. For example, see line 4 in Listing 28 on page 173. Unlike the other general MOOS scope tools, the uHelmScope allows for stepping backwards through helm iterations to see when the mission mode changed and perhaps what precipitated the change. See the section on stepping through saved scope history in Section 11.3.

The uHelmScope tool also has a mode in which the entire mode hierarchy may be rendered - solely to provide a visual confirmation that the hierarchy specified with the mode declarations in the behavior file does in fact correspond to what the user intended. Currently there are no tools to automatically render the mode hierarchy in a manner like the right hand side of Figure 14. The

uHelmScope output for the example in Figure 14 is shown in listing 12 below.

Listing 12: The mode hierarchy output from uHelmScope for the example in Figure 14.

```

0  ModeSet Hierarchy:
1  -----
2  Alpha
3      Delta
4      Echo
5          Sierra
6          Tango
7  Bravo
8  Charlie
9      Foxtrot
10     Golf
11 -----
12  CURENT MODE(S): Charlie:Foxtrot
13
14  Hit 'r' to resume outputs, or SPACEBAR for a single update

```

More on this feature of the uHelmScope can be found in Section 11. It's worth noting that poking the value of a mode variable will have no effect on the helm operation. The mission mode cannot be commanded directly. The mode variable is reset at the outset of the helm iteration, and the helm doesn't even register for mail on mode variables.

6.5 Behavior Participation in the IvP Helm

The primary work of the helm comes when the behaviors participate and do their thing, at each round of the helm `Iterate()` loop. As depicted in Figure 12 on page 60, once the mode has been re-evaluated taking into consideration newly received mail, it is time for the behaviors (well, some at least) to step up and do their thing.

6.5.1 Behavior Run Conditions

On any single iteration a behavior may participate by generating an objective function to influence the helm's output over its decision space. Not all behaviors participate in this regard, and the primary criteria for participation is whether or not it has met each of its "run conditions". These are the conditions laid out in the behavior file of the form:

```
condition = <logic-expression>
```

The `<logic-expression>` syntax is described in Appendix A. Conditions are built from simple relational expressions, the comparison of MOOS variables to specified literal values, or the comparison of MOOS variables to one another. Conditions may also involve Boolean logic combinations of relation expressions. A behavior may base its conditions on any MOOS variable such as:

```
condition = (DEPLOY=true) and (STATION_KEEP != true)
```

A run condition may also be expressed in terms of a helm mode, as described in the next Section 6.5.2 such as:

```
condition = (MODE == LOITERING)
```

All MOOS variables involved in run condition expressions are automatically subscribed for by the helm to the MOOSDB.

6.5.2 Behavior Run Conditions and Mode Declarations

The use of hierarchical mode declarations potentially simplify the expressions used as run conditions. The conditions in practice could be limited to:

```
condition = <mode-variable> = <mode-value>, or
condition = <mode-variable> == <mode-value>.
```

Conditions were used in this way with the Bravo mission in Listing 11 on page 66, as an alternative to their usage in the Alpha mission example in Listing 5 on page 38.

Note the use of the double-equals relation above. This relation is used for matching against the strings used to represent the hierarchical mode. The two strings match if the ordered components of one side are a subset of the ordered components of the other. Components are colon-separated. For example, using the illustrative hierarchy from Figure 14:

```
"Alpha:Echo:Sierra" == "Sierra"
"Alpha:Echo:Sierra" == "Echo:Sierra"
"Alpha:Echo:Sierra" == "Alpha"
    "Sierra" == "Alpha:Echo:Sierra"
    "Charlie:Foxtrot" == "Charlie:Foxtrot"

"Alpha:Echo:Sierra" != "Alpha:Sierra"
```

6.5.3 Behavior Run States

On any given helm iteration a behavior may be in one of four states depicted in Figure 15:



Figure 15: **Behavior States:** A behavior may be in one of these four states at any given iteration of helm `Iterate()` loop. The state is determined by examination of MOOS variables stored locally in the helm's information buffer.

- **Idle:** A behavior is `idle` if it is not `complete` and it has not met its run conditions as described above in Section 6.5.1. The helm will invoke an idle behavior's `onIdleState()` function.
- **Running:** A behavior is `running` if it has met its run conditions and it is not `complete`. The helm will invoke a running behavior's `onRunState()` function thereby giving the behavior an opportunity to contribute an objective function.
- **Active:** A behavior is `active` if it is running and it did indeed produce an objective function when prompted. There are a number of reasons why a running behavior may not be active. For example, a collision avoidance behavior where the object of the behavior is sufficiently far away.

- **Complete:** A behavior is `complete` when the behavior itself determines it to be complete. It is up to the behavior author to implement this, and some behaviors may never complete. The function `setComplete()` is defined generally at the behavior superclass level, for calling by a behavior author. This provides some standard steps to be taken upon completion, such as posting of `endflags`, described below in Section 6.5.4. Once a behavior is in the `complete` state, it remains in that state permanently. All behaviors have a `DURATION` parameter defined to allow it to be configured to time-out if desired. When a time-out occurs the behavior state will be set to `complete`.

6.5.4 Behavior Flags and Behavior Messages

Behaviors may post some number of messages, i.e., variable-value pairs, on any given iteration (see Figure 12, p. 60). These message can be critical for coordinating behaviors with each other and to other MOOS processes. The can also be invaluable for monitoring and debugging behaviors configured for particular missions. To be more accurate, behaviors don't post messages to the MOOSDB, they request the helm to post messages on its behalf. The helm collects these requests and publishes them to the MOOSDB at the end of the `Iterate()` loop. It also filters them for successive duplicates as discussed in Section 5.7.

There is a standard method, configurable in the behavior file, for posting messages based on the run state of the behavior. These are referred to as behavior flags, and there are five types, (1) `endflag`, (2) `idleflag`, (3) `runflag`, (4) `activeflag`, (5) `inactiveflag`. The variable-value pairs representing each flag are set in the behavior file for the corresponding behavior. See line 12 in 5 on page 38 for example.

- **endflag:** An `endflag` is posted once when or if the behavior enters the `complete` state. The variable-value pair representing the `endflag` is given in the `endflag` parameter in the behavior file. Multiple `endflags` may be configured for a behavior.
- **idleflag:** An `idleflag` is posted on each iteration of the helm when the behavior is determined to be in the `idle` state. The variable-value pair representing the `idleflag` is given in the `idleflag` parameter in the behavior file. Multiple `idleflags` may be configured for a behavior.
- **runflag:** An `runflag` is posted on each iteration of the helm when the behavior is determined to be in the `running` state, regardless of whether it is further determined to be active or not. A `runflag` is posted exactly when an `idleflag` is not. The variable-value pair representing the `runflag` is given in the `runflag` parameter in the behavior file. Multiple `runflags` may be configured for a behavior.
- **activeflag:** An `activeflag` is posted on each iteration of the helm when the behavior is determined to be in the `active` state. The variable-value pair representing the `activeflag` is given in the `activeflag` parameter in the behavior file. Multiple `activeflags` may be configured for a behavior.
- **inactiveflag:** An `inactiveflag` is posted on each iteration of the helm when the behavior is determined to be not in the `active` state. The variable-value pair representing the `inactiveflag` is given in the `inactiveflag` parameter in the behavior file. Multiple `inactiveflags` may be configured for a behavior.

A `runflag` is meant to “complement” an `idleflag`, by posting exactly when the other one does not. Similarly with the `inactiveflag` and `activeflag`. The situation is shown in Figure 16:



Figure 16: **Behavior Flags:** The four behavior flags `idleflag`, `runflag`, `activeflag`, and `inactiveflag` are posted depending on the behavior state and can be considered complementary in the manner indicated.

Behavior authors may implement their behaviors to post other messages as they see fit. For example the waypoint behavior used in the Alpha example in Section 4 also published the variable `WPT_STAT` with a status message similar to `"vname=alpha,index=0,dist=124,eta=62"` indicating the name of the vehicle, the index of the next point in the list of waypoints, the distance to that waypoint, and the estimated time of arrival, in seconds. (You might want to re-run the Alpha mission with `uXMS` scoping on this variable to watch it change as the mission unfolds.)

6.5.5 Monitoring Behavior Run States and Messages During Mission Execution

The run states for each behavior, are wrapped up on each iteration by the helm into a single string and published in the variable `IVPHELM.SUMMARY`. This variable is subscribed for by the `uHelmScope` tool and behavior states are parsed from this variable and summarized in the main output, as in lines 12-17 in Listing 28 on page 173. These lines are provided in the below excerpt:

```

12 Behaviors Active: ----- (1)
13   waypt_survey (13.0) (pwt=100.00) (pcs=1227) (cpu=0.01) (upd=0/0)
14 Behaviors Running: ----- (0)
15 Behaviors Idle: ----- (1)
16   waypt_return (22.8)
17 Behaviors Completed: ----- (0)

```

Behaviors are grouped into the four possible states, with a summary line for each state, e.g., lines 12, 14, 15, 17, containing the number of behaviors in that state in parentheses at the end of the line. Each behavior configured for the helm shows up on a dedicated line in the appropriate group, e.g., lines 13 and 16. In these lines immediately following the behavior name, the number of seconds is displayed in parentheses indicating how long the behavior has been in that state.

The `uHelmScope` tool can also be used to monitor the messages generated by each behavior on each iteration. The helm, in addition to posting all the variable-value pairs to the `MOOSDB` at the end of the `Iterate()` loop, also builds a summary of all such posts into a single string and publishes it as `IVPHELM.POSTINGS`. This variable is subscribed for and parsed by `uHelmScope` to generate the “Behavior-Posts” section of the `uHelmScope` output. An example can be seen in lines 28-39 in Listing 28, and this part of the `uHelmScope` output is described in Section 11.2.3.

6.6 Behavior Reconciliation in the IvP Helm - Multi-Objective Optimization

6.6.1 IvP Functions

IvP functions are produced by behaviors to influence the decision produced by the helm on the current iteration (see Figure 12, p. 60). The decision is typically comprised of the desired `heading`, `speed`, and `depth` but the helm decision space could be comprised of any arbitrary configuration (see section 5.4, p. 49). Some points about IvP functions:

- IvP functions are piecewise linearly defined. Each piece is defined by an interval over some subset of the decision space, and there is a linear function associated with each piece (see Figure 18).
- IvP functions are an *approximation* of an underlying function. The linear function for a single piece is the best linear approximation of the underlying function for the portion of the domain covered by that piece.
- IvP domains are discrete with an upper and lower bound for each variable, so an IvP function *may* achieve zero-error in approximating an underlying function by associating a piece with each point in the domain. Behaviors seldom need to do so in practice however.
- The IvP function construct and IvP solver are generalizable to N dimensions.
- The pieces in IvP functions need not be uniform size or shape. More pieces can be dedicated to parts of the domain that are harder to approximate with linear functions.
- IvP functions need only be defined over a subset of the domain. Behaviors are not affected if the helm is configured for additional variables that a behavior may not care about. Behaviors that produce functions solely over vehicle `depth` are perfectly ok.

How are IvP functions built? The IvP Build Toolbox is a set of tools for creating IvP functions based on any underlying function defined over an IvP Domain. Many, if not all of the behaviors in this document make use of this toolbox, and authors of new behaviors have this at their disposal. A primary component of writing a new behavior is the development of the “underlying function”, the function approximated by an IvP function with the help of the toolbox. The underlying function represents the relationship between a candidate helm decision and the expected utility with respect to the behavior’s objectives. The IvP Toolbox is not covered in detail in this document, but an overview is given below.

6.6.2 The IvP Build Toolbox

The IvP Toolbox is a set of tools (a C++ library) for building IvP functions. It is typically utilized by behavior authors in a sequence of library calls within a behavior’s (C++) implementation. There are two sets of tools - the *Reflector* tools for building IvP functions in N dimensions, and the *ZAIC* tools for building IvP functions in one dimension as a special case. The Reflector tools work by making available a function to be approximated by an IvP function. The tools simply need this function for sampling. Consider the Gaussian function rendered below in Figure 17:

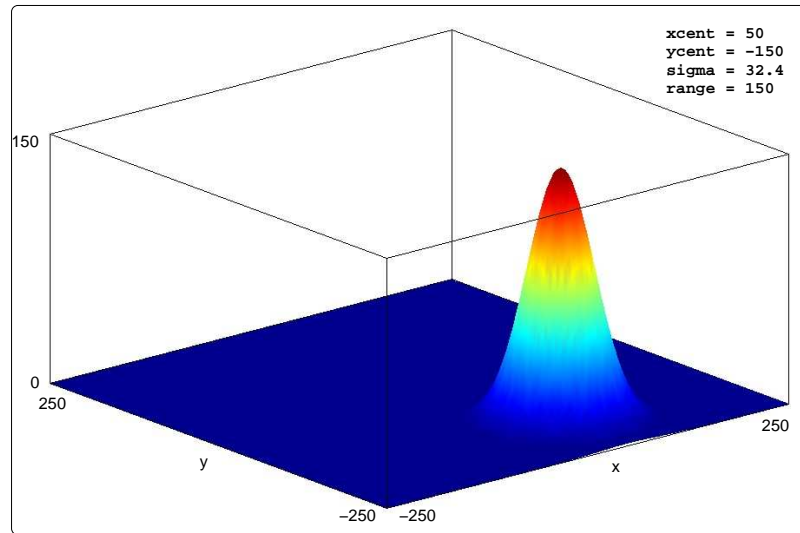


Figure 17: A rendering of the function $f(x, y) = Ae^{-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}}$ where $A = \text{range} = 150$, $\sigma = \text{sigma} = 32.4$, $x_0 = \text{xcent} = 50$, $y_0 = \text{ycent} = -150$. The domain here for x and y ranges from -250 to 250 .

The 'x' and 'y' variables, each with a range of $[-250, 250]$, are discrete, taking on integer values. The domain therefore contains $501^2 = 251,001$ points, or possible decisions. The IvP Build Toolbox can generate an IvP function approximating this function over this domain by using a uniform piece size, as rendered in Figure 18(a) and 18(b). The difference in these two figures is only the size of the piece. More pieces (Figure 18(a)) results in a more accurate approximation of the underlying function, but takes longer to generate and creates further work for the IvP solver when the functions are combined. IvP functions need not use uniformly sized pieces.

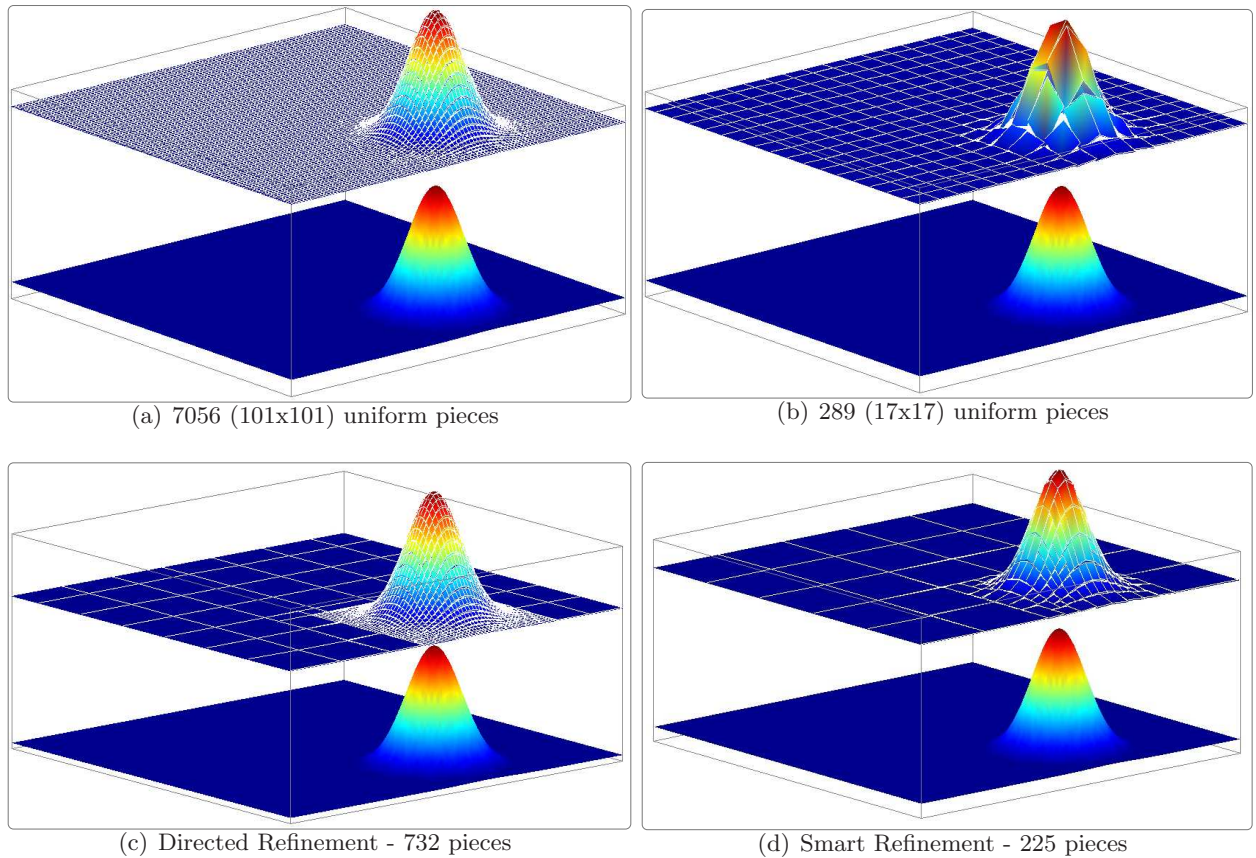


Figure 18: **A rendering of four different IvP functions approximating the same underlying function:** The function in (a) uses a uniform distribution of 7056 pieces. The function in (b) uses a uniform distribution of 1024 pieces. The function in (c) was created by first building a uniform distribution of 49 pieces and then focusing the refinement on a sub-domain of the function. This is called directed-refinement in the IvP Build toolbox. The function in (d) was created by first building a uniform function of 25 pieces and repeatedly refining the function based on which pieces were noted to have a poor fit to the underlying function. This is termed smart-refinement in the IvP Build toolbox.

By using the *directed refinement* option in the IvP Build Toolbox, an initially uniform IvP function can be further refined with more pieces over a sub-domain directed by the caller, with smaller uniform pieces of the caller's choosing. This is rendered in Figure 18(c). Using this tool requires the caller to have some idea where, in the sub-domain, further refinement is needed or desired. Often a behavior author indeed has this insight. For example, if one of the domain variables is vehicle heading, it may be good to have a fine refinement in the neighborhood of heading values close to the vehicle's current heading.

In other situations, insight into where further refinement is needed may not be available to the caller. In these cases, using the *smart refinement* option of the IvP Build Toolbox, an initially uniform IvP function may be further refined by asking the toolbox to automatically “grade” the pieces as they are being created. The grading is in terms of how accurate the linear fit is between the piece's linear function and the underlying function over the sub-domain for that piece. A priority

queue is maintained based on the grades, and pieces where poor fits are noted, are automatically refined further, up to a maximum piece limit chosen by the caller. This is rendered in Figure 18(d).

The Reflector tools work similarly in N dimensions and on multi-modal functions. The only requirement for using the Reflector tool is to provide it with access to the underlying function. Since the tool repetitively samples this function, a central challenge to the user of the toolbox is to develop a fast implementation of the function. In terms of the time consumed in generating IvP functions with the Reflector tool, the sampling of the underlying function is typically the long pole in the tent.

6.6.3 The IvP Solver and Behavior Priority Weights

The IvP Solver collects a set of weighted IvP functions produced by each of the behaviors and finds a point in the decision space that optimizes the weighted combination. If each IvP objective function is represented by $f_i(\vec{x})$, and the weight of each function is given by w_i , the solution to a problem with k functions is given by:

$$\vec{x}^* = \underset{\vec{x}}{\operatorname{argmax}} \sum_{i=0}^{k-1} w_i f_i(\vec{x})$$

The algorithm is described in detail in [3], but is summarized in the following few points.

- *The search tree:* The structure of the search algorithm is branch-and-bound. The search tree is comprised of an IvP function at each layer, and the nodes at each layer are comprised of the individual pieces from the function at that layer. A leaf node represents a single piece from each function. A node in the tree is realizable if the piece from that node and its ancestors intersect, i.e., share common points in the decision space.
- *Global optimality:* Each point in the decision space is in exactly one piece in each IvP function and is thus in exactly one leaf node of the search tree. If the search tree is expanded fully, or pruned properly (only when the pruned out sub-tree does not contain the optimal solution), then the search is guaranteed to produce the globally optimal solution. The search algorithm employed by the IvP solver does indeed start with a fully expanded tree, and utilizes proper pruning to guarantee global optimality. The algorithm does allow for a parameter for guaranteed limited back-off from the global optimality - a quicker solution with a guarantee of being within a fixed percent of global optima. This option is not exposed to the IvP Helm which always finds the global optimum.
- *Initial solution:* A key factor of an effective branch-and-bound algorithm is seeding the search with a decent initial solution. In the IvP Helm, the initial solution used is the solution (typically heading, speed, depth) generated on the previous helm iteration. Upon casual observation this appears to provide a speed-up by about a factor of two.

In cases where there is a “tie” between optimal decisions, the solution generated by the solver is non-deterministic. This is mitigated somewhat by the fact that the solution is seeded with the output of the previous iteration as discussed above.

6.6.4 Monitoring the IvP Solver During Mission Execution

The performance of the solver can be monitored with the `uHelmScope` tool described in Section 11. The output shown below in Listing 13 is an excerpt of the full output shown in Listing 28 on page 173. On line 5, the total time needed to solve the multi-objective optimization problem is given in seconds, and the max time need for all recorded loops is given in parentheses. It is zero here since there is only one objective function in this example. On line 6 is the total time for creating the IvP functions in all behaviors, with the max across all iterations in parentheses. On line 7 is the total loop time - the sum of the previous two lines. Active behaviors display useful information regarding the IvP solver. For example, on line 13, the Survey waypt behavior had a priority weight of 100 and generated 1,227 pieces, taking 0.01 seconds of CPU time to create.

Listing 13 - Example uHelmScope output containing information about the IvP solver.

```

1 ===== uHelmScope Report ===== ENGAGED (17)
2 Helm Iteration: 66 (hz=0.38)(5) (hz=0.35)(66) (hz=0.56)(max)
3 IvP functions: 1
4 Mode(s): Surveying
5 SolveTime: 0.00 (max=0.00)
6 CreateTime: 0.02 (max=0.02)
7 LoopTime: 0.02 (max=0.02)
8 Halted: false (0 warnings)
9 Helm Decision: [speed,0,4,21] [course,0,359,360]
10 speed = 3.00
11 course = 177.00
12 Behaviors Active: ----- (1)
13 waypt_survey (13.0) (pwt=100.00) (pcs=1227) (cpu=0.01) (upd=0/0)
14 Behaviors Running: ----- (0)
15 Behaviors Idle: ----- (1)
16 waypt_return (22.8)
17 Behaviors Completed: ----- (0)
18

```

The solver can be additionally monitored and analyzed through the two MOOS variables `LOOP_CPU` and `CREATE_CPU` published on each helm iteration. The former indicates the system wall time for building each IvP function and solving the multi-objective optimization problem, and the latter indicates just the time to create the IvP functions.

7 Properties of Helm Behaviors

The objective of this section is to describe properties common to all IvP Helm behaviors, describe how to overload standard functions for 3rd party behaviors, and to provide a detailed simple example of a behavior. It builds on the discussion from Chapter 6. The focus in this section is an expansion of detail of Step 3 in Figure 12 on page 60.

7.1 Brief Overview

Behaviors are implemented as C++ classes with the helm having one or more instances at runtime, each with a unique descriptor. The properties and implemented functions of a particular behavior are partly derived from the `IvPBehavior` superclass, shown in Figure 19. The is-a relationship of a derived class provides a form of code re-use as well as a common interface for constructing mission files with behaviors.

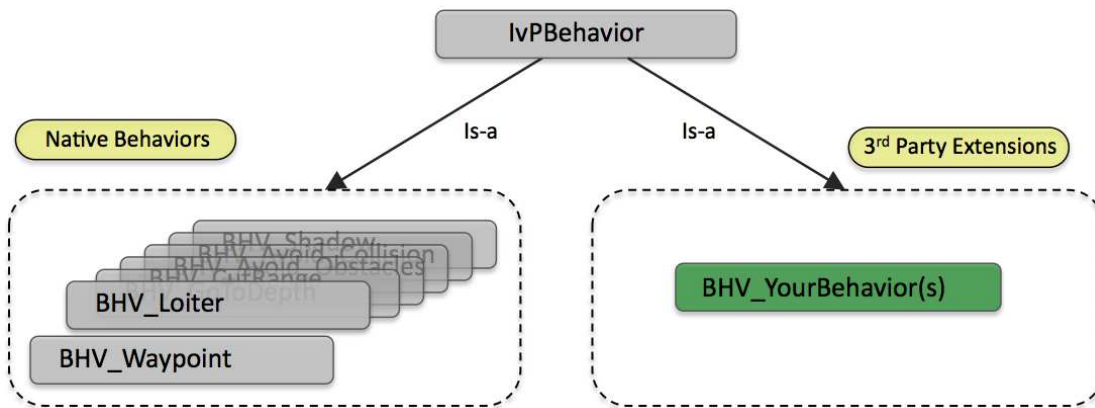


Figure 19: **Behavior inheritance:** Behaviors are derived from the `IvPBehavior` superclass. The native behaviors are the behaviors distributed with the helm. New behaviors also need to be subclass of the `IvPBehavior` class to work with the helm. Certain virtual functions invoked by the helm may be optionally but typically overloaded in all new behaviors. Other private functions may be invoked within a behavior function as a way of facilitating common tasks involved in implementing a behavior.

The `IvPBehavior` class provides three virtual functions which are typically overloaded in a particular behavior implementation:

- The `setParam()` function: parameter-value pairs are handled to configure a behavior's unique properties distinct from its superclass.
- The `onRunState()` function: the meat of a behavior implementation, performed when the behavior has met its conditions for running, with the output being an objective function and a possibly empty set of variable-value pairs for posting to the MOOSDB.
- The `onIdleState()` function: what the behavior does when it has not met its run conditions. It may involve updating internal state history, generation of variable-value pairs for posting to the MOOSDB, or absolutely nothing at all.

This section discusses the properties of the `IvPBehavior` superclass that an author of a third-party behavior needs to be aware of in implementing new behaviors. It is also relevant material for users of the native behaviors as it details general properties.

7.2 Parameters Common to All IvP Behaviors

A behavior has a standard set of parameters defined at the `IvPBehavior` level as well as unique parameters defined at the subclass level. By configuring a behavior during mission planning, the setting of parameters is the primary venue for affecting the overall autonomy behavior in a vehicle. Parameters are set in the behavior file, but can also be dynamically altered once the mission has commenced. A parameter is set with a single line of the form:

```
parameter = value
```

The left-hand side, the parameter component, is case insensitive, while the value component is typically case sensitive. This was discussed in depth in Section 6.3. In this section, the parameters defined at the superclass level and available to all behaviors are exhaustively listed and discussed. Each behavior typically augments these parameters with new ones unique to the behavior, and in the next section the issue of implementing new parameters by overloading the `setParam()` function is addressed.

7.2.1 A Summary of the Full Set of General Behavior Parameters

The following parameters are defined for all behaviors at the superclass level. They are listed here for reference - certain related aspects are discussed in further detail in other sections.

NAME: The name of the behavior - should be unique between all behaviors. Duplicates may be confusing, but should not cause helm errors. Logging and output sent to the helm console during operation will organize information by the behavior name.

PRIORITY: The priority weight of the produced objective function. The default value is 100. A behavior may also be implemented to determine its own priority weight depending on information about the world.

DURATION: The time in seconds that the behavior will remain running before declaring completion. If no duration value is provided, the behavior will never time-out. The clock starts ticking once the behavior satisfies its run conditions (becoming non-idle) the first time. *Should the behavior switch between running and idle states, the clock keeps ticking even during the idle periods.* See Section 7.2.3 for more detail.

DURATION_STATUS: If the `DURATION` parameter is set, the remaining duration time, in seconds, can be posted by naming a `DURATION_STATUS` variable. This variable will be update/posted only when the behavior is in the running state. See Section 7.2.3 for more detail.

DURATION_RESET: This parameter takes a variable-pair such as `MY_RESET=true`. If the `DURATION` parameter is set, the duration clock is reset when the variable is posted to the MOOSDB with the specified value. Each time such a post is noted, the duration clock is reset. See Section 7.2.3 for more detail.

POST_MAPPING: This parameter takes a comma-separated pair such as `WPT_STAT, WAYPT_STATUS` where the left-hand value is a variable normally posted by the behavior, and the right-hand value is an alternative variable name to be used. There is no error-checking to ensure that the left-hand value names a variable actually posted by the behavior. Transitive relationships are not respected. For example, if the two remappings are declared, `FOO,BAR`, and `BAR,CAR`, `FOO` will be posted as `BAR`, not `CAR`. To disable the normal posting of a variable `FOO`, use `POST_MAPPING = FOO,SILENT`.

DURATION_IDLE_DECAY: If this parameter is `false` the duration clock is paused when the vehicle is in the “idle” state. The default value is `true`. See Section 7.2.3 for more detail.

CONDITION: This parameter specifies a condition that must be met for the behavior to be active. Conditions are checked for each behavior at the beginning of each control loop iteration. Conditions are based on current MOOS variables, such as `STATE = normal` or $((K \leq 4))$. More than one condition may be provided, as a convenience, treated collectively as a single conjunctive condition. The helm automatically subscribes for any condition variables. See Section 6.5.1 for more detail on run conditions.

RUNFLAG: This parameter specifies a variable and a value to be posted when the behavior has met all its conditions for being in the *running* state. It is an equal-separated pair such as `TRANSITING=true`. More than one flag may be provided. These can be used to satisfy or block the conditions of other behaviors. See Section 6.5.4 on page 70 for more detail on posting flags to the MOOSDB from the helm.

IDLEFLAG: This parameter specifies a variable and a value to be posted when the behavior is in the *idle* state. See the Section 6.5.3 for more on run states. It is an equal-separated pair such as `WAITING=true`. More than one flag may be provided. These can be used to satisfy or block the conditions of other behaviors. See Section 6.5.4 on page 70 for more detail on posting flags to the MOOSDB from the helm.

ACTIVEFLAG: This parameter specifies a variable and a value to be posted when the behavior is in the *active* state. See the Section 6.5.3 for more on run states. It is an equal-separated pair such as `TRANSITING=true`. More than one flag may be provided. These can be used to satisfy or block the conditions of other behaviors. See Section 6.5.4 on page 70 for more detail on posting flags to the MOOSDB from the helm.

INACTIVEFLAG: This parameter specifies a variable and a value to be posted when the behavior is *not* in the *active* state. See the Section 6.5.3 for more on run states. It is a equal-separated pair such as `OUT_OF_RANGE=true`. More then one flag may be provided. These can be used to satisfy or block the conditions of other behaviors. See Section 6.5.4 on page 70 for more detail on posting flags to the MOOSDB from the helm.

ENDFLAG: This parameter specifies a variable and a value to be posted when the behavior has set the `completed` state variable to be true. The circumstances causing completion are unique to the individual behavior. However, if the behavior has a `DURATION` specified, the `completed` flag is set to true when the duration is exceeded. The value of this parameter is a equal-separated pair such as `ARRIVED_HOME=true`. Once the completed flag is set to true for a behavior, it remains inactive thereafter, regardless of future events, barring a complete helm restart. See Section 6.5.4 on page 70 for more detail on posting flags to the MOOSDB from the helm.

UPDATES: This parameter specifies a variable from which updates to behavior configuration parameters are read from after the behavior has been initially instantiated and configured at the helm startup time. Any parameter and value pair that would have been legal at startup time is legal at runtime. The syntax for this string is a #-separated list of parameter-value pairs: `"param=value # param=value # ... # param=value"`. This is one of the primary hooks to the helm for mission control - the other being the behavior conditions described above. See Section 7.2.2 for more detail.

NOSTARVE: The `NOSTARVE` parameter allows a behavior to assert a maximum staleness for one or more MOOS variables, i.e., the time since the variable was last updated. The syntax for this parameter is a comma-separated pair `"variable, ..., variable, value"`, where last component in the list is the time value given in seconds. See Section 7.2.5 on page 82 for more detail.

PERPETUAL: Setting the `perpetual` parameter to `true` allows the behavior to continue to run even after it has completed and posted its end flags. The parameter value is not case sensitive and the only two legal values are `true` and `false`. See Section 7.2.4 for more detail.

TEMPLATING: The `templating` parameter may be used to turn a behavior specification into a template for spawning new behaviors dynamically after the helm has been launched. Instantiation requests are received via the `updates` parameter described in Section 7.7.

7.2.2 Altering Behavior Parameters Dynamically with the UPDATES Parameter

The parameters of a behavior can be made to allow dynamic modifications - after the helm has been launched and executing the initial mission in the behavior file. The modifications come in a single MOOS variable specified by the parameter `UPDATES`. For example, consider the simple waypoint behavior configuration below in Listing 14. The return point is the (0,0) point in local coordinates, and return speed is 2.0 meters/second. When the conditions are met, this is what will be executed.

Listing 14 - An example behavior configuration using the UPDATES parameter.

```

0 Behavior = BHV_Waypoint
1 {
2   name      = WAYPT_RETURN
3   priority  = 100
4   speed     = 2.0
5   radius    = 8.0
6   points    = 0,0
7   UPDATES   = RETURN_UPDATES
8   condition = RETURN = true
9   condition = DEPLOY = true
10 }

```

If, during the course of events, a different return point or speed is desired, this behavior can be altered dynamically by writing to the variable specified by the UPDATES parameter, in this case the variable RETURN_UPDATES (line 7 in Listing 14). The syntax for this variable is of the form:

```
parameter = value # parameter = value # ... # parameter = value
```

White space is ignored. The '#' character is treated as special for parsing the line into separate parameter-value pairs. It cannot be part of a parameter component or value component. For example, the return point and speed for this behavior could be altered by any other MOOS process that writes to the MOOS variable:

```
RETURN_UPDATES = 'points = (50,50) # speed = 1.5'
```

Each parameter-value pair is passed to the same parameter setting routines used by the behavior on initialization. The only difference is that an erroneous parameter-value pair will simply be ignored as opposed to halting the helm as done on startup. If a faulty parameter-value pair is encountered, a warning will be written to the variable BHV_WARNING. For example:

```
BHV_WARNING = "Faulty update for behavior: WAYPT_RETURN. Bad parameter(s): speed."
```

Note that a check for parameter updates is made at the outset of helm iteration loop for a behavior with the call `checkUpdates()`. Any updates received by the helm on the current iteration will be applied prior to behavior execution and in effect for the current iteration.

7.2.3 Limiting Behavior Duration with the DURATION Parameter

The `duration` parameter specifies a time period in seconds before a behavior times out and permanently enters the completed state. If left unspecified, there is no time limit to the behavior. By default, the duration clock begins ticking as soon as the helm engages. The duration clock remains ticking when or if the behavior subsequently enters the idle state. It even remains ticking if the helm temporarily disengages. When a timeout occurs, end flags are posted. The behavior can be configured to post the time remaining before a timeout with the `duration_status` parameter. The forms for each are:

```

duration      = value (positive numerical)
duration_status = value (variable name)

```

Note that the duration status variable will only be published/updated when the behavior is in the running state. The duration status is rounded to the nearest integer until less than ten seconds remain, after which the time is posted out to two decimal places. The behavior can be configured to have the duration clock pause when it is in the idle state with the following:

```
duration_idle_decay = false // The default is true
```

Configured in the above manner, a behavior's duration clock will remain paused until its conditions are met. The behavior may also be configured to allow for the duration clock to be reset upon the writing of a MOOS variable with a particular value. For example:

```
duration_reset = BRAVO_TIMER_RESET=true
```

The behavior checks for and notes that the variable-value pair holds true and the duration clock is then reset to the original duration value. The behavior also marks the time at which the variable-value pair was noted to have held true. Thus there is no need to "un-set" the variable-value pair, e.g., setting `BRAVO_TIMER_RESET=false`, to allow the duration clock to resume its count-down.

7.2.4 The PERPETUAL Parameter

When a behavior enters the *completed* state, it by default remains in that state with no chance to change. When the `perpetual` parameter is set to `true`, a behavior that is declared to be complete does not actually enter the complete state but performs all the other activity normally associated with completion, such as the posting of end flags. See Section 6.5.4 for more detail on posting flags to the MOOSDB from the helm. The default value for `perpetual` is `false`. The form for this parameter is:

```
perpetual = value
```

The value component is case insensitive, and the only legal values are either `true` or `false`. A behavior using the `duration` parameter with `perpetual` set to `true` will post its end flags upon time out, but will reset its clock and begin the count-down once more the next time its run conditions are met, i.e., enters the running state. Typically when a behavior is used in this way, it also posts an endflag that would put itself in the idle state, waiting for an external event.

7.2.5 Detection of Stale Variables with the NOSTARVE Parameter

A behavior utilizing a variable generated by a MOOS process outside the helm, may require the variable to be sufficiently up-to-date. The staleness of a variable is the time since it was last written to by any process. The `NOSTARVE` parameter allows the mission writer to set a staleness threshold. The form for this parameters is:

```
nostarve = variable_1, ..., variable_n, duration
```

The value of this parameter is a comma-separated list such as "`NAV_X, NAV_Y, 5.0`". The variable components name MOOS variables and the duration component, the last entry in the list, represents the tolerated staleness in seconds. If staleness is detected, a behavior failure condition is triggered which will trigger the helm to post all-stop values and relinquish to manual control.

7.3 Overloading the `setParam()` Function in New Behaviors

The `setParam()` function is a virtual function defined in the `IvPBehavior` class, with parameters implemented in the superclass (Section 7.2) handled in the superclass version of this function:

```
bool IvPBehavior::setParam(string parameter, string value);
```

The `setParam()` function should return `true` if the parameter is recognized and the value is in an acceptable form. In the rare case that a new behavior has no additional parameters, leaving this function undefined in the subclass is appropriate. The example below in Listing 15 gives an example for a fictional behavior `BHV_YourBehavior` having a single parameter `period`.

Listing 15 - An example `setParam()` implementation for fictional `BHV_YourBehavior`.

```
0 bool BHV_YourBehavior::setParam(string param, string value)
1 {
2     if(param == "period") {
3         double time_value = atof(value.c_str());
4         if((time_value < 0) || (!isNumber(value)))
5             return(false);
6         m_period = time_value;
7         return(true);
8     }
9     return(false);
10 }
```

Since the `period` parameter refers to a time period, a check is made on line 4 that the value component indeed is a positive number. (The `atof()` function on line 6, which converts an ASCII string to a floating point value, returns zero when passed a non-numerical string, therefore the `isNumber()` function is also used to ensure the string represented by `value` represents a numerical value.) A behavior implementation of this function without sufficient syntax or semantic checking simply runs the risk that faulty parameters are not detected at the time of helm launch, or during dynamic updates. Solid checking in this function will reduce debugging headaches down the road.

7.4 Behavior Functions Invoked by the Helm

The `IvPBehavior` superclass implements a number of functions invoked by the helm on each iteration. Two of these functions are overloadable as described previously - the `onRunState()` and `onIdleState()` functions. The basic flow of calls to a behavior from the helm are shown in Figure 20. These are discussed in more detail later in the section, but the idea is to execute certain behavior functions based on the *activity state*, which may be one of the four states depicted.

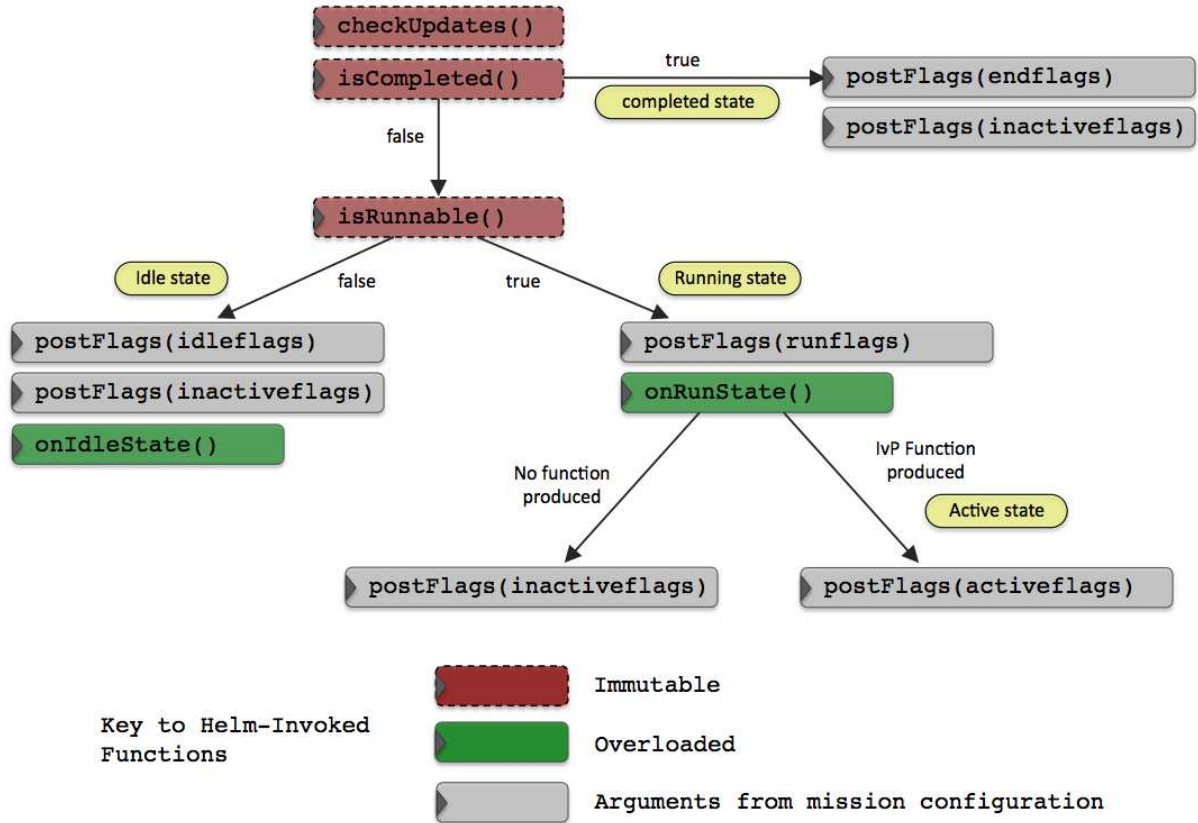


Figure 20: **Behavior function-calls by the helm:** The helm invokes a sequence of functions on each behavior on each iteration of the helm. The sequence of calls is dependent on what the behavior returns, and reflects the behaviors activity state. Certain functions are immutable and can not be overloaded by a behavior author. Two key functions, `onRunState()` and `onIdleState()` can be indeed overloaded as the usual hook for an author to provide the implementation of a behavior. The `postFlags` function is also immutable, but the parameters (flags) are provided in the helm configuration (`*.bhv`) file.

An *idle* behavior is one that has not met its conditions for running. A *completed* behavior is one that has reached its objectives or exceeded its duration. A *running* behavior is one that has not yet completed, has met its run conditions, but may still opt not to produce any output. An *active* behavior is one that is running and is producing output in the form of an objective function.

The types of functions defined at the superclass level fall into one of the three categories below, only the first two of which are shown in Figure 20:

- Helm-invoked immutable functions - functions invoked by the helm on each iteration that the author of a new behavior may not re-implement.
- Helm-invoked overloadable functions - functions invoked by the helm that an author of a new behavior typically re-implements or overloads.
- User-invoked functions - functions invoked within a behavior implementation.

The user-invoked functions are utilities for common operations typically invoked within the implementation of the `onRunState()` and `onIdleState()` functions written by the behavior author.

7.4.1 Helm-Invoked Immutable Functions

These functions, implemented in the `IvPBehavior` superclass, are called by the helm but are *not* defined as virtual functions which means that attempts to overload them in a new behavior implementation will be ignored. See Figure 20 regarding the sequence of these function calls.

`void checkUpdates()`: This function is called first on each iteration to handle requested dynamic changes in the behavior configuration. This needs to be the very first function applied to a behavior on the helm iteration so any requested changes to the behavior parameters may be applied on the present iteration. See Section 7.2.2 for more on dynamic behavior configuration with the `UPDATES` parameter.

`bool isComplete()`: This function simply returns a Boolean indicating whether the behavior was put into the *complete* state during a prior iteration.

`bool isRunnable()`: Determines if a behavior is in the *running* state or not. Within this function call four things are checked: (a) if the `duration` is set, the duration time remaining is checked for timeout, (b) variables that are monitored for staleness are checked against (Section 7.2.5). (c) the run conditions must be met. (d) the behavior's decision domain (IvP domain) is a proper subset of the helm's configured IvP domain. See Section 6.5.1 for more detail on run conditions.

`void postFlags(string flag_type)`: This function will post flags depending on whether the value of `flag_type` is set to "idleflags", "runflags", "activeflags", "inactiveflags", or "endflags". Although this function is immutable, not overloadable by subclass implementations, its effect is indeed mutable since the flags are specified in the mission configuration `*.bhv` file. See Section 6.5.4 for more detail on posting flags to the MOOSDB from the helm.

7.4.2 Helm-Invoked Overloaded Functions

These are functions called by the helm. They are defined as virtual functions so that a behavior author may overload them. Typically the bulk of writing a new behavior resides in implementing these three functions.

`IvPFunction* onRunState()`: The `onRunState()` function is called by the helm when deemed to be in the *running* state (Figure 20). The bulk of the work in implementing a new behavior is in this function implementation, and is the subject of Section 7.6.

`void onIdleState()`: This function is called by the helm when deemed to be in the *idle* state (Figure 20). Many behaviors are implemented with this function left undefined, but it is a useful hook to have in many cases.

`bool setParam(string, string)`: This function is called by the helm when the behavior is first instantiated with the set of parameter and parameter values provided in the behavior file. It is also called by the helm within the `checkUpdates()` function to apply parameter updates dynamically.

7.5 Local Behavior Utility Functions

The bulk of the work done in implementing a new behavior is in the implementation of the `onIdleState()` and `onRunState()` functions. The utility functions described below are designed to aid in that implementation and are generally “protected” functions, that is callable only from within the code of another function in the behavior, such as the `onRunState()` and `onIdleState()` functions, and not invoked by the helm.

7.5.1 Summary of Implementor-Invoked Utility Functions

The following is summary of utility functions implemented at the `IvPBbehavior` superclass level.

`void setComplete()`: The notion of what it means for a behavior to be “complete” is largely an issue specific to an individual behavior. When or if this state is reached, a call to `setComplete()` can be made and end flags will be posted, and the behavior will be permanently put into the *completed* state unless the *perpetual* parameter is set to `true`.

`void addInfoVars(string var_names)`: The helm will register for variables from the MOOSDB on a need-only basis, and a behavior is obligated to inform the helm that certain variables are needed on its behalf. A call to the `addInfoVars()` function can be made from anywhere with a behavior implementation to declare needed variables. This can be one call per variable, or the string argument can be a comma-separated list of variables. The most common point of invoking this function is within a behavior’s constructor since needed variables are typically known at the point of instantiation. More on this issue in Section 7.5.3.

`double getBufferDoubleVal(string varname, bool& result)`: Query the `info_buffer` for the latest (double) value for a given variable named by the string argument. The bool argument indicates whether the queried variable was found in the buffer. More on this in Section 7.5.2.

`double getBufferStringVal(string varname, bool& result)`: Query the `info_buffer` for the latest (string) value for a given variable named by the string argument. The bool argument indicates whether the queried variable was found in the buffer. More on this in Section 7.5.2.

`double getBufferCurrTime()`: Query the `info_buffer` for the current buffer local time, equivalent to the duration in seconds since the helm was launched. More on this in Section 7.5.2.

`vector<double> getBufferDoubleVector(string var, bool& result)`: Query the `info_buffer` for all changes to the variable (of type double) named by the string argument, since the last iteration. The bool argument indicates whether the queried variable was found in the buffer. More on this in Section 7.5.2.

`vector<string> getBufferStringVector(string var, bool& result)`: Query the `info_buffer` for all changes to the variable (of type string) named by the string argument, since the last iteration. The bool argument indicates whether the queried variable was found in the buffer. More on this in Section 7.5.2.

`void postMessage(string varname, string value, string key)`: The helm can post messages (variable-value pairs) to the MOOSDB at the end of the helm iteration. Behaviors can request such postings via a call to the `postMessage()` function where the first argument is the variable name, and the second is the variable value. The optional *key* parameter is used in conjunction with the duplication filter and by default is the empty string. See Section 5.7 for more on the duplication filter.

`void postMessage(string varname, double value, string key)`: Same as above except used when the posted variable is of type `double` rather than `string`. The optional *key* parameter is used in conjunction with the duplication filter and by default is the empty string. See Section 5.7 for more on the duplication filter.

`void postBoolMessage(string varname, bool value, string key)`: Same as above, except used when the posted variable is a `bool` rather than `string`. The optional *key* parameter is used in conjunction with the duplication filter and by default is the empty string. See Section 5.7 for more on the duplication filter.

`void postIntMessage(string varname, double value, string key)`: Same as `postMessage(string, double)` above except the numerical output is rounded to the nearest integer. This, combined with the helm's use of the *duplication filter*, can reduce the number of posts to the MOOSDB. The optional *key* parameter is used in conjunction with the duplication filter and by default is the empty string. See Section 5.7 for more on the duplication filter.

`void postWMessage(string warning_msg)`: Identical to the `postMessage()` function except the variable name is automatically set to `BHV_WARNING`. Provided as a matter of convenience to the caller and for uniformity in monitoring warnings.

`void postEMessage(string error_msg)`: Similar to the `postWMessage()` function except the variable name is `BHV_ERROR`. This call is for more serious problems noted by the behavior. It also results in an internal `state_ok` bit being flipped which results in the helm posting all-stop values to the actuators.

7.5.2 The Information Buffer

Behaviors do not have direct access to the MOOSDB - they don't read mail, and they don't post changes directly, but rather through the helm as an intermediary. The information buffer, or `info_buffer`, is a data structure maintained by the helm to reflect a subset of the information in the MOOSDB and made available to each behavior. This topic is hidden from a user configuring existing behaviors and can be safely skipped, but is an important issue for a behavior author implementing a new behavior. The `info_buffer` is a data structure shared by all behaviors, each behavior having an pointer to a single instance of the `InfoBuffer` class. This data structure is maintained by the helm, primarily by reading mail from the MOOSDB and reflecting the change onto the buffer on each helm iteration, before the helm requests input from each behavior. Each behavior therefore has the exact same snapshot of a subset of the MOOSDB. A behavior author needs to know two things - how to ensure that certain variables show up in the buffer, and how to access that information from within the behavior. These two issues are discussed next.

7.5.3 Requesting the Inclusion of a Variable in the Information Buffer

A variable can be specifically requested for inclusion in the `info_buffer` by invoking the following function:

```
void IvPBehavior::addInfoVars(string varnames)
```

The string argument is either a single MOOS variable or a comma-separated list of variables. Duplicate requests are simply ignored. Typically such calls are invoked in a behavior's constructor, but may be done dynamically at any point after the helm is running. The helm will simply register with the MOOSDB for the requested variable at the end of the current iteration. Certain variables are registered for automatically on behalf of the behavior. All variables referenced in run conditions will be registered and accessible in the buffer. Variables named in the `updates` and `nostarve` parameters will also be automatically registered.

7.5.4 Accessing Variable Information from the Information Buffer

A variable value can be queried from the buffer with one of the following two function calls, depending on whether the variable is of type double or string.

```
string IvPBehavior::getBufferStringVal(string varname, bool& result)
double IvPBehavior::getBufferDoubleVal(string varname, bool& result)
```

The first string argument is the variable name, and the second argument is a reference to a Boolean variable which, upon the function return, will indicate whether the queried variable was found in the buffer. A duration value indicating the elapsed time since the variable was last changed in the buffer can be obtained from the following function call:

```
double IvPBehavior::getBufferTimeVal(string varname);
```

The string argument is the variable name. The returned value should be exactly zero if this variable was updated by new mail received by the helm at the beginning of the current iteration. If the variable name is not found in the buffer, the return value is -1. The "current" buffer time, equivalent to the cumulative time in seconds since the helm was launched, can be retrieved with the following function call:

```
double IvPBehavior::getBufferCurrTime()
```

The buffer time is a local variable of the `info_buffer` data structure. It is updated once at the beginning of the helm `OnNewMail()` loop prior to processing all new updates to the buffer from the MOOS mail stack, or at the beginning of the `Iterate()` loop if no mail is processed on the current iteration. Thus the time-stamp returned by the above call should be exactly the same for successive calls by all behaviors within a helm iteration.

The values returned by `getBufferStringVal()` and `getBufferDoubleVal()` represent the latest value of the variable in the MOOSDB at the point in time when the helm began its iteration and processed its mail stack. The value may have changed several times in the MOOSDB between iterations, and this information may be of use to a behavior. This is particularly true when a variable is being posted in pieces, or a sequence of delta changes to a data structure. In any event, this information can be recovered with the following two function calls:

```
vector<string> IvPBehavior::getBufferStringVector(string varname, bool& result)
vector<double> IvPBehavior::getBufferDoubleVector(string varname, bool& result)
```

They return all values updated to the buffer for a given variable since the last iteration in a vector of strings or doubles respectively. The latest change is located at the highest index of the vector. An empty vector is returned if no changes were received at the outset of the current iteration.

7.6 Overloading the `onRunState()` and `onIdleState()` Functions

The `onRunState()` function is declared as a virtual function in the `IvPBehavior` superclass intended to be overloaded by the behavior author to accomplish the primary work of the behavior. The primary behavior output is the objective function. This is what drives the vehicle. The objective function is an instance of the class `IvPFunction`, and a behavior generates an instance and returns a pointer to the object in the following function:

```
IvPFunction* onRunState()
```

This function is called automatically by the helm on the current iteration if the behavior is deemed to be in the *running* state, as depicted in Figure 20 on page 84. The invocation of `onRunState()` does not necessarily mean an objective function is returned. The behavior may opt not to for whatever reason, in which case it returns a null pointer. However, if it does generate a function, the behavior is said to be in the *active* state. The steps comprising the typical implementation of the `onRunState()` implementation can be summarized as follows:

- Get information from the `info_buffer`, and update any internal behavior state.
- Generate any messages to be posted to the MOOSDB.
- Produce an objective function if warranted.
- Return.

The same steps hold for the `onIdleState()` function except for producing an objective function. The first two steps have been discussed in detail. Accessing the `info_buffer` was described in Sections 7.5.2 - 7.5.4. The functions for posting messages to the MOOSDB from within a behavior were discussed in Section 7.5.1. Further issues regarding the posting of messages were covered in Section 6.5.4. The remaining issue to discuss is how objective functions are generated. This is covered in the `IvPBuild` Toolbox in a separate document.

7.7 Dynamic Behavior Spawning

In certain scenarios it may not be practical or possible to know in advance all the behaviors needed to accomplish mission objectives. For example, if the helm uses a certain kind of behavior to deal with another vehicle in its operation area, for collision avoidance or trailing etc., the identities or number of such vehicles may not be known when the mission planner is configuring the helm's behavior file. One way to circumvent this problem is to design a collision avoidance behavior, for example, to

handle all known contacts. However, this has a couple drawbacks. It would entail a degree of multi-objective optimization be implemented within the behavior to produce an objective function that was comprehensive across all contacts. This would likely be much more computationally expensive than simply generating an objective function for each contact. It also may be advantageous to have different types of collision avoidance behaviors for different contact types or collision avoidance protocols. In any event, the helm support for dynamic behavior spawning gives behavior architects and mission planners another potentially powerful option for implementing an autonomy system.

7.7.1 Behavior Specifications Viewed as Templates

The `templating` parameter may be used to turn an otherwise static behavior specification into a template for spawning new behaviors dynamically after the helm has been launched. Instantiation requests are received via the `updates` parameter described in Section 7.2.2. Updates received through this variable are normally used to change behavior parameters dynamically, but they can be further used to request the spawning of a new behavior by including the following component:

```
name = <new-behavior-name>
```

If the `<new-behavior-name>` is not the name of the behavior given in the behavior specification, and if it is not the name of a behavior already presently instantiated by the helm, the helm interprets this as a request to spawn a new behavior, if templating is enabled. Templating is enabled by including the following component in the behavior specification:

```
templating = <templating-mode>
```

The `<templating-mode>` may be set to either "disallowed" (the default), "clone", or "spawn". In the "clone" mode, the helm will instantiate a behavior immediately upon helm startup. In the "spawn" mode, the helm will not instantiate a behavior until it receives a request to do so via the `updates` parameter as described above. An example of a behavior configured to allow dynamic spawning is given in Listing 26 on page 168, taken from the Berta example mission.

For a behavior configured with templating enabled in the "spawn" mode, the helm will *not* spawn a behavior at the helm startup time. However, internally it will indeed spawn such a behavior, check that it can be found and built as configured, and then destroy it immediately. This means that the behavior configuration found in the `.bhv` configuration file must not have an invalid configuration. It is preferable to know at helm launch time that a behavior is misconfigured, rather than waiting for the spawning event to occur perhaps hours into a mission and being surprised that a critical behavior, such as collision avoidance, failed to be spawned.

7.7.2 Behavior Completion and Removal from the Helm

All behaviors, whether statically spawned upon helm startup, or dynamically spawned during the mission, are capable of dying and being removed from the helm. Death and removal are part of the consequences of a behavior entering the `completed` state. Behavior run states were discussed in Section 6.5.3 on page 69. A completed behavior configured with `perpetual=true` will not die

upon completion. Once a behavior dies, its name is removed from the helm’s internal registry of currently-spawned behaviors and a new behavior by the same name may be spawned at a future time.

7.7.3 Example Missions with Dynamic Behavior Spawning

Two example missions are provided that demonstrate the workings of dynamic behavior spawning, The Echo mission in Section 10.4, and the Berta mission in Section 10.6. The Echo mission involves a single vehicle with its helm configured to spawn dynamic behaviors of the type `BHV_BearingLine`. These behaviors do nothing more than post a viewable line segment to the MOOSDB between ownship and a point in the operation area. The interesting thing about this example is that the mission is configured with an event script (via `uTimerScript`) to automatically cue the spawning of 5000 behaviors over about one hour. Each behavior has a random duration of less than a minute, so behaviors are spawning and dying quite rapidly with visual confirmation via the viewable line segments.

The second example mission, the Berta mission, involves two vehicles that are loitering near one another. Periodically their loiter assignments are randomly altered (again through `uTimerScript`). The change in loiter locations repeatedly puts them on an unpredictable and random near-collision course and each vehicle needs to spawn a collision avoidance behavior. The interesting thing about this scenario is that the behavior, the `BHV_AvoidCollision` behavior, is an actual behavior of common use, unlike the `BHV_BearingLine` behavior used in the Echo mission. This example also uses the `pBasicContactMgr` to coordinate the receiving of contact reports with helm behavior spawning.

7.7.4 Examining the Helm’s Life Event History

Behavior spawning, and behavior completion and removal from the helm, are two types of *life events* the helm takes note of and posts in the MOOS variable `IVPHELM_LIFE_EVENT`. A third type of life event occurs when a behavior spawning is aborted due to either a syntax error or a name collision. Monitoring life events at run time is possible by scoping on the variable `IVPHELM_LIFE_EVENT` with either `uXMS` or `uMS`. A better method is available via the `uHelmScope` application (versions 4.1 or later). It automatically registers for the `IVPHELM_LIFE_EVENT` variable and will generate a formatted report like that shown in Listing 16. In the post-mission analysis phase, the `aloghelm` application may be used to examine the life event history and will generate the same formatted report from a given `alog` file.

Listing 16 - A Life Event History generated with either the `uHelmScope` or `aloghelm` utilities.

```

0 *****
1 *          Summary of Behavior Life Events          *
2 *****
3
4 Time      Iter  Event  Behavior      Behavior Type      Spawning Seed
5 -----  ----  ----  -----  -----  -----
6 47.84     1  spawn  loiter        BHV_Loiter         helm startup
7 47.84     1  spawn  waypt_return  BHV_Waypoint       helm startup
8 47.84     1  spawn  station-keep BHV_StationKeep    helm startup
9 101.79    218 spawn  avd_henry     BHV_AvoidCollision name=avd_henry#contact=henry
10 161.20    423 death  avd_henry     BHV_AvoidCollision

```

11	297.07	969	spawn	avd_henry	BHV_AvoidCollision	name=avd_henry#contact=henry
12	351.80	1159	death	avd_henry	BHV_AvoidCollision	
13	461.37	1599	spawn	avd_henry	BHV_AvoidCollision	name=avd_henry#contact=henry
14	516.51	1795	death	avd_henry	BHV_AvoidCollision	
15	644.94	2311	spawn	avd_henry	BHV_AvoidCollision	name=avd_henry#contact=henry
16	704.31	2517	death	avd_henry	BHV_AvoidCollision	
17	730.02	2620	abort		BHV_AvoidCollision	name=avd_henry#foo=bar
18	825.17	3002	spawn	avd_henry	BHV_AvoidCollision	name=avd_henry#contact=henry

The life event history shown in Listing 16 was taken from the Berta example mission, the "gilda" vehicle, described in Section 10.6. The time-stamp reported in column one is the elapsed time between the event and the time of the helm's startup. The first three events, in lines 6-8, reflect the three static behaviors spawned when the helm was launched, in first iteration of the helm. The collision avoidance behavior was spawned each time (lines 9, 11, 13 etc.) the vehicle "henry" came within sufficiently close range. Each time the "henry" vehicle passed and opened range to a sufficient amount, the collision avoidance behavior completed and died (lines 10, 12, 14, etc.). Line 17 shows an example of an aborted spawning. This was brought about purposely by poking the MOOSDB with the Spawning Seed shown for that line. Since the collision avoidance parameter does not have a parameter "foo", the spawning failed.

Accessing the life event history via `uHelmScope` may be done by launching the scope with the vehicle's mission file, and hitting the 'L' key to toggle into the life event history mode. Or one may launch the scope directly into this mode via:

```
> uHelmScope --life targ_gilda.moos
```

The same summary may also be accessed after mission completion via the log files:

```
> aloghelm --life gilda.alog
```

Note that perhaps not all life events will be displayed when using `uHelmScope`, depending on when it is launched relative to `pHelmIvP`. When `uHelmScope` connects to the MOOSDB it will only receive the latest and all following posts to the variable `IVPHELM_LIFE_EVENT`. If `uHelmScope` connects after `pHelmIvP` is launched and engaged, it may have missed older postings. The initial spawning events do not occur in the helm until the helm enters the `ENGAGED` engagement state. (See Section 5.2 about helm engagement). In the example in Listing 16, the helm apparently was in the `DISENGAGED` state for about 48 seconds before it was engaged and began to execute its first iteration. The full event history should always be accessible via the log file however.

8 Behaviors of the IvP Helm

The following is a description of some single-vehicle behaviors currently written for the IvP Helm. The below is a guide for users of these behaviors. The topic of developing new behaviors is addressed in [6]. The setting of behavior parameters is the primary method for affecting the overall autonomy behavior in a vehicle. Parameters may also be dynamically altered once the mission has commenced. A parameter is set with a single line of the form:

```
parameter = value
```

The left-hand side, the parameter component, is case insensitive, while the value component is typically case sensitive. When the helm is launched, each behavior is created and the parameters are set. If a parameter setting in the behavior file references an unknown parameter, or if the value component fails a syntactic or semantic test, the line is noted and the helm ceases to launch.

Overview of Parameters Common to All Behaviors

The parameters below are common to all IvP behaviors, although they may have more relevance to some behaviors than others. They are defined in the IvPBehavior superclass of which all the behaviors described in this section are a subclass. More information on the functionality behind these parameters was given in Section 7.2.1.

Parameter	Description
NAME	A unique identifier for the behavior instance.
PRIORITY	Priority weight of the IvP function produced by behavior.
DURATION	Behavior duration, in seconds. Default is "unlimited".
DURATION_IDLE_DECAY	If true, clock will progress even if in the idle state.
DURATION_RESET	If limited duration, duration is reset when this variable is received.
DURATION_STATUS	MOOS variable informing of remaining duration, if duration is set.
POST_MAPPING	A mapping to change the default MOOS variable output of a behavior.
CONDITION	A logical condition that must satisfied for the behavior to run.
RUNFLAG	A flag (MOOSVar,Data) pair, posted when in the running state.
IDLEFLAG	A flag (MOOSVar,Data) pair, posted when in the idle state.
ACTIVEFLAG	A flag (MOOSVar,Data) pair, posted when in the active state.
INACTIVEFLAG	A flag (MOOSVar,Data) pair, posted when in the inactive state.
ENDFLAG	A flag (MOOSVar,Data) pair, posted when the behavior completes.
UPDATES	A MOOSVar from which behavior parameter updates are received.
NOSTARVE	If a given MOOSVar is stale by a given amount, an error is posted.
PERPETUAL	If true, a behavior may be reset after completion or duration timeout.
TEMPLATING	Enable the behavior spec as a template for dynamic spawning.

Table 6: Configuration parameters common to all IvP Behaviors.

Configuring One Variable Objective Functions

Several behaviors use a common tool for constructing objective functions over a single decision variable. These behaviors have a similar interface for configuring this tool, and it is described

here to avoid redundancy. Examples of behaviors that use this tool are the Waypoint, Loiter, PeriodicSurface, ConstantDepth, ConstantSpeed, ConstantHeading, and Shadow behaviors. This tool is called the *ZAIC-PEAK* tool, and is describe in more detail in [6]. This tool is designed with the objective function form shown in Figure 21 in mind, where there is an identifiable preferred single decision choice (the *summit*) with maximum utility, and then a gradual drop in utility as the variable varies from the preferred choice.

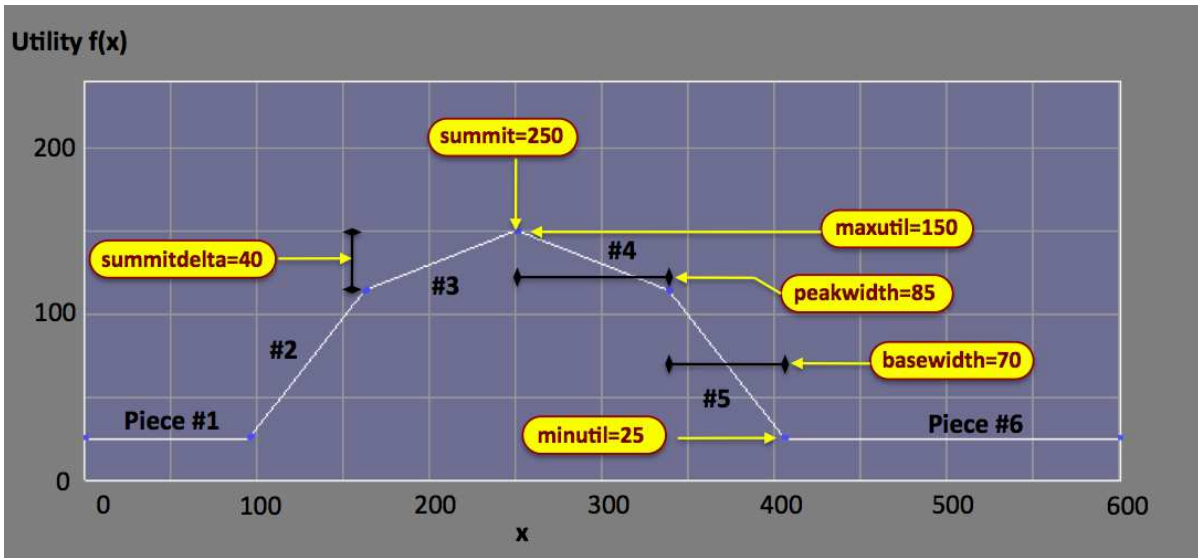


Figure 21: **The ZAIC-PEAK tool:** defines an IvP function over one variable defined by the four parameters shown here. In the case rendered here, the tool would create an IvP function with six pieces. The function rendered was created with *summit=180*, *peakwidth=85*, *basewidth=70*, *summitdelta=40*.

The form in which the utility drops is dependent on the settings of other parameters shown in the figure. The *summit*, *peakwidth*, and *basewidth* values are given in units native to the decision variable, while the *summitdelta*, *minutil*, and *maxutil* values are given in terms of units of utility. The latter two variables default to 0 and 100 respectively and are not typically exposed as configuration parameters in behaviors that use this tool, unlike the other four parameters.

8.1 BHV_Waypoint

The `BHV_Waypoint` behavior is used for transiting to a set of specified waypoint in the x-y plane. The primary parameter is the set of waypoints. Other key parameters are the inner and outer radius around each waypoint that determine what it means to have met the conditions for moving on to the next waypoint. The basic idea is shown in Figure 22.

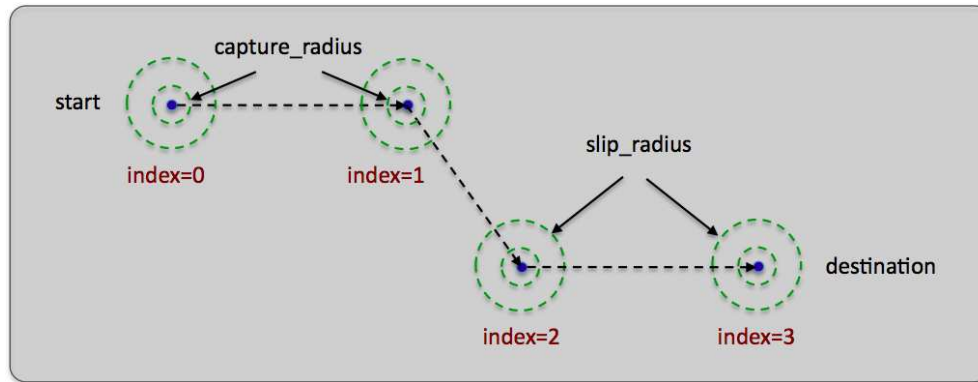


Figure 22: **The BHV_Waypoint behavior:** The waypoint behavior basic purpose is to traverse a set of waypoints. A capture radius is specified to define what it means to have achieved a waypoint, and a non-monotonic radius is specified to define what it means to be "close enough" should progress toward the waypoint be noted to degrade.

The behavior may also be configured to perform a degree of track-line following, that is, steering the vehicle not necessarily toward the next waypoint, but to a point on the line between the previous and next waypoint. This is to ensure the vehicle stays closer to this line in the face of external forces such as wind or current. The behavior may also be set to "repeat" the set of waypoints indefinitely, or a fixed number of times. The waypoints may be specified either directly at start-up, or supplied dynamically during operation of the vehicle. There are also a number of accepted geometry patterns that may be given in lieu of specific waypoints, such as polygons, lawnmower pattern and so on.

8.1.1 Brief Overview of Configuration Parameters and Variables Published

The configuration parameters and variables published collectively define the interface for the behavior. A more detailed description of usage is provided other parts of this section, and in Table 29 on page 231.

Configuration Parameters for the BHV_Waypoint Behavior

The following are the parameters for this behavior, in addition to the configuration parameters defined for all behaviors, described in Section 7.2 beginning on page 78.

Parameter	Description	BHV_Waypoint
CAPTURE_RADIUS	The radius tolerance, in meters, for satisfying the arrival at a waypoint.	
CYCLEFLAG	MOOS variable-value pairs posted at end of each cycle through waypoints.	
LEAD	If this parameter is set, track-line following between waypoints is enabled.	
LEAD_DAMPER	Distance from trackline within which the <code>lead</code> distance is stretched out.	
LEAD_ON_START	The track-line following lead value in traversing to the first waypoint.	
NM_RADIUS	A deprecated alias for <code>SLIP_RADIUS</code> .	
ORDER	The order in which waypoints are traversed - "normal", or "reverse".	
POINTS	A colon separated list of x,y pairs given as points in 2D space, in meters.	
POINT:	A single x,y pair given as a point in 2D space, in meters.	
POLYGON	An alias for <code>POINTS</code> .	
POST_SUFFIX	A suffix tagged onto the <code>WPT_STATUS</code> , <code>WPT_INDEX</code> and <code>CYCLE_INDEX</code> variables.	
RADIUS	An alias for <code>CAPTURE_RADIUS</code> .	
SLIP_RADIUS	An "outer" capture radius. Arrival declared when the vehicle is in this range and the distance to the next waypoint begins to increase.	
SPEED	The desired speed (m/s) at which the vehicle travels through the points.	
REPEAT	The number of <i>extra</i> times traversed through the waypoints. Or "forever".	
VISUAL_HINTS	Hints for visual properties in variables posted intended for rendering.	

Table 7: Configuration parameters for the BHV_Waypoint behavior.

Variables Published by the BHV_Waypoint Behavior

The below MOOS variables will be published by the behavior during normal operation, in addition to any configured flags. A variable published by any behavior may be suppressed or changed to a different variable name using the `post_mapping` configuration parameter described in Section 7.2.1 on page 79.

MOOS Variable	Description
WPT_STAT	A comma-separated string showing the status in hitting the list of points.
WPT_INDEX	The index of the current waypoint. First point has index 0.
CYCLE_INDEX	The number of times the full set of points has been traversed, if repeating.
VIEW_POINT	A visual cue for indicating the waypoint currently heading toward.
VIEW_POINT	A visual cue for indicating the steering point, if the <code>lead</code> parameter is used.
VIEW_SEGLIST	A visual cue for rendering the full set of waypoints.

Table 8: Variables posted by the BHV_Waypoint behavior.

The following are some examples:

```

WPT_STAT = vname=alpha,behavior-name=waypt_survey,index=1,hits=1/1,cycles=0,dist=30,eta=15
WPT_INDEX = 3
CYCLE_INDEX = 1
VIEW_POINT = active,true:label,alpha's track-point:label_color,0,0.5,0:
              type,track_point:source,alphawaypt_survey:vertex_color,1,0,0:60,-152.57,0
VIEW_SEGLIST = label,alpha_waypt_survey:vertex_color,1,1,0:edge_size,1.0:
               vertex_size,2.0:60,-40:60,-160:150,-160:180,-100:150,-40

```

8.1.2 Specifying Waypoints - the points, order, and repeat Parameters

The waypoints may be specified explicitly as a colon-separated list of comma-separated pairs, or implicitly using a geometric description. The order of the parameters may also be reversed with the `order` parameter. An example specification:

```
points    = 60,-40:60,-160:150,-160:180,-100:150,-40
order     = reverse // default is "normal"
repeat    = 3       // default is 0
```

A waypoint behavior with this specification will traverse the five points in reverse order (150, -40 first) four times (one initial cycle and then repeated three times) before completing. If there is a syntactic error in this specification at helm start-up, an output error will be generated and the helm will not continue to launch. If the syntactic error is passed as part of a dynamic update (see Section 7.2.2), the change in waypoints will be ignored and the a warning posted to the `BHV_WARNING` variable. See Section 12 for more methods for specifying sets of waypoints. The behavior can be set to repeat its waypoints indefinitely by setting `repeat="forever"`.

8.1.3 The `capture_radius` and `nonmonotonic_radius` Parameters

The `capture_radius` parameter specifies the distance to a given waypoint the vehicle must be before it is considered to have arrived at or achieved that waypoint. It is the inner radius around the points in Figure 22. The non-monotonic radius or `nm_radius` parameter specifies an alternative criteria for achieving a waypoint.

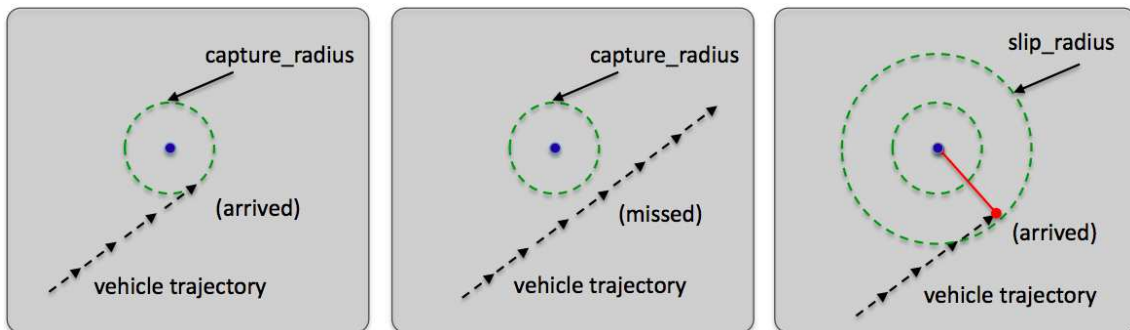


Figure 23: **The capture radius and non-monotonic radius:** (a) a successful waypoint arrival by achieving proximity less than the capture radius. (b) a missed waypoint likely resulting in the vehicle looping back to try again. (c) a missed waypoint but arrival declared anyway when the distance to the waypoint begins to increase and the vehicle is within the non-monotonic radius.

As the vehicle progresses toward a waypoint, the sequence of measured distances to the waypoint decreases monotonically. The sequence becomes non-monotonic when it hits its waypoint or when there is a near-miss of the waypoint capture radius. The `nm_radius`, is a capture radius distance within which a detection of increasing distances to the waypoint is interpreted as a waypoint arrival. This distance would have to be larger than the capture radius to have any effect. As a rule of thumb, a distance of twice the capture radius is practical. The idea is shown in Figure 23. The

behavior keeps a running tally of hits achieved with the capture radius and those achieved with the non-monotonic radius. These tallies are reported in a status message described in Section 8.1.5 below.

8.1.4 Track-line Following using the lead Parameter

By default the waypoint behavior will output a preference for the heading that is directly toward the next waypoint. By setting the `lead` parameter, the behavior will instead output a preference for the heading that keeps the vehicle closer to the track-line, or the line between the previous waypoint and the waypoint currently being driven to.

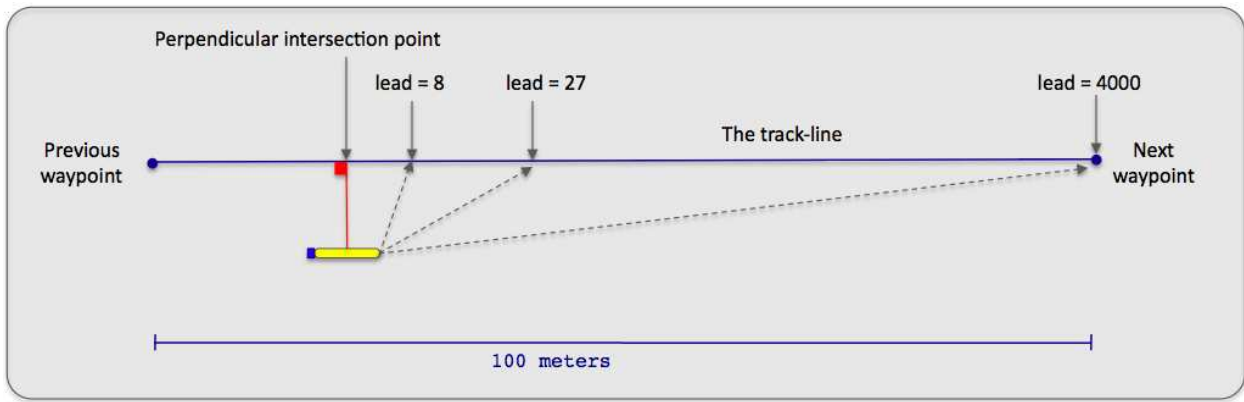


Figure 24: **The track-line mode:** When in track line mode, the vehicle steers toward a point on the track line rather than simply toward the next waypoint. The steering-point is determined by the `lead` parameter. This is the distance from the perpendicular intersection point toward the next waypoint.

The distance specified by the `lead` parameter is based on the perpendicular intersection point on the track-line. This is the point that would make a perpendicular line to the track-line if the other point determining the perpendicular line were the current position of the vehicle. The distance specified by the `lead` parameter is the distance from the perpendicular intersection point toward the next waypoint, and defines an imaginary point on the track-line. The behavior outputs a heading preference based on this imaginary steering point. If the lead distance is greater than the distance to the next waypoint along the track-line, the imaginary steering point is simply the next waypoint.

Normally, when trackline following is enabled, it is enabled only between the first waypoint and all success waypoints. When the parameter `lead_on_start` is set to true, trackline following is attempted even to the first waypoint, by defining a trackline from the vehicle's present position when the behavior first enters the running mode.

If the `lead` parameter is enabled, it may be optionally used in conjunction with the `lead_damper` parameter. This parameter expresses a distance from the trackline in meters. When the vehicle is within this distance, the value of the `lead` parameter is stretched out toward the next waypoint to soften, or dampen, the approach to the trackline and reduce overshooting the trackline.

8.1.5 Variables Published by the BHV_Waypoint Behavior

The waypoint behavior publishes five variables for monitoring the performance of the behavior as it progresses: `WPT_STAT`, `WPT_INDEX`, `CYCLE_INDEX`, `VIEW_POINT`, `VIEW_SEGLIST`. The `WPT_STAT` contains information identifying the vehicle, the index of the current waypoint, the type of hits recorded for each waypoint, the distance to the current waypoint, and the estimated time of arrival to the current waypoint. Example output:

```
WPT_STAT = "vname=alpha,behavior=traverse1,index=0,hits=10/11,dist=43,eta=23"
```

The "`hits=10/11`" component in the above example indicates that, of the 11 waypoint arrivals achieved so far, 10 of them were achieved by meeting the capture radius criteria, and one of them was achieved by meeting the nonmonotonic radius criteria.

The `WPT_INDEX` variable simply publishes the index of the current waypoint. This is a bit redundant since this information is also in the `WPT_STAT` posting, but this variable is logged as a numerical variable, not a string, and facilitates the plotting of the index value as a step function in post mission analysis tools. The `CYCLE_INDEX` variable publishes the number of times the behavior has traversed the entire set of waypoints. The behavior may be configured to post the information in these three variables using alternative variables of the user's liking:

```
post_mapping = WPT_STAT, MY_WPT_STATUS_VAR
post_mapping = WPT_INDEX, MY_WPT_INDEX_VAR
post_mapping = CYCLE_INDEX, MY_CYCLE_INDEX
```

or, to suppress the reports completely:

```
post_mapping = WPT_STAT, SILENT
post_mapping = WPT_INDEX, SILENT
post_mapping = CYCLE_INDEX, SILENT
```

Further posts to the MOOSDB can be configured to be made at the end of each cycle, that is, after reaching the last waypoint. Normally, if the `repeat` parameter remains at its default value of zero, then the end of a cycle and completing are identical and `endflags` can be used to post the desired information. However, when the behavior is configured to repeat the set of waypoints one or more times before completed, the `cycleflag` parameter may be used to post one or more variable-value pairs at the end of each cycle. Likewise, if the `repeat` parameter is zero, but the behavior is set with `perpetual=true`, the cycle flags will be posted each new time that the behavior completes.

The `VIEW_POINT` and `VIEW_SEGLIST` variables provide information consumable by a GUI application such as `pMarineViewer` or `alogview` for rendering the set of waypoints traversed by the behavior (`VIEW_SEGLIST`) and the behavior's next waypoint (`VIEW_POINT`). These two variables are responsible for the visual output in the Alpha Example Mission in Section 4 in Figure 6 on page 37.

The Objective Function Produced by the Waypoint Behavior

The waypoint behavior produces a new objective function, at each iteration, over the variables `speed` and `course/heading`. The behavior can be configured to generate this objective function in one of two forms, either by coupling two independent one-variable functions, or by generating a single coupled function directly. The functions rendered in Figure 25 are built in the first manner.

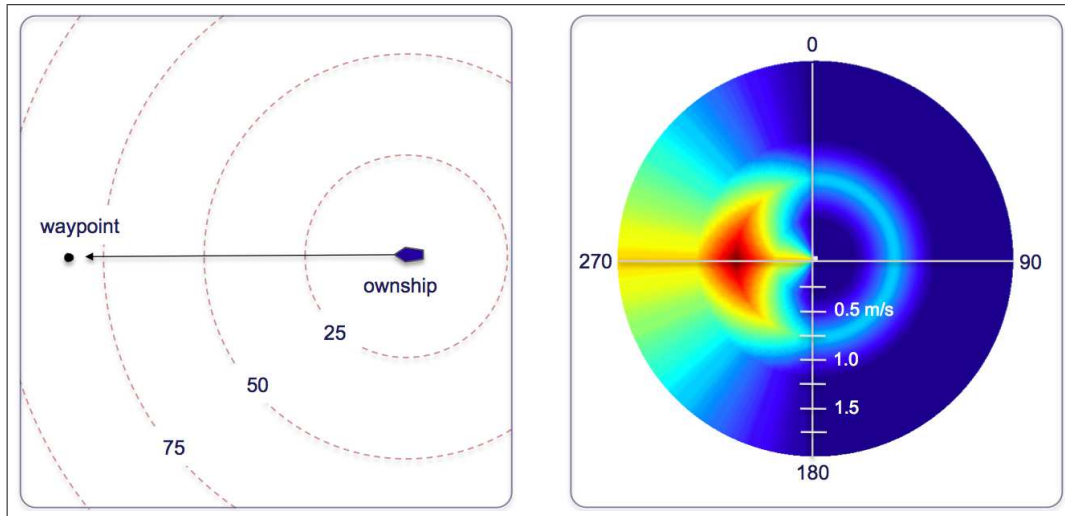


Figure 25: **A waypoint objective function:** The objective function produced by the waypoint behavior is defined over possible heading and speed values. Depicted here is an objective function favoring maneuvers to a waypoint 270 degrees from the current vehicle position and favoring speeds closer to the mid-range of capable vehicle speeds. Higher speeds are represented farther radially out from the center.

8.1.6 Further Clarification on the repeat vs. perpetual parameter

It's worth clarifying the difference in usage and effect between the `repeat` parameter, which is specific to the Waypoint behavior, and the `perpetual` parameter which is defined for all helm behaviors. Normally when a behavior completes, it is entered into the completed state, never again to be called upon by the helm. See Section 6.5.3 for more on behavior run states. It is up to the behavior implementor to decide what it means to be complete, and the implentor typically invokes the `setComplete()` function from within the code. See Section 7.5.1 for more on this function. In the case of the Waypoint behavior, completion by default occurs when the vehicle has hit all its waypoints. By setting `perpetual=true` the behavior, upon hitting all its waypoints, still invokes the `setComplete()` function, which causes it to post its endflags, but it does not enter the completed state. This feature is used, for example, in the Alpha example mission to allow the behavior to repeatedly return to the start point and be re-deployed, and later return to its start point again using the same Waypoint behavior.

The `repeat` parameter is used to change the criteria for completion. Whereas the normal criteria for completion is hitting all waypoints once, using `repeat=N` changes the criteria to be hitting all waypoints $N+1$ times. A few rules of thumb may be helpful in keeping things straight:

- When `perpetual=false`, the default setting, the behavior will permanently enter the completed state once it has hit all its waypoints.
- When `perpetual=true` and the behavior does not post endflags leading to its run conditions being unsatisfied, the behavior will repeat its waypoints indefinitely.
- When `perpetual=true` and it does indeed post endflags that lead to its run conditions being unsatisfied, it will remain in a running state until all its waypoints are hit. If the `repeat` parameter is used, it won't post its endflags until it has repeated all waypoints the specified

number of times. During the course of traversal, the `cycleflag` posts will be made each time it has completed the set of waypoints. Upon completion, it will post its endflags and reset its cycle counter.

- By setting `repeat=N`, where $N > 0$, the `perpetual` parameter is automatically set to `true`.

8.2 BHV_OpRegion

This behavior provides four different types of safety functionality, (a) a boundary box given by a convex polygon in the x-y or lat-lon plane, (b) an overall timeout, (c) a depth limit, (d) an altitude limit. The behavior does not produce an objective function to influence the vehicle to avoid violating these safety constraints. This behavior merely monitors the constraints and posts an error which results in the posting of all-stop commands, and puts the vehicle into the DISENGAGED mode.

8.2.1 Brief Overview of Configuration Parameters and Variables Published

The configuration parameters and variables published collectively define the interface for the behavior. A more detailed description of usage is provided other parts of this section, and in Table 30 on page 233.

Configuration Parameters for the BHV_OpRegion Behavior

The following are the parameters for this behavior, in addition to the configuration parameters defined for all behaviors, described in Section 7.2 beginning on page 78.

Parameter	Description	BHV_OpRegion
MAX_TIME	The max allowable time in seconds. Section 8.2.3.	
MAX_DEPTH	The max allowable depth in meters. Section 8.2.3.	
MIN_ALTITUDE	The min allowable altitude in meters. Section 8.2.3.	
POLYGON	The lat-lon area the vehicle is restricted to stay within. Section 8.2.2.	
TRIGGER_ENTRY_TIME	The time required for the vehicle to have been within the polygon region before triggering the polygon requirement. Section 8.2.2.	
TRIGGER_EXIT_TIME	The time required to have been outside the polygon before declaring a polygon containment failure. Section 8.2.2.	
VISUAL_HINTS	Hints for visual properties in variables posted intended for rendering.	

Table 9: Configuration paramters for the BHV_OpRegion behavior.

Variables Published by the BHV_OpRegion Behavior

The below MOOS variables will be published by the behavior during normal operation, in addition to any configured flags. A variable published by any behavior may be suppressed or changed to a different variable name using the `post_mapping` configuration parameter described in Section 7.2.1 on page 79.

MOOS Variable	Description
OPREG_TRAJECTORY_PERIM_DIST:	Distance, in meters, to the perimeter on the current trajectory.
OPREG_TRAJECTORY_PERIM_ETA:	Time to the perimeter on the current speed and trajectory.
OPREG_ABSOLUTE_PERIM_DIST:	Distance, in meters, to the op-region in any direction.
OPREG_ABSOLUTE_PERIM_ETA:	Time to the op-region perimeter at current speed in any direction.
OPREG_TIME_REMAINING:	Time, in seconds, until the <code>max_time</code> upper bound is exceeded.
VIEW_POLYGON:	A visual cue for rendering the polygon containment region.

Table 10: Variables posted by the BHV_OpRegion behavior.

The following are some examples:

```
OPREG_TRAJECTORY_PERIM_DIST = 498.4
OPREG_TRAJECTORY_PERIM_ETA = 875.0
OPREG_ABSOLUTE_PERIM_DIST = 17.9
OPREG_ABSOLUTE_PERIM_ETA = 30.2
OPREG_TIME_REMAINING = 1134.0
VIEW_POLYGON = edge_size,0.0:vertex_size,0.0:0,-50:0,-150:150,-150:150,-50
```

8.2.2 Safety Checking Applied to an Operation Region

One safety check performed by the OpRegion behavior is to ensure that the vehicle remains in an operation region defined by a convex polygon in the x-y plane.

POLYGON: A colon separated list of x,y pairs given as points in space, typically meters. A pair given by “label,string” can associate an optional label with the point list. *The collection of points must be a convex polygon.* A check for convexity is done upon helm/behavior start-up. Behavior initialization will fail if it is not convex. If no polygon is provided, no X,Y checks are made.

TRIGGER_ENTRY_TIME: The amount of time required for the vehicle to have been within the polygon containment region before triggering the polygon containment requirement. This is useful when launching vehicles from a dock structure such as the MIT Sailing Pavilion. The default setting is zero meaning the polygon containment requirement is active immediately.

TRIGGER_EXIT_TIME: The amount of time required to have been outside the polygon containment region before declaring a polygon containment failure. This is useful if the vehicle NAV_X and NAV_Y position is based on a sensor without outlier detection. The kayaks, for example, are often relying solely on GPS which occasionally emits an outlier well out of the containment region. By setting this value high enough, outliers are ignored. Each time a recorded position is contained within the polygon region, the clock is set to zero. The default setting is zero, meaning the very first detection outside the polygon will result in a polygon containment error.

8.2.3 Safety Limits on Operation Time, Vehicle Depth, and Vehicle Altitude

MAX_TIME: The maximum allowable time (in seconds) that the helm is allowed to run. The clock starts when the pHelmIvP process first takes control, i.e., enters the Engaged mode. If no maximum time is specified, then no time checks are made.

MAX_DEPTH: The maximum allowable depth of the vehicle (in meters). If no depth is provided, no depth checks are made.

MIN_ALTITUDE: The minimum allowable altitude of the vehicle (in meters). If no altitude is provided, no altitude checks are made.

8.2.4 Variables Published by the BHV_OpRegion Behavior

The behavior also produces a set of status variables regarding the vehicle position with respect to the containment region. Since a violation of this constraint results in a vehicle full-stop and the helm relinquishing control, other behaviors or MOOS processes may want to take measures to avoid it. These status variables provide information on the position and estimated time between the vehicle and the perimeter, based both on the absolute position as well as the current vehicle trajectory. See Figure 26.

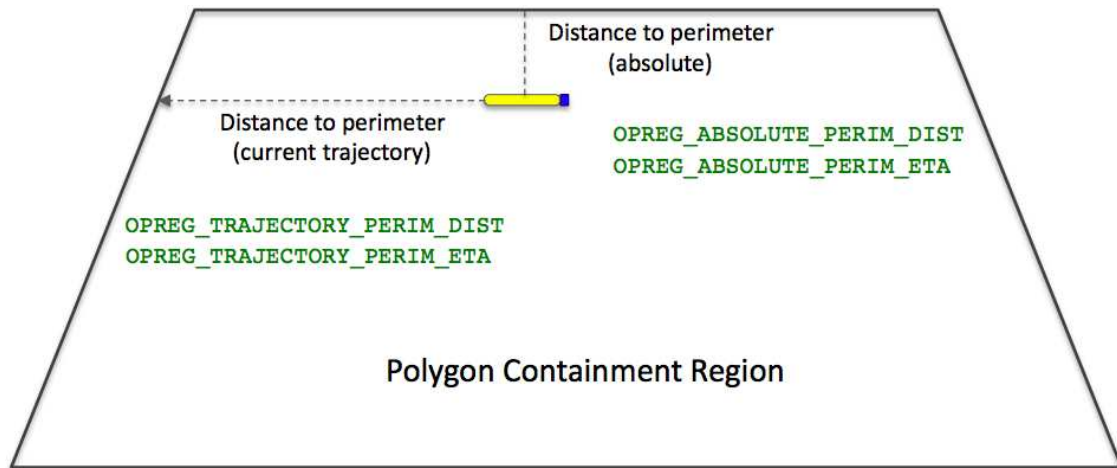


Figure 26: **The OpRegion polygon and status variables:** The OpRegion behavior publishes information regarding its estimated distance and time of arrival (ETA) to the perimeter of the polygon containment region. It publishes two sets of information; one based on the current trajectory and the other based on the absolute distance to the perimeter at top vehicle speed.

The four variables produced by the behavior (and posted to the MOOSDB by the Helm) are:

OPREG_TRAJECTORY_PERIM_DIST: The distance (in meters) between the current vehicle position to the perimeter of the polygon containment region (given by the `POLYGON` parameter), based on the vehicle remaining on the current trajectory.

OPREG_TRAJECTORY_PERIM_ETA: The amount of time (in seconds) needed for the vehicle to reach the perimeter of the polygon containment region (given by the `POLYGON` parameter), based on the vehicle remaining on the current trajectory.

OPREG_ABSOLUTE_PERIM_DIST: The distance (in meters) between the current vehicle position to the perimeter of the polygon containment region (given by the `POLYGON` parameter), regardless of the current vehicle trajectory.

OPREG_ABSOLUTE_PERIM_ETA: The amount of time (in seconds) needed for the vehicle to reach the perimeter of the polygon containment region (given by the POLYGON parameter), regardless of the current vehicle trajectory. Calculated on the maximum vehicle speed.

8.3 BHV_Loiter

A behavior for transiting to and repeatedly traversing a set of waypoints. A similar effect can be achieved with the BHV_Waypoint behavior but this behavior assumes a set of waypoints forming a convex polygon to exploit certain useful algorithms discussed below. It also utilizes the non-monotonic arrival criteria use in the BHV_Waypoint behavior to avoid loop-backs upon waypoint near-misses. It also robustly handles dynamic exit and re-entry modes when or if the vehicle diverges from the loiter region due to external events. And it is dynamically reconfigurable to allow a mission control module to repeatedly reassign the vehicle to different loiter regions by using a single persistent instance of the behavior.

8.3.1 Brief Overview of Configuration Parameters and Variables Published

The configuration parameters and variables published collectively define the interface for the behavior. A more detailed description of usage is provided other parts of this section, and in Table 31 on page 234.

Configuration Parameters for the BHV_Loiter Behavior

The following are the parameters for this behavior, in addition to the configuration parameters defined for all behaviors, described in Section 7.2 beginning on page 78.

Parameter	Description	BHV_Loiter
ACQUIRE_DIST:	Distance to polygon outside which the behavior will be in “acquire” mode.	
CAPTURE_RADIUS:	The radius tolerance, in meters, for satisfying the arrival at a point.	
CENTER_ACTIVATE:	If true , center of polygon is set to present position when behavior activates.	
CENTER_ASSIGN:	An x,y pair, in meters, indicating a (new) center of the loiter polygon.	
CLOCKWISE:	If true , loitering is done clockwise (the default setting).	
NM_RADIUS	A deprecated alias for SLIP_RADIUS.	
POLYGON:	Polygon about which the vehicle traverse and loiter.	
POST_SUFFIX:	A string to add as a suffix to variables posted by this behaviors.	
RADIUS:	An alias for CAPTURE_RADIUS.	
SLIP_RADIUS:	An “outer” capture radius. Arrival declared when the vehicle is in this range and the distance to the point begins to increase.	
SPEED:	Speed in meters per second.	
SPIRAL_FACTOR:	The degree of spiraling when activated at th ecenter of the polygon.	
VISUAL_HINTS:	Hints for visual properties in variables posted intended for rendering.	
XCENTER_ASSIGN:	A x-value, in meters, indicating a (new) x-position of the loiter polygon.	
YCENTER_ASSIGN:	A y-value, in meters, indicating a (new) y-position of the loiter polygon.	

Table 11: Configuration parameters for the BHV_Loiter behavior.

Variables Published by the BHV_Loiter Behavior

The below MOOS variables will be published by the behavior during normal operation, in addition to any configured flags. A variable published by any behavior may be suppressed or changed to a

different variable name using the `post_mapping` configuration parameter described in Section 7.2.1 on page 79.

MOOS Variable	Description
<code>LOITER_REPORT</code>	A status string with current mode, current vertex, and prior arrivals.
<code>LOITER_INDEX</code>	The index of the vertex in the loiter polygon currently heading toward.
<code>LOITER_ACQUIRE</code>	Posts 1 when in the “acquire” mode, 0 otherwise.
<code>LOITER_DIST_TO_POLY</code>	Current distance, in meters, to the loiter polygon.
<code>LOITER_ETA_TO_POLY</code>	Estimated time of arrival to the polygon at present speed and trajectory.
<code>VIEW_POINT:</code>	A visual cue for rendering the next point in the loiter polygon.
<code>VIEW_POLYGON:</code>	A visual cue for rendering the loiter polygon.

The following are some examples:

```

LOITER_REPORT = index=5,capture_hits=51,nonmono_hits=0,acquire_mode=false
LOITER_INDEX = 5
LOITER_ACQUIRE = 1
LOITER_DIST_TO_POLY = 2.2
VIEW_POLYGON = edge_size,0.0:vertex_size,0.0:0,-50:0,-150:150,-150:150,-50

```

8.3.2 How Things Work

POLYGON: A colon separated list of comma-separated x,y pairs indicating points in 2D space. Units are in meters. Unlike the waypoint behavior, these points must describe a convex polygon; if the convexity condition fails the behavior will not instantiate. As an alternative to listing a sequence of points, a orbit-style polygon can be given by four values (1),(2) the x and y position, (3) the radius in meters, and (4) the number of points on the circle. This specification is denoted with the “radial” tag as follows “radial:50,50,200,16”.

SPEED: The desired speed, in meters/second, at which the vehicle travels through the points.

RADIUS: The radius tolerance, in meters, for satisfying the arrival at a waypoint. As soon as the vehicle is within this distance to the waypoint the waypoint behavior begins operating on the next waypoint in the sequence, or completes and posts its endflags if there are no more waypoints.

SLIP_RADIUS: As the vehicle progresses toward a waypoint, the sequence of measured distances to the waypoint decreases monotonically. The sequence becomes non-monotonic when it hits its waypoint or when there is a near-miss of the waypoint arrival radius. The `SLIP_RADIUS`, a.k.a, the `NM_RADIUS`, short for *non-monotonic radius* is an arrival radius distance within which a detection of increasing distances to the waypoint is interpreted as a waypoint arrival. This distance would have to be larger than the arrival radius to have any effect (see Figure 23). As a rule of thumb, a distance of twice the arrival radius is practical.

CLOCKWISE: If “true”, the behavior will influence the vehicle in a clockwise direction around the polygon. Values are case insensitive, but must spell either true or false. The default is true.

ACQUIRE_DIST: The distance in meters between the vehicle and the polygon that will trigger the vehicle to return to *acquire* mode. This notion applies to the case where the vehicle is both inside and outside the polygon. (The re-acquire algorithms are different however.)

POST_SUFFIX: This string will be added as a suffix to each of the status variables posted by the behavior (`LOITER_REPORT`, `LOITER_INDEX`, `LOITER_ACQUIRE`, `LOITER_DIST2POLY`). By default, the suffix is the empty string and the variables will be posted as above. When multiple Loiter behaviors are configured in the helm it may help to distinguish the posted variables by a suffix. A given suffix of "FOO" would result in the posting of `LOITER_INDEX_FOO` for example. The extra '_' character is inserted automatically.

When the behavior is active, it is in either one of two modes; the *acquire* mode or *normal* mode. In the normal mode it is merely proceeding to the next waypoint on the polygon. In the acquire mode, each iteration begins by first determining the next polygon point to treat as the next waypoint. This is useful for ensuring the entry waypoint isn't followed by a need for a sharp vehicle turn. The acquire point depends on the chosen direction of polygon traversal, as shown in Figure 27.

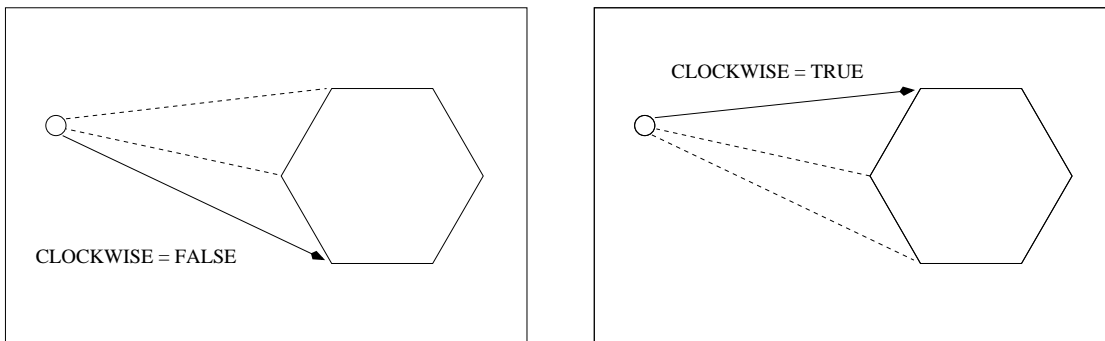


Figure 27: In the *acquire* mode, the polygon points are evaluated for suitability in terms of a smooth entry trajectory. Only the “viewable” points, those viewable if the polygon were an opaque object and the viewer were at the current vehicle location, are contenders. The contenders are rated on the follow-on angle given the desired clockwise or counter-clockwise loiter direction. Larger follow-on angles are preferred as shown.

When the behavior is in the acquire mode and *outside* the polygon, the chosen vertex is the one most tangential in either the clockwise or counter-clockwise direction as shown in the figure. When the vehicle is *inside* the polygon, the chosen vertex is the one which forms the most obtuse angle between the current vehicle position, the vertex, and the follow-on vertex. Unlike the case when outside the polygon, the chosen vertex changes as the vehicle makes progress back to the polygon perimeter. The effect is for the vehicle to “spiral” out to the perimeter for the smoothest re-entry in to a normal loitering path.

The circumstance most common for triggering the acquire mode is the initial assignment to the vehicle to loiter at a new given region in the X,Y plane. This assignment *could* occur while the vehicle happens to already be within the polygon for a number of reasons. Furthermore, the vehicle could be driven off the polygon loiter trajectory due to environmental (wind or current) forces or the temporary dominance of other vehicle behaviors such as collision avoidance or tracking of another vehicle.

Once the behavior enters the acquire mode, it remains in this mode until arriving at the first waypoint (defined by the arrival and non-monotonic radii settings), after which it switches to normal mode until the acquire mode is re-triggered or the behavior run conditions are no longer met. There is currently no “complete” condition for this behavior other than a time-out which is defined for all behaviors.

8.4 BHV_PeriodicSpeed

This behavior will periodically influence the speed of the vehicle while remaining neutral at other times. The timing is specified by a given period in which the influence is on (busy), and a period specifying when the influence is off (lazy), as depicted in Figure 28.

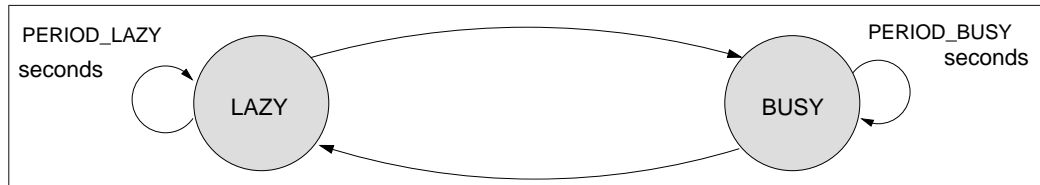


Figure 28: **Busy and Lazy Modes:** In the busy mode the behavior will produce an objective function defined over speed that will potentially influence the speed of the vehicle. In the lazy mode, it simply will not produce an objective function.

It was conceived for use on an AUV equipped with an acoustic modem to periodically slow the vehicle to reduce self-noise and reduce communication difficulty. One can also specify a flag (a MOOS variable and value) to be posted at the start of the period to prompt an outside action such as the start of communication attempts.

8.4.1 Brief Overview of Configuration Parameters and Variables Published

The configuration parameters and variables published collectively define the interface for the behavior. A more detailed description of usage is provided other parts of this section, and in Table 32 on page 235.

8.4.2 Parameters of the BHV_PeriodicSpeed Behavior

The following are the parameters for this behavior, in addition to the configuration parameters defined for all behaviors, described in Section 7.2 beginning on page 78.

Parameter	Description	BHV_PeriodicSpeed
BASEWIDTH:	The width of the ZAIC basewidth, in m/sec, in the IvP function.	
INITIALLY_BUSY:	If true the initial state is busy. The default is false.	
PEAKWIDTH:	The width of the ZAIC peakwidth, in m/sec in the IvP function.	
PERIOD_BUSY:	The duration of the busy period, in seconds.	
PERIOD_LAZY:	The duration of the lazy period, in seconds.	
PERIOD_SPEED:	The desired speed, in m/sec, in the IvP function.	
RESET_UPON_RUNNING:	Initial conditions reset upon entering the running state. Default is true .	
SUMMIT_DELTA:	The extent of the ZAIC summit delta in the IvP function.	

8.4.3 State Transition Policy and Initial Condition Parameters

The behavior alternates between one of two modes, the busy mode or the lazy mode. In the former, it will produce an objective function over the `speed` decision variable, and in the latter mode it will simply refrain from producing the objective function. Note that these modes are different from the general behavior run states described in Section 6.5.3 on page 69. If this behavior is idle, i.e., has not met the conditions for being in the running state, it will not generate an objective function regardless of whether it is in the busy or lazy mode.

When the behavior enters the busy mode, it resets a timer which counts down from `PERIOD_BUSY` seconds, after which it enters the lazy mode. When it enters the lazy mode, it resets a timer which counts down from `PERIOD_LAZY` seconds, after which it goes back to the busy mode. By default the behavior is initially in the lazy mode, but it can be configured in the opposite manner by setting `INITIALLY_BUSY` to `true`.

By default, when `RESET_UPON_RUNNING` is `true`, each time the behavior enters the running state, the busy/lazy mode is set to its initial value, and all timers are reset to their initial values. This is true regardless of whether it is entering the running state upon initial helm engagement, or due to transitioning from the idle state. This can be changed by setting `RESET_UPON_RUNNING` to `false`. In this case the timers are counting down immediately upon helm engagement and continue to do so regardless of the behavior run state.

8.4.4 Variables Published by the `BHV_PeriodicSpeed` Behavior

This behavior publishes three variables for monitoring and logging performance - `PS_PENDING_BUSY`, `PS_PENDING_LAZY`, and `PS_BUSY_COUNT`.

The `PS_PENDING_BUSY` variable publishes the amount of time in seconds until the behavior reaches the busy mode. During the busy mode this value is zero, and it resets to the value given by the `PERIOD_LAZY` parameter upon transitioning into the lazy mode. The `PS_PENDING_LAZY` variable publishes the amount of time in seconds until the behavior reaches the lazy mode. During the lazy mode this value is zero, and it resets to the value given by `PERIOD_BUSY` upon transitioning back into the busy mode. To reduce posting volume, the values posted will be rounded to the nearest second until less than one second remains, after which fractions are posted. The `PS_BUSY_COUNT` is posted by the behavior each time it enters the busy mode. The value is an integer indicating the number of times it has entered the busy mode, posting zero initially.

8.5 BHV_PeriodicSurface

This behavior will periodically influence the depth and speed of the vehicle while remaining neutral at other times. The purpose is to bring the vehicle to the surface periodically to achieve some event specified by the user, typically the receipt of a GPS fix. Once this event is achieved, the behavior resets its internal clock to a given period length and will remain idle until a clock time-out occurs. The behavior can be in one of four states as described in Figure 29 below.

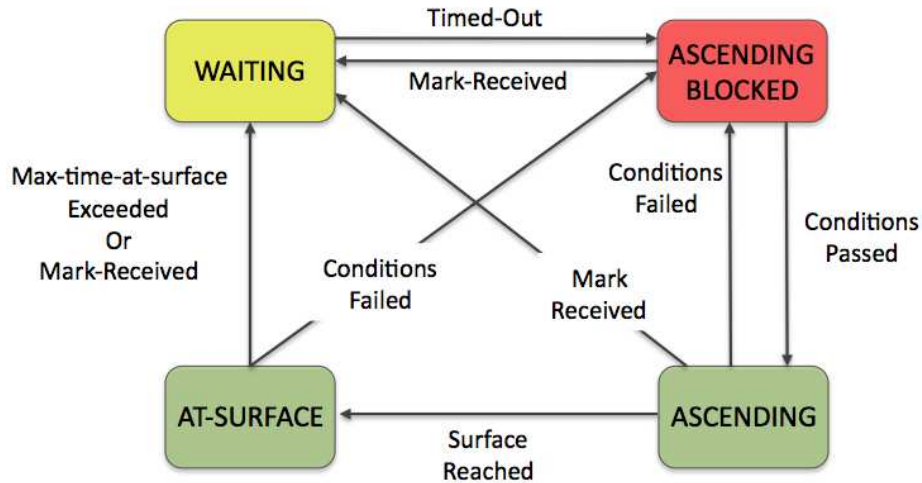


Figure 29: Possible modes of the PeriodicSurface behavior.

In the `WAITING` state the behavior is simply waiting for its clock to wind down to zero. The duration is given by the `PERIOD` parameter listed below. The clock is active despite any other run conditions that may apply to the behavior. It is started when the behavior is first instantiated and also when the desired event occurs at the surface. The `ASCENDING_BLOCKED` state indicates that the behavior timer has reached zero, but another run condition has not been met. This is to prevent the behavior from trying to surface the vehicle when other circumstances override the need to surface. In the `ASCENDING` state, the behavior will produce an objective function over depth and speed to bring the vehicle to the surface. A couple parameters described below can determine the trajectory of the vehicle during ascent. This state can transition back to the `ASCENDING_BLOCKED` state if run conditions become no longer satisfied prior to the vehicle reaching the surface. In the `AT_SURFACE` state the vehicle is at the surface waiting for a specified event.

Parameter	Description	BHV_PeriodicSurface
<code>ACOMMS_MARK_VARIABLE</code>	The incoming MOOS variable for resetting the acomms period clock.	
<code>ASCENT_GRADE</code>	Manner in which desired speed approaches zero on the approach to the surface.	
<code>ASCENT_SPEED</code>	Desired speed of the vehicle during the <code>ASCENT</code> mode.	
<code>MARK_VARIABLE</code>	The incoming MOOS variable for resetting the period clock.	
<code>MAX_TIME_AT_SURFACE</code>	The maximum time, in seconds, the vehicle will wait at the surface.	
<code>PERIOD</code>	Duration of the <code>WAITING</code> mode.	
<code>ZERO_SPEED_DEPTH</code>	The depth, in meters, at which the desired speed becomes zero on ascent.	

Table 12: Configuration parameters for the `BHV_PeriodicSurface` behavior.

PERIOD: The duration of the period, in seconds, during which the behavior will remain in the `IDLE_WAITING` state.

MARK_VARIABLE: The name of a variable used for indicating when the behavior witnesses the event that would reset the period clock. On each iteration, the variable is checked against its last known value and if different, the clock is reset. The default value for this parameter is `GPS_UPDATE_RECEIVED`. If this variable is populated by another process with a value indicating the time a GPS fix is obtained, then the mark will occur on each GPS fix. Since the value of this argument names a MOOS variable, it is case sensitive.

PENDING_STATUS_VAR: This variable will be written to with the value of the remaining time on the idle clock, rounded to integer seconds. The default value is `PENDING_SURFACE`. Since the value of this argument names a MOOS variable, it is case sensitive.

ATSURFACE_STATUS_VAR: This variable will be written to with the number of seconds that the vehicle has been waiting at the surface (for the event indicated by the `MARK_VARIABLE`). The number of seconds is rounded to the nearest integer and will be zero when the vehicle is not at the surface. The default value is `TIME_AT_SURFACE`. Since the value of this argument names a MOOS variable, it is case sensitive.

ASCENT_SPEED: This parameter indicates the desired speed (m/s) of the vehicle during the ascent state. If left unspecified, the ascent speed will be equal to the current noted speed at moment it transitions into the ascent state.

ASCENT_GRADE: This parameter indicates the manner in which the ascent speed approaches zero as the vehicle progresses toward the `ZERO_SPEED_DEPTH`. It has four legal values: *fullspeed*, *linear*, *quadratic*, and *quasi*. In all four cases, the initial speed is determined by the parameter `ASCENT_SPEED`, and the desired speed will be zero once the `ZERO_SPEED_DEPTH` has been achieved. The four settings determine the manner of slowing to zero speed during the ascent. The *fullspeed* setting indicates that desired speed should remain constant through the ascent right up to the instant the vehicle achieves `ZERO_SPEED_DEPTH`. For the other three settings the speed reduction is relative to the starting depth (the depth noted at the outset of the ascent state) and the `ZERO_SPEED_DEPTH`. With the *linear* setting, the speed reduction is linear. With the *quadratic* setting, the speed reduction is quadratic (quicker initial speed reduction). With the *quasi* setting the speed reduction is between linear and quadratic. The value passed to this parameter is not case sensitive.

ZERO_SPEED_DEPTH: The depth (in meters) during the ascent state at which the desired speed becomes zero, and presumably further ascent is achieved through positive buoyancy.

MAX_TIME_AT_SURFACE: The maximum time (in seconds) spent in the `AT_SURFACE` state, waiting for the event indicated by the `MARK_VARIABLE`, before the behavior transitions into the `IDLE` state.

8.6 BHV_ConstantDepth

This behavior will drive the vehicle at a specified depth. Analogous to the ConstantDepthTask in the pHelm task library, but somewhat different. This behavior merely expresses a preference for a particular depth. If other behaviors also have a depth preference, coordination/compromise will take place through the multi-objective optimization process. The following parameters are defined for this behavior:

Parameter	Description	BHV_ConstantDepth
DEPTH	The desired depth of the vehicle, in meters.	
PEAKWIDTH	The width of the peak, in meters, in the produced ZAIC-style IvP function.	
PEAKWIDTH	The width of the base, in meters, in the produced ZAIC-style IvP function.	
DURATION	Behavior duration, in seconds. Mandatory configuration for this behavior.	

Table 13: Configuration parameters for the ConstantDepth behavior.

DEPTH: The desired depth in meters.

PEAKWIDTH: The width of the peak in meters in the produced objective function.

BASEWIDTH: The width of the base, in meters in the produced objective function.

DURATION: This is a parameter defined for all general behaviors, but for this behavior, specification is mandatory for safety reasons. The default if not specified is 0 seconds which will result in the behavior completing immediately. If no duration limit is desired, e.g., if the behavior is tied to another behavior or event via condition variables, then setting “duration = no-time-limit” will result in no time duration checks for this behavior.

8.7 BHV_ConstantHeading

This behavior will drive the vehicle at a specified depth. Analogous to the ConstantHeadingTask in the pHelm task library, but somewhat different. This behavior merely expresses a preference for a particular heading. If other behaviors also have a heading preference, coordination/compromise will take place through the multi-objective optimization process. The following parameters are defined for this behavior:

Parameter	Description	BHV_ConstantHeading
HEADING	The desired speed of the vehicle, in degrees (North=0).	
PEAKWIDTH	The width of the peak, in degrees, in the produced ZAIC-style IvP function.	
PEAKWIDTH	The width of the base, in degrees, in the produced ZAIC-style IvP function.	
DURATION	Behavior duration, in seconds. Mandatory configuration for this behavior.	

Table 14: Configuration parameters for the ConstantHeading behavior.

HEADING: The desired heading in degrees (-180, +180].

PEAKWIDTH: The width of the peak in degrees in the produced objective function.

BASEWIDTH: The width of the base, in degrees in the produced objective function.

DURATION: This is a parameter defined for all general behaviors, but for this behavior, specification is mandatory for safety reasons. The default if not specified is 0 seconds which will result in the behavior completing immediately. If no duration limit is desired, e.g., if the behavior is tied to another behavior or event via condition variables, then setting “duration = no-time-limit” will result in no time duration checks for this behavior.

8.8 BHV_ConstantSpeed

This behavior will drive the vehicle at a specified speed. Analogous to the ConstantSpeedTask in the pHelm task library, but somewhat different. This behavior merely expresses a preference for a particular speed. If other behaviors also have a speed preference, coordination/compromise will take place through the multi-objective optimization process. The following parameters are defined for this behavior:

Parameter	Description	BHV_ConstantSpeed
SPEED	The desired speed of the vehicle, in meters per second.	
PEAKWIDTH	The width of the peak, in meters per second, in the produced ZAIC-style IvP function.	
PEAKWIDTH	The width of the base, in meters per second, in the produced ZAIC-style IvP function.	
DURATION	Behavior duration, in seconds. Mandatory configuration for this behavior.	

Table 15: Configuration parameters for the ConstantSpeed behavior.

SPEED: The desired speed in meters/second.

PEAKWIDTH: The width of the peak in meters/second in the produced objective function.

BASEWIDTH: The width of the base, in meters/second in the produced objective function.

DURATION: This is a parameter defined for all general behaviors, but for this behavior, specification is mandatory for safety reasons. The default if not specified is 0 seconds which will result in the behavior completing immediately. If no duration limit is desired, e.g., if the behavior is tied to another behavior or event via condition variables, then setting “duration = no-time-limit” will result in no time duration checks for this behavior.

8.9 BHV_GoToDepth

This behavior will drive the vehicle to a sequence of specified depths and duration at each depth. The duration is specified in seconds and reflects the time at depth *after* the vehicle has first achieved that depth, where achieving depth is defined by the `CAPTURE_DELTA` parameter. The behavior subscribes for `NAV_DEPTH` to examine the current vehicle depth against the target depth. If the current depth is within the delta given by `CAPTURE_DELTA`, that depth is considered to have been achieved. The behavior also stores the previous depth from the prior behavior iteration, and if the target depth is between the prior depth and current depth, the depth is considered to be achieved regardless of whether the prior or current depth is actually within the `CAPTURE_DELTA`. This behavior merely expresses a preference for a particular depth. If other behaviors also have a depth preference, coordination/compromise will take place through the multi-objective optimization process. The following parameters are defined for this behavior:

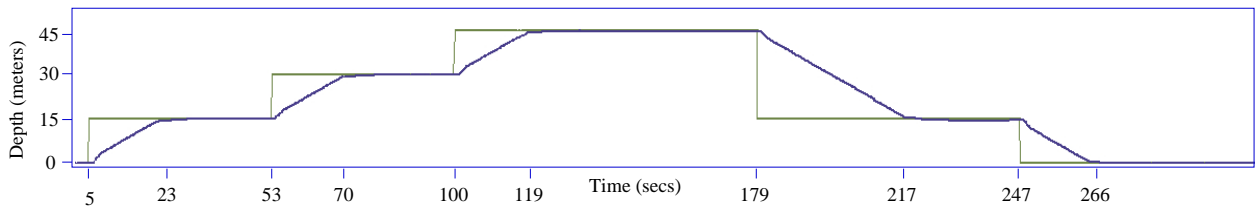


Figure 30: Depth log from simulation with the depth parameters shown in Listing 8. The lighter, step-like line indicates the values of `DESIRED_DEPTH` generated by the helm, and the darker line indicates the recorded depth value of the vehicle. The depth plateaus start from the moment the vehicle achieves depth. For example, the vehicle achieved a depth of 45 meters at 119 seconds and retained that desired depth for another 60 seconds as requested in the configuration shown in Listing 8.

DEPTH: A colon-separated list of comma-separated pairs. Each pair contains a desired depth and a duration at that depth. The duration applies from the point in time that the depth is first achieved. If a time duration is not provided for any pair, it defaults to zero. Thus “depth = 20” is a valid parameter setting.

REPEAT: The number of times the vehicle will traverse through the evolution of depths, proceeding to the 1st depth after the nth depth has been hit. The default value is zero.

PERPETUAL: If equal to *true*, when the vehicle completes its evolution of depths (perhaps several evolutions if `REPEAT` is non-zero), the endflags will be posted. But rather than setting the complete variable to true and thus never receiving any further run consideration, the behavior is reset to its initial state. Presumably the user sets endflags that will cause the condition flags to be not immediately satisfied, thus putting the behavior in a state waiting again for an external event flag to be posted. The default value of this parameter is *false*.

CAPTURE_DELTA: The delta depth, in meters, between the current observed depth and the current target depth, below which the behavior will declare the depth to have been achieved.

CAPTURE_FLAG: The name of a MOOS variable incremented each time a target depth level has been achieved. Useful for logfile debugging/analyzing and also allows other behaviors to be

conditioned on a depth event. If this behavior is completed in *perpetual* mode, the counter is reset to zero. If the behavior is repeating a set of depths by setting REPEAT greater than zero, the counter will continue to increment through evolutions.

8.10 BHV_MemoryTurnLimit

The objective of the Memory-Turn-Limit behavior is to avoid vehicle turns that may cross back on its own path and risk damage to the towed equipment. Its configuration is determined by the two parameters described below which combine to set a vehicle turn radius limit. However, it is not strictly described by a limited turn radius; it stores a time-stamped history of recent recorded headings and maintains a *heading average*, and forms its objective function on a range deviation from that average. This behavior merely expresses a preference for a particular heading. If other behaviors also have a heading preference, coordination/compromise will take place through the multi-objective optimization process. The following parameters are defined for this behavior:

MEMORY_TIME: The duration of time for which the heading history is maintained and heading average calculated.

TURN_RANGE: The range of heading values deviating from the current heading average outside of which the behavior reflects sharp penalty in its objective function.

The heading history is maintained locally in the behavior by storing the currently observed heading and keeping a queue of n recent headings within the **MEMORY_TIME** threshold. The heading average calculation below handles the issue of angle wrap in a set of n headings $h_0 \dots h_{n-1}$ where each heading is in the range $[0, 359]$.

$$\text{heading_avg} = \text{atan2}(s, c) \cdot 180/\pi,$$

where s and c are given by:

$$s = \sum_{k=0}^{n-1} \sin(h_k \pi / 180), \quad c = \sum_{k=0}^{n-1} \cos(h_k \pi / 180).$$

The vehicle turn radius r is not explicitly a parameter of the behavior, but is given by:

$$r = v / ((u/180)\pi),$$

where v is the vehicle speed and u is the turn rate given by:

$$u = \text{TURN_RANGE} / \text{MEMORY_TIME}.$$

The same turn radius is possible with different pairs of values for **TURN_RANGE** and **MEMORY_TIME**. However, larger values of **TURN_RANGE** allow sharper initial turns but temper the turn rate after the initial sharper turn has been achieved.

A Rendering of the MemoryTurnLimit Objective Function

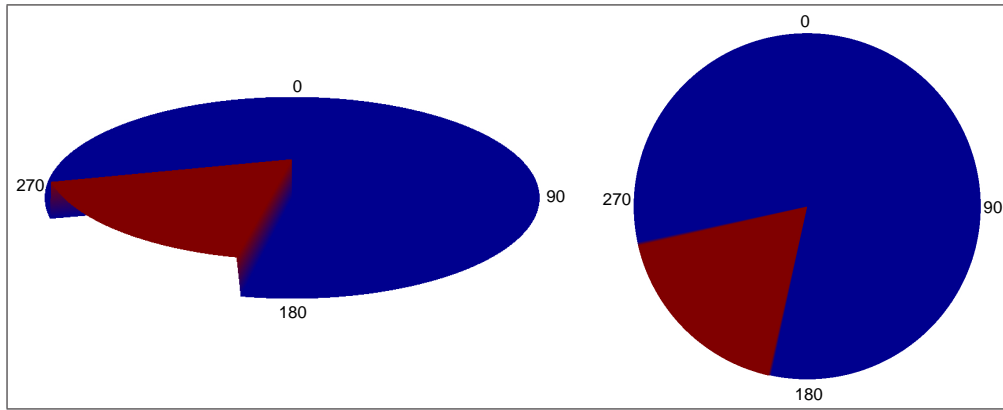


Figure 31: **The MemoryTurnLimit objective function:** The objective function produced by the MemoryTurnLimit behavior is defined over possible heading values. Depicted here is an objective function formed when the recent heading history is 225 degrees and the `turn_range` parameter is set to 30 degrees. The resulting objective function highly favors headings in the range of 190-240 degrees. On the right is a “birds-eye” view of the function, and on the left the function is viewed at an angle to appreciate the 3D quality of the function. Higher (red) values correspond to higher utility.

8.11 BHV_StationKeep

8.11.1 Overview

This behavior is designed to keep the vehicle at a given lat/lon or x,y station-keep position by varying the speed to the station point as a linear function of its distance to the point. The parameters allow one to choose the two distances between which the speed varies linearly, the range of linear speeds, and a default transit speed if the vehicle is outside the outer radius.

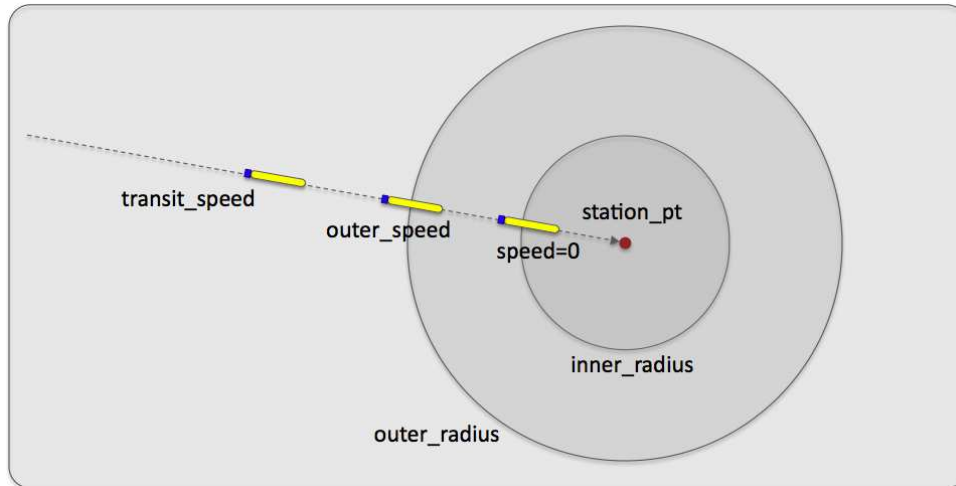


Figure 32: **The station-keep behavior parameters:** The station-keep behavior can be configured to approach the outer station circle with a given transit speed, and will decrease its preference for speed linearly between the outer radius and inner radius. The preferred speed is zero when the vehicle is at or inside the inner radius.

An alternative to this station keeping behavior is an active loiter around a very tight polygon with the `BHV_LOITER` behavior. This station keeping behavior conserves energy and aims to minimize propulsor use. The behavior can be configured to station-keep at a pre-set point, or wherever the vehicle happens to be when the behavior transitions into an active state.

The station-keep behavior was initially developed for use on an autonomous kayak. It's worth pointing out that a vehicle's control system, i.e., the front-seat driver described in Section 2.3, may have a native station-keeping mode, in which case the activation of this behavior would be replaced by a message from the backseat autonomy system to invoke the station-keeping mode. It's also worth pointing out that most UUVs are positively buoyant and will simply come to the surface if commanded with a zero-speed.

8.11.2 Brief Summary of the BHV_StationKeep Behavior Parameters

The following parameters are defined for this behavior. A more detailed description is provided other parts of this section, and in Table 39 on page 242.

Parameter	Description	BHV_StationKeep
STATION_PT	An x,y pair given as a point in local coordinates.	
POINT	A supported alias for STATION_POINT.	
CENTER_ACTIVE	If <code>true</code> , station-keep at position upon activation.	
INNER_RADIUS	Distance to station-point within which the preferred speed is zero.	
OUTER_RADIUS	Distance within which the preferred speed begins to decrease.	
OUTER_SPEED	Preferred speed at outer radius, decreasing toward inner radius.	
SWING_TIME	Duration of drift of station circle with vehicle upon activation.	
TRANSIT_SPEED	Preferred speed beyond the outer radius.	
EXTRA_SPEED	A deprecated alias for TRANSIT_SPEED.	
PASSIVE.STATION.RADIUS	A radius used for low-power, passive station-keeping.	

8.11.3 Setting the Station-Keep Point and Radial-Speed Relationships

The station-keep point is set in one of two ways: either with a pre-specified fixed position, or with the vehicle's current position when the vehicle transitions into the running state. To set a fixed station-keep position:

```
station_pt = 100,250
```

To configure the behavior to station-keep at the vehicle's current position when it enters the running state:

```
center_active = true // "true" is case insensitive
```

At the outset of station-keeping via `center_activate`, the vehicle typically is moving at some speed. Despite the fact that station-keeping is immediately active and typically results in a desired speed of zero if no other behaviors are active, the vehicle will continue some distance before coming to a near or complete stop in the water, thus “over-shooting” the station-keep point. This often means that the station-keep behavior will immediately turn the vehicle around to come back to the station-keep point. This can be countered by setting the behavior's “swing time” parameter, the amount of time after initial center-activation that the station-keep point is allowed to drift with the current position of the vehicle before becoming fixed. The format is:

```
swing_time = <time-duration> // default is 0
```

The `<time-duration>` is given in seconds and the duration is clipped by the range `[0, 60]`.

If the behavior enters the running state, but center-activation is not set to true, and no pre-specified fixed position is given, the behavior will not produce an objective function. It will remain in the running state, but not the active state. (See Section 6.5.3 for more detail on behavior run states.) In this situation, a warning will be posted: `BHV_WARNING="STATION_POINT_NOT_SET"`.

The `INNER_RADIUS` and `OUTER_RADIUS` parameters affect the preferred speed of the behavior as it relates to the vehicle's current range to the station point. The preferred speed at the outer radius is given by the parameter `OUTER_SPEED`. The preferred speed decreases linearly to zero as the vehicle approaches the inner radius. The default values for the inner and outer radii are 4 and 15

respectively. If configured with values such that the inner is greater than the outer, this will not trigger an error, but the two radii parameters will be collapsed to the value of the inner radius on the first iteration of the behavior.

8.11.4 Passive Low-Energy Station Keeping Mode

The station-keep behavior can be configured to operate in a “passive” mode. This mode differs from the default mode primarily in the way it acts after it reaches the inner-radius, i.e., the point at which the behavior regards the vehicle to be on-station and outputs a preferred speed of zero. In the normal mode, the behavior will begin to output a preferred heading and non-zero speed as soon as the vehicle slips beyond the inner-radius. In the passive mode, the behavior will let the vehicle drift or otherwise move to a distance specified by the `PASSIVE_STATION_RADIUS` before it resumes outputting a preferred heading and non-zero speed. The idea is shown in Figure 33.

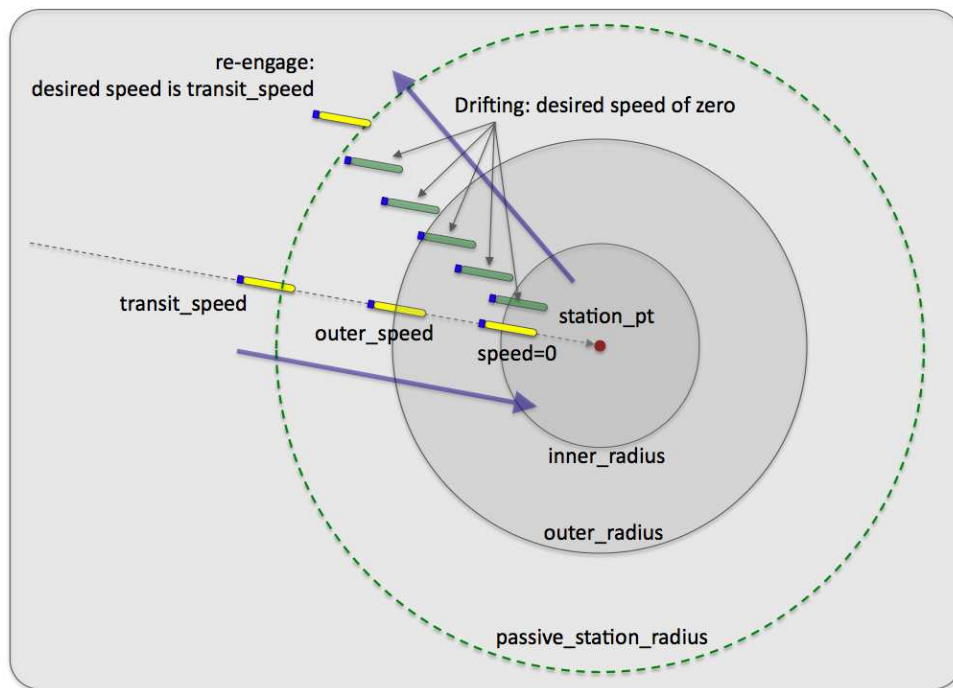


Figure 33: **Passive station-keeping:** The station-keep behavior can be configured in the “passive” mode. The vehicle will move toward the station point until it reaches the `inner_radius` or until progress ceases. It will then drift until its distance to the station point is beyond the `passive_station_radius`. At this point it will re-engage to reach the station-point and may trigger another behavior to dive.

This mode was built with UUVs in mind. Most UUVs are deployed having a positive buoyancy (battery dies - vehicle floats to the surface). They need to be moving at some speed to maintain a depth. Furthermore, it may not be safe to assume that a UUV can effectively execute a desired heading when it is operating on the surface. For these reasons, when operating in the passive mode, this behavior will publish a variable indicating whether it is in the mode of drifting or attempting to make progress toward the station point. The status is published in the variable `PSKEEP_MODE`,

short for “passive station-keeping mode”. This variable will be set to "SEEKING_STATION" when outputting a non-zero speed preference, and presumably moving toward the station-point. The variable will be set to "HIBERNATING" otherwise. This opens the option of configuring the helm with the ConstantDepth behavior to work in conjunction with the StationKeep behavior by conditioning the ConstantDepth behavior to be running only when PSKEEP_MODE="SEEKING_STATION". The idea is shown in Figure 34.

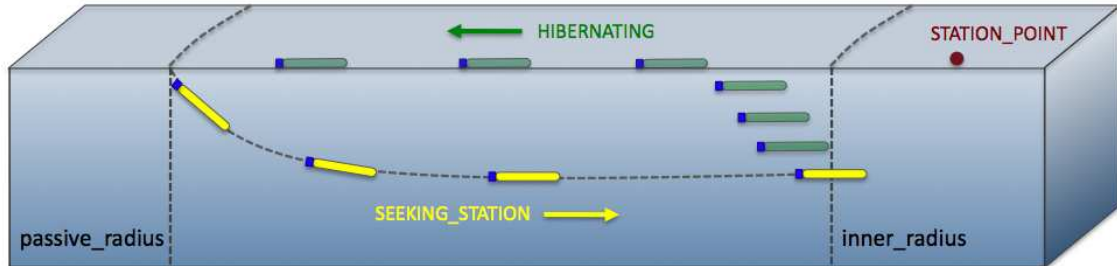


Figure 34: **Passive station-keeping with depth coordination:** The passive mode can be coordinated with the ConstantDepth behavior to dive each time the StationKeep behavior enters the "SEEKING_STATION" mode. This ensures that a UUV needing to be at depth to have reliable heading control will indeed be at depth when it needs to be.

This behavior mode is regarded as “low-power” due to the presumably long periods of drifting before resuming actively seeking the station point. A couple of safeguards are designed to ensure that when the behavior is in the "STATION_SEEKING" mode, that it does not get hung or stuck in this mode for much longer than intended or needed. How could one become stuck in this mode? Two ways - by either reaching an equilibrium at-speed, (and perhaps at-depth) state where the vehicle is neither progressing toward or way from the inner_radius, or by repeatedly “missing” the inner_radius by heading right past it.

Both cases can be guarded against and detected by monitoring the history of vehicle speed in the direction of the station-point. If this speed becomes zero, an equilibrium state is assumed, and if it becomes negative, it is assumed that the vehicle missed the inner radius circle entirely. In short, the StationKeep behavior exits the "STATION_SEEKING" mode and enters the "HIBERNATING" mode when it detects the vehicle speed toward the station-point reach zero. To calculate this vehicle speed, a ten-second history of range to the station-point is kept by the behavior. A zero speed, or “stale-progress” criteria is declared simply if the range to the station-point for the most recent measure in the history is not less than the range of ten seconds ago in the history list. The behavior will transition into the "HIBERNATING" mode if either the inner-radius or stale-progress criteria are met.

It is also possible that when the StationKeep behavior enters the "SEEKING_STATION" mode from the "HIBERNATING" mode, that the vehicle initially begins to open its range to the station-point before it begins to close range. This would be expected, for example, if the vehicle were pointed away from the station-point when the behavior first entered the "SEEKING_STATION" mode. In this case it’s quite possible that the behavior would correctly, but unwantingly, infer that the stale-progress criteria has been met. For this reason, the stale-progress criteria is not applied until an

“initial-progress” criteria is met after entering the "SEEKING_STATION" mode. The same ten second history is used to detect when the vehicle begins to make initial progress, i.e., closing range, toward the station-point.

8.11.5 Station Keeping On Demand

A common, and perhaps recommended configuration, is to have one station-keep behavior defined for a given helm configuration and have it set to be usable in one of three ways: (a) station-keep at a default pre-specified position, (b) station-keep at a specified position dynamically provided, or (c) station-keep at the vehicle’s present position when activated. The behavior would be configured as follows:

```
STATION_PT      = 100,200 // The default station-keep point
CENTER_ACTIVE   = false
UPDATES         = STATION_UPDATES
CONDITION       = STATION_REQUEST = true
```

Then, to use the station-keep behavior in the above three ways, the following three pairs of postings, i.e., pokes, to the MOOSDB would be used. See Section 7.2.2 for more on the UPDATES parameter defined for all behaviors - by utilizing this dynamic configuration hook, the one behavior configuration above can be used in these different manners. The first pair would result in the behavior keeping station at its pre-arranged point of 100,200:

```
STATION_REQUEST = true
STATION_UPDATES = CENTER_ACTIVATE=false"
```

The second line above dynamically configures the behavior parameter CENTER_ACTIVATE to be false to ensure that the point given by the original STATION_PT parameter is used. Even though the CENTER_ACTIVATE parameter is initially set to false, the above usage sets it to false anyway, to be safe, and in case it has been dynamically set to true in a prior usage.

In the second case below, again the CENTER_ACTIVATE parameter is dynamically set to false for the same reasons. In this case the STATION_POINT parameter is also dynamically configured with a given point:

```
STATION_REQUEST = true
STATION_UPDATES = "STATION_PT=45,-150 # CENTER_ACTIVATE=false"
```

In the last case, below, the behavior is activated and configured to station-keep at the vehicle’s present position when activated. There is no need to tinker with the STATION_PT parameter since this parameter is ignored when CENTER_ACTIVATE is true:

```
STATION_REQUEST = true
STATION_UPDATES = "CENTER_ACTIVATE=true"
```

It’s worth noting that above variable-value pairs that trigger the station-keep behavior could have come from a variety of sources. They could be endflags from another behavior. They could have come from a poke using uPokeDB, uTermCommand, pMarineViewer or any third party command and control interface.

8.12 BHV_Timer

The Timer behavior is a somewhat unique behavior in that it never produces an objective function. It has virtually no functionality beyond what is derived from the parent IvPBehavior class. It can be used to set a timer between the observation of one or more events (with condition flags) and the posting of one or more events (with end flags). The `DURATION`, `DURATION_STATUS`, `CONDITION`, `RUNFLAG` and `ENDFLAG` parameters are all defined generally for behaviors. There are no additional parameters defined for this behavior.

8.12.1 Brief Overview of Configuration Parameters and Variables Published

This behavior publishes two variables for monitoring and logging performance - `TIMER_IDLE`, `TIMER_RUNNING`.

9 Contact Related Behaviors of the IvP Helm

The section contains is a description of four behaviors currently written for the IvP Helm that reason about relative position to another vehicle or *contact*.

- The AvoidCollision behavior
- The CutRange behavior
- The Shadow behavior
- The Trail behavior

Each behavior needs to know about the position and trajectory of a given contact. The helm subscribes to the MOOS variable, `NODE_REPORT`, which may have content similar to:

```
NODE_REPORT= "NAME=alpha,TYPE=UUV,MOOSDB_TIME=39.01,UTC_TIME=1252348077.59,  
             X=51.71,Y=-35.50,LAT=43.824981,LON=-70.329755,SPD=2.00,HDG=118.85,  
             YAW=118.84754,DEPTH=4.63,LENGTH=3.8,MODE=SURVEYING"
```

This contact information is stored in the helm information buffer for any behavior that wishes to retrieve it on any iteration.

Contact related behaviors may be configured to operate on a fixed particular contact, or they may be configured as templates where the contact name is provided dynamically at run time as new instances of the behavior are spawned. Configuring behaviors enabled for dynamic spawning is discussed in Section 7.7 on page 89. Contact related behaviors are not spawned automatically for new contacts. A separate contact manager process, `pBasicContactMgr`, manages the node reports and posts alerts based on the contact range. The alerts are MOOS variable-value pairs that may be coordinated with the behavior configuration to spawn new behaviors. The `pBasicContactManager` application is discussed in Section 15, and the Berta mission in Section 10.6 shows a working example of the contact manager used with the helm to dynamically spawn collision avoidance behaviors.

9.1 Properties Common to All Contact Related Behaviors

Contact related behaviors are distinct from non contact related behaviors in that they share a fair amount of functionality in dealing with their contact of interest. Contact related behaviors are implemented as a subclass of the `IvPContactBehavior` class, which is a subclass of the `IvPBehavior` class. Much of the shared functionality of contact related behaviors is implemented in the former. The shared functionality includes several common configuration parameters, and mechanisms for reasoning about the closest point of approach (CPA) between the platform and contact for candidate maneuver considerations. These topics are discussed next, prior to the sections on the behaviors themselves.

9.1.1 Common Behavior Configuration Parameters

The following set of parameters are common to all the contact related behaviors:

Parameter	Description
CONTACT	Name or unique identifier of a contact to be avoided.
DECAY	Time interval during which extrapolated position slows to a halt.
EXTRAPOLATE	If "true", contact position is extrapolated from last position and trajectory.
ON_NO_CONTACT_OK	If false, a helm error is posted if no contact information exists.
TIME_ON_LEG	The time on leg, in seconds, used for calculating closest point of approach.

Table 16: Configuration parameters common to contact-related behaviors.

The CONTACT parameter specifies the contact name or identifier. This name is used as a key by the behaviors for querying the contact position and trajectory. It must match the contact name received by the helm in an incoming NODE_REPORT message. The contact name may be specified at helm launch time, but it may also be specified at run time if the behavior is configured as a template for dynamic spawning. The latter is more common, for example, in a collision avoidance behavior where the name or ID of the contact is not known until a contact manager alerts the helm. See the Berta mission in Section 10.6 for an example of this usage.

The EXTRAPOLATE and DECAY parameters are used to address the situation where a contact/node report has significant delays between updates. Extrapolation is enabled by setting the EXTRAPOLATE parameter to true, which is the default. The behavior may be configured to have limited extrapolation by setting a decay time interval. The extrapolated position is based on the last known contact position, heading and speed. The speed used for calculations may begin decaying at the beginning of the decay interval and will have decayed to zero at the end of the decay interval. The default setting is "decay = 15, 30", in seconds. The idea is shown in Figure 35.

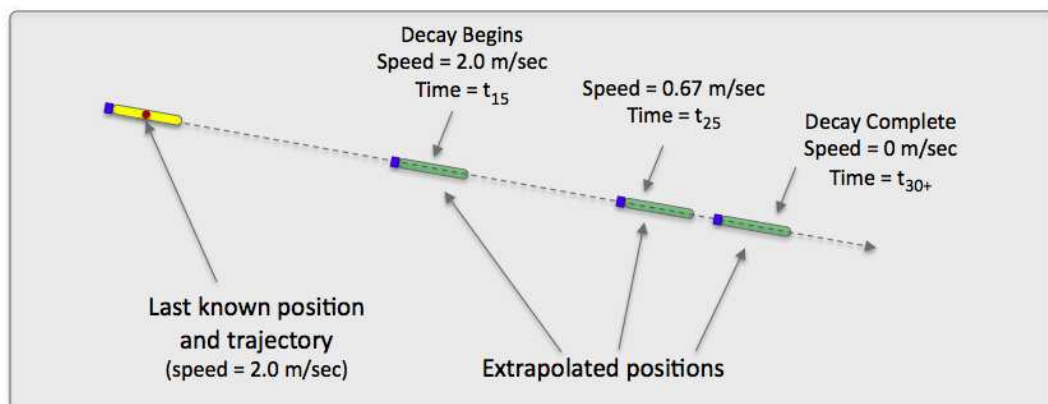


Figure 35: **Contact Extrapolations:** Contact related behaviors may use an extrapolated position of the contact to compensate for periods of no new reports for the contact. A decay period may be used to effectively halt the extrapolated contact position after some specified period of time. In the example in this figure, the decay window is [15, 30] seconds. After 30 seconds, the extrapolated position does not extend further.

The `ON_NO_CONTACT_OK` parameter determines how the behavior should regard the situation where it is unable to find any information about a given contact. If this parameter is set to `true`, the default, then the behavior will post a warning, `BHV_WARNING` if no contact information is found. Otherwise the behavior will post an error with `BHV_ERROR`. In the latter case the helm may interpret this as request to halt the helm and come to zero speed and depth.

The `TIME_ON_LEG` parameter refers to the behavior’s calculations of the closest point of approach (CPA) for candidate maneuver legs. A candidate maneuver leg is defined by a the heading, speed, and time-on-leg components. Longer time-on-leg settings tend to report deceptively worrisome CPA distances even for contacts at a great distance, and lower time-on-leg settings tend to report deceptively comfortable CPA distances even for vehicles at relatively low distances. The default setting for this parameter is 60 seconds.

9.1.2 Closest Point of Approach Calculations

The IvP functions produced by contact-related behaviors are defined over the domain of possible heading and speed choices. The utility assigned to a point in this domain (a heading-speed pair) depends in part on the calculated closest point of approach (CPA) between the candidate maneuver leg, and the contact leg formed from the contact’s position and trajectory. Figure 36 shows the relationship $cpa(\theta, v)$ between CPA and candidate maneuvers (θ, v) , where θ =heading and v =speed, for a given relative position between ownship and a given contact vehicle and trajectory. The IvP function generated by the AvoidCollision behavior applies a further user-defined utility function to the CPA calculation for a candidate maneuver, $f(cpa(\theta, v))$. The form of $f()$ is determined by configuration parameters specific to the individual behavior.

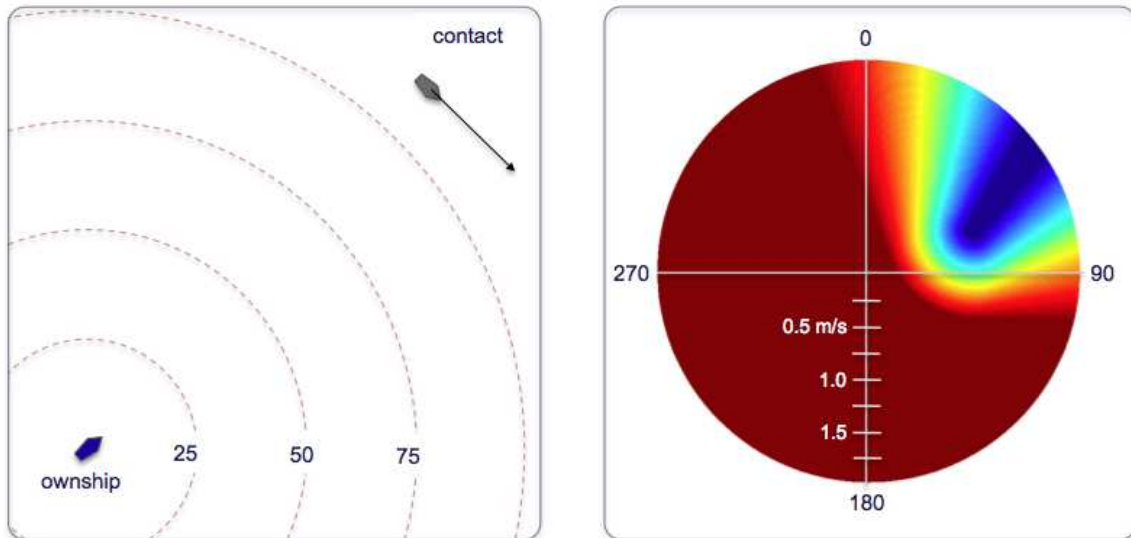


Figure 36: **The closest point of approach mapping:** The function on the right indicates the relative change in calculated closest point of approach between ownship and contact position and trajectory shown on the left.

For contact related behaviors, an important quality of a candidate action $\langle \theta, v, t \rangle$, is the *closest point of approach (CPA)* between two vehicles during a candidate leg. A behavior producing an

objective function with CPA as a component of its utility function needs to perform many variations of this calculation on each new call to generate an IvP objective function. The algorithm is given here, highlighting a few areas where caching may be exploited to improve efficiency.

Our own current position is known and given by (x, y) , and the other vehicle's current position and trajectory is given by $(x_b, y_b, \theta_b, v_b)$. To compute the CPA distance for a given $\langle \theta, v, t \rangle$, first the time t_{min} when the minimum distance between two vehicles occurs is computed. The distance between the two vehicles at the current time can be determined by the Pythagorean theorem. Generally, for any given time t (where the current time is $t = 0$), and assuming the other vehicle stays on a constant trajectory, the distance between the two vehicles for any chosen $\langle \theta, v, t \rangle$ is given by:

$$dist^2(\theta, v, t) = k_2 t^2 + k_1 t + k_0, \quad (1)$$

where

$$\begin{aligned} k_2 &= \cos^2(\theta)v^2 - 2\cos(\theta)v\cos(\theta_b)v_b + \cos^2(\theta_b)v_b^2 + \sin^2(\theta)v^2 - \\ &\quad 2\sin(\theta)v\sin(\theta_b)v_b + \sin^2(\theta_b)v_b^2 \\ k_1 &= 2\cos(\theta)vy - 2\cos(\theta)vy_b - 2y\cos(\theta_b)v_b + 2\cos(\theta_b)v_by_b + \\ &\quad 2\sin(\theta)vx - 2\sin(\theta)vx_b - 2x\sin(\theta_b)v_b + 2\sin(\theta_b)v_bx_b \\ k_0 &= y^2 - 2yy_b + y_b^2 + x^2 - 2xx_b + x_b^2 \end{aligned}$$

The stationary point is obtained by taking the first derivative with respect to t :

$$dist^2(\theta, v, t)' = 2k_2 t + k_1.$$

Since there is no "maximum" distance, this stationary point always represents the closest point of approach, and therefore:

$$t' = \frac{-k_1}{2k_2}.$$

The value of t_{min} may be in the past, i.e., less than zero, if the two vehicles are currently opening range. Or t_{min} may be well beyond t , the time length of the candidate maneuver $\langle \theta, v, t \rangle$. Therefore the value of t_{min} is clipped by $[0, t]$. Furthermore t_{min} is zero when the two vehicles have the same heading and speed (the only condition where k_2 is zero). The actual CPA value is then obtained by plugging t_{min} back into (1).

$$CPA(\theta, v, t) = \sqrt{k_2 t_{min}^2 + k_1 t_{min} + k_0}. \quad (2)$$

As mentioned before, this calculation is a common component in the underlying utility function for behaviors dealing with relative vehicle motion. A behavior, within a single iteration of the control cycle, will perform a sequence of calculations on different $\langle \theta, v, t \rangle$ values. However, all calculations have the same values of current vehicle position (x, y) , and current position and trajectory of the other vehicle $(x_b, y_b, \theta_b, v_b)$. To make this overall sequence of calculations faster,

all terms in (1) comprised exclusively of $x, y, x_b, y_b, \theta_b, v_b$ are calculated once and cached for later calculations.

9.2 The AvoidCollision Behavior

The AvoidCollision behavior will produce IvP objective functions designed to avoid collisions (and near collisions) with another specified vehicle. The IvP functions produced by this behavior are defined over the domain of possible heading and speed choices. The utility assigned to a point in this domain (a heading-speed pair) depends in part on the calculated closest point of approach (CPA) between the candidate maneuver leg, and the contact leg formed from the contact's position and trajectory. A further user-defined utility function is applied to the CPA calculation for a candidate maneuver.

9.2.1 Brief Overview of Configuration Parameters and Variables Published

The configuration parameters and variables published collectively define the interface for the behavior. A more detailed description of usage is provided other parts of this section.

Configuration Parameters for the BHV_AvoidCollision Behavior

The following are the parameters for this behavior, in addition to the configuration parameters defined for all behaviors, described in Section 7.2 beginning on page 78.

Parameter	Description	BHV_AvoidCollision
BEARING_LINES	Color code specification for rendering bearing lines, off by default.	
COMPLETED_DIST	Range to contact outside of which the behavior completes and dies.	
MAX_UTIL_CPA_DIST	Range to contact outside which a considered maneuver will have max utility.	
MIN_UTIL_CPA_DIST	Range to contact within which a considered maneuver will have min utility.	
PWT_GRADE	Grade of priority growth as the contact moves from the PWT_OUTER_DIST to the PWT_INNER_DIST. Choices are <code>linear</code> , <code>quadratic</code> , or <code>quasi</code> .	
PWT_INNER_DIST	Range to contact within which the behavior has maximum priority weight.	
PWT_OUTER_DIST	Range to contact outside which the behavior has zero priority weight.	
CONTACT	Name or unique identifier of a contact to be avoided.	
DECAY	Time interval during which extrapolated position slows to a halt.	
EXTRAPOLATE	If <code>"true"</code> , contact position is extrapolated from last position and trajectory.	
ON_NO_CONTACT_OK	If false, a helm error is posted if no contact information exists.	
TIME_ON_LEG	The time on leg, in seconds, used for calculating closest point of approach.	

Table 17: Configuration parameters for the BHV_AvoidCollision behavior.

Variables Published by the BHV_Waypoint Behavior

The below MOOS variables will be published by the behavior during normal operation, in addition to any configured flags. A variable published by any behavior may be suppressed or changed to a different variable name using the `post_mapping` configuration parameter described in Section 7.2.1 on page 79.

Variable	Description	BHV_AvoidCollision
CLOSING_SPD_AVD	The current closing speed, in meters per second, to the contact.	
CONTACT_RESOLVED	Posted with contact name when the behavior completes and dies.	
RANGE_AVD	The current range, in meters, to the contact.	
VIEW_SEGLIST	A bearing line between ownship and the contact if configured for rendering.	

Table 18: Variables posted by the BHV_AvoidCollision behavior.

Configuring and Using the AvoidCollision Behavior

The AvoidCollision behavior produces an objective function based on the relative positions and trajectories between the vehicle and a given contact. The objective function is based on applying a utility to the calculated closest point of approach (CPA) for a candidate maneuver. The user may configure a priority weight, but this weight is typically degraded as a function of the range to the contact. The behavior may be configured for avoidance with respect to a known contact, or it may be configured to spawn a new instance upon demand as contacts present themselves.

Specifying the Priority Policy - the `pwt_*.dist` Parameters

The AvoidCollision behavior may be configured to increase its priority as its range to the contact diminishes. The priority weight specified in its configuration represents the *maximum* possible priority applied to the behavior, presumably in close range to the contact. The range at which this maximum priority applies is specified in the `PWT_INNER_DIST` parameter. Likewise, the `PWT_OUTER_DIST` parameter specifies a range to the contact where the priority weight becomes zero, regardless of the priority weight specified in the configuration file. This relationship is shown in Figure 37.

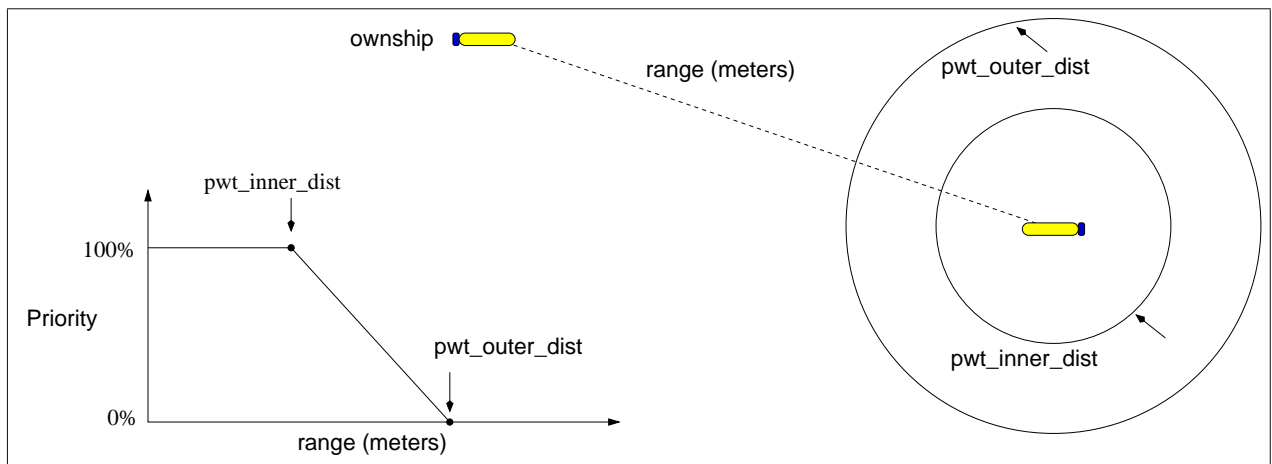


Figure 37: **Parameters for the BHV_AvoidCollision behavior:** The *ownship* vehicle is the platform running the helm. The range between the two vehicles affects whether the behavior is active and with what priority weight. Beyond the range specified by `PWT_OUTER_DIST`, the behavior is not be active. Within the range of `PWT_INNER_DIST`, the behavior is active with 100% of its configured priority weight.

By default, the priority weight decreases linearly between the two depicted ranges. The `PWT.GRADE` parameter allows the degradation from maximum priority to zero priority to fall more steeply by setting `PWT.GRADE=quadratic`.

Associating Utility to CPA of Candidate Maneuvers

`MIN_UTIL_CPA_DIST`: The distance (in meters) between ownship and the contact at the closest point of approach (CPA) for a candidate maneuver, below which the behavior treats the distance as it would an actual collision between the two vehicles.

`MIN_UTIL_CPA_DIST`: The distance (in meters) between ownship and the contact at the closest point of approach (CPA) for a candidate maneuver, above which the behavior treats the distance as having the maximum utility.

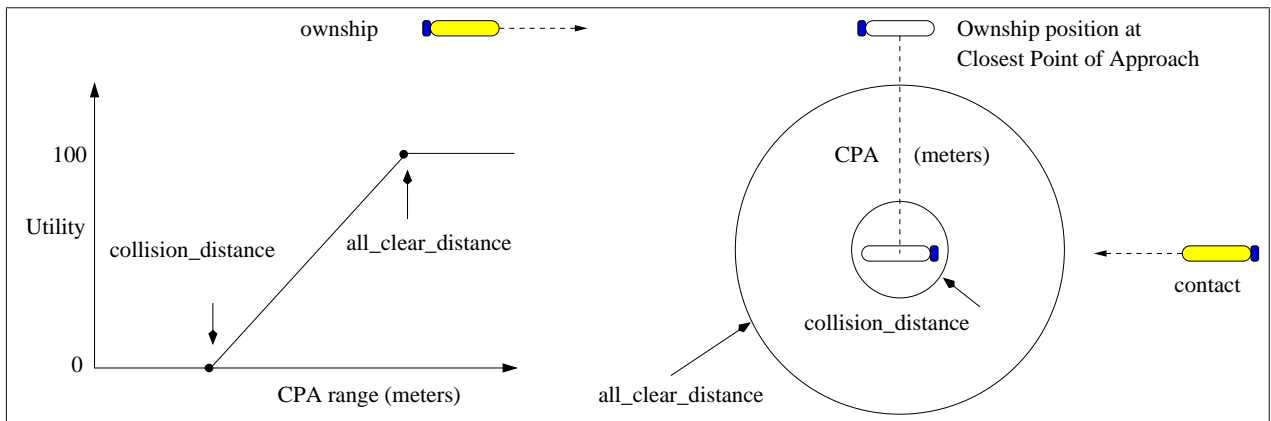


Figure 38: Parameters for the `BHV_AvoidCollision` behavior. The *ownship* vehicle is the platform running the helm. The `collision_distance` is used when applying a utility metric to a calculated closest point of approach (CPA) for a candidate maneuver. A CPA less than or equal to the `collision_distance` is treated as an actual collision with the lowest utility rating.

9.3 BHV_CutRange

This behavior will drive the vehicle to reduce the range between itself and another specified vehicle (nearly the opposite of the BHV_AvoidCollision behavior). The following parameters are defined for this behavior:

9.3.1 Brief Overview of Configuration Parameters and Variables Published

The behavior configuration parameters, and variables published by the behavior, collectively define the interface for the behavior. A more detailed description of usage is provided other parts of this section.

Configuration Parameters for the BHV_Waypoint Behavior

The following are the configuration parameters for this behavior, in addition to the configuration parameters defined for all behaviors, described in Section 7.2 beginning on page 78.

Parameter	Description	BHV_CutRange
PWT_OUTER_DIST	Range to contact outside which the behavior has maximum priority.	
PWT_INNER_DIST	Range to contact within which the behavior has zero priority.	
GIVEUP_DIST	Range to contact outside which the behavior will give up (become inactive).	
PATIENCE	Linear scale choice between preferring heading directly to the contact (patience=0) or heading on the lowest closest point of approach (patience=100).	
CONTACT	Name or unique identifier of a contact to be avoided.	
DECAY	Time interval during which extrapolated position slows to a halt.	
EXTRAPOLATE	If "true", contact position is extrapolated from last position and trajectory.	
ON_NO_CONTACT_OK	If false, a helm error is posted if no contact information exists.	
TIME_ON_LEG	The time on leg, in seconds, used for calculating closest point of approach.	

Table 19: Configuration paramters for the BHV_CutRange behavior.

Variables Published by the BHV_CutRange Behavior

The below MOOS variables will be published by the behavior during normal operation, in addition to any configured flags. A variable published by any behavior may be suppressed or changed to a different variable name using the `post_mapping` configuration parameter described in Section 7.2.1 on page 79.

Variable	Description	BHV_CutRange
VIEW_SEGLIST	A bearing line between ownship and the contact if configured for rendering.	

Table 20: Variables posted by the BHV_CutRange behavior.

9.3.2 Specifying the Priority Policy - the `pwt*_dist` Parameters

DIST_PRIORITY_INTERVAL: Two distance values given by a comma-separated pair `min,max` where the `min` value is the range at or below which the behavior will have a zero priority. The `min` value is the range at or above which the behavior will have 100% of its statically assigned priority. The percentage between the two values scales linearly.

TIME_ON_LEG: The behavior uses a closest-point-of-approach (CPA) calculation to evaluate candidate heading-speed maneuvers. The CPA calculation is based on a 60 second maneuver by default, but this time duration can be altered with this parameter.

GIVE_UP_RANGE: The range between ownship and the contact at or above which the behavior will cease to provide output (the objective function) to influence the vehicle heading and speed. By default this value is zero which is interpreted as infinity - it will never give up.

PATIENCE: The `PATIENCE` parameter ranges between 0 and 100 and is clipped automatically if out of range. A value of 0 will result in the behavior attempting to steer the vehicle directly toward the current position of the contact. A value of 100 will result in an attempt to steer toward the closest point of approach given the current linear track of the contact, and the prevailing setting of the `TIME_ON_LEG` parameter.

9.4 BHV_Shadow

This behavior will drive the vehicle to match the trajectory of another specified vehicle. This behavior in conjunction with the BHV_CutRange behavior can produce a “track and trail” capability. The following parameters are defined for this behavior:

Parameter	Description	BHV_Shadow
PWT_OUTER_DIST	Range to contact outside which the behavior has zero priority.	
HEADING_PEAKWIDTH	Width of the peak, in degrees, in the produced ZAIC-style IvP function.	
HEADING_BASEWIDTH	Width of the base, in degrees, in the produced ZAIC-style IvP function.	
SPEED_PEAKWIDTH	Width of the peak, in m/sec, in the produced ZAIC-style function.	
SPEED_BASEWIDTH	Width of the base, in m/sec, in the produced ZAIC-style IvP function.	
CONTACT	Name or unique identifier of a contact to be avoided.	
DECAY	Time interval during which extrapolated position slows to a halt.	
EXTRAPOLATE	If "true", contact position is extrapolated from last position and trajectory.	
ON_NO_CONTACT_OK	If false, a helm error is posted if no contact information exists.	

Table 21: Configuration paramters for the BHV_Shadow behavior.

MAX_RANGE: The distance (in meters) that the contact must be within for the behavior to be active and produce an objective function. The default is max_range value is zero meaning it will be active regardless of the distance to the contact.

HEADING_PEAKWIDTH: This behavior uses the ZAIC_PEAK tool from the IvP Toolbox for generating an objective function over heading and speed. This parameter sets the peakwidth parameter of the heading component.

HEADING_BASEWIDTH: This behavior uses the ZAIC_PEAK tool from the IvP Toolbox for generating an objective function over heading and speed. This parameter sets the basewidth parameter of the heading component.

SPEED_PEAKWIDTH: This behavior uses the ZAIC_PEAK tool from the IvP Toolbox for generating an objective function over heading and speed. This parameter sets the peakwidth parameter of the speed component.

SPEED_BASEWIDTH: This behavior uses the ZAIC_PEAK tool from the IvP Toolbox for generating an objective function over heading and speed. This parameter sets the basewidth parameter of the speed component.

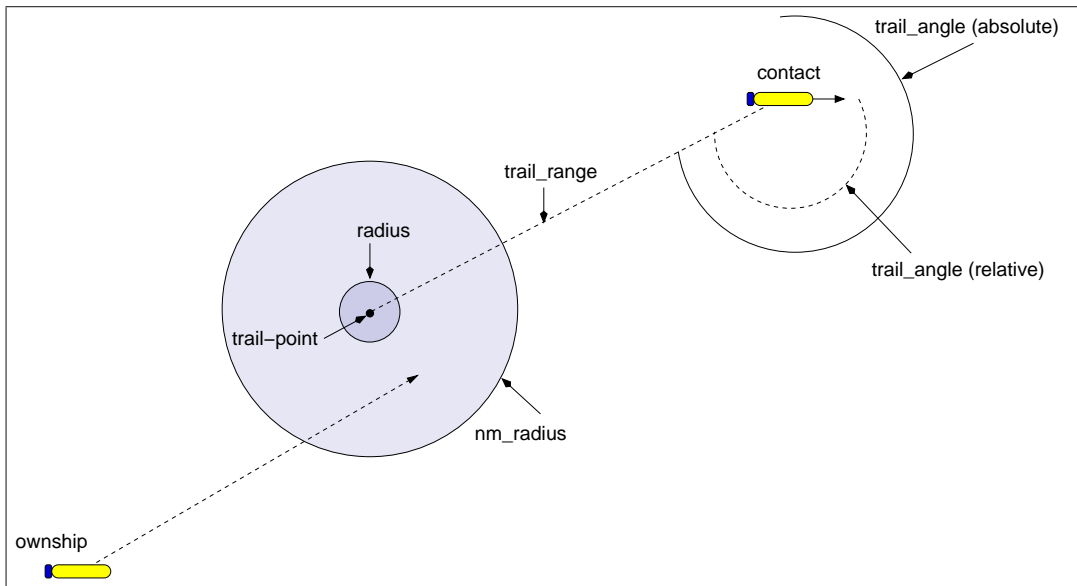


Figure 39: Interpolation of vehicle speed inside the radius set by `NM_RADIUS` relative to the extrapolated trail position.

9.5 BHV_Trail

This behavior will drive the vehicle to trail or follow another specified vehicle at a given relative position. A tool for “formation flying”. The following parameters are defined for this behavior:

9.5.1 Brief Overview of Configuration Parameters and Variables Published

The behavior configuration parameters, and variables published by the behavior, collectively define the interface for the behavior. A more detailed description of usage is provided other parts of this section.

Configuration Parameters for the BHV_Trail Behavior

The following are the configuration parameters for this behavior, in addition to the configuration parameters defined for all behaviors, described in Section 7.2 beginning on page 78.

Parameter	Description	BHV_Trail
PWT_OUTER_DIST	Range to contact outside which the behavior has zero priority.	
NM_RADIUS	If in this range to contact and ahead of it, slow down.	
RADIUS	If outside this radius to the contact, head to <code>nm_radius</code> ahead of trail point	
TRAIL_ANGLE	Relative angle to the contact to set the trail-point.	
TRAIL_ANGLE_TYPE	Either "relative" or "absolute" bearing/angle to the contact.	
TRAIL_RANGE	Relative distance to the contact to set the trail-point.	
CONTACT	Name or unique identifier of a contact to be avoided.	
DECAY	Time interval during which extrapolated position slows to a halt.	
EXTRAPOLATE	If "true", contact position is extrapolated from last position and trajectory.	
ON_NO_CONTACT_OK	If false, a helm error is posted if no contact information exists.	
TIME_ON_LEG	The time on leg, in seconds, used for calculating closest point of approach.	

Table 22: Configuration paramters for the BHV_Trail behavior.

Variables Published by the BHV_CutRange Behavior

The below MOOS variables will be published by the behavior during normal operation, in addition to any configured flags. A variable published by any behavior may be suppressed or changed to a different variable name using the `post_mapping` configuration parameter described in Section 7.2.1 on page 79.

Variable	Description	BHV_CutRange
VIEW_SEGLIST	A bearing line between ownship and the contact if configured for rendering.	

Table 23: Variables posted by the BHV_Trail behavior.

9.5.2 Specifying the Priority Policy - the `pwt*_dist` Parameters

TRAIL_RANGE: The range component of the relative position to the contact to trail.

TRAIL_ANGLE: The relative angle of the relative position to the contact to trail. (180 is directly behind, 90 is a parallel track to the contacts starboard side, -90 is on the port side of the contact.)

TRAIL_ANGLE_TYPE: The trail angle may be set to either `relative` (the default), or `absolute`.

RADIUS: The distance (in meters) from the trail position that will result in the behavior "cutting range" to the trail position, and inside of which will result in the behavior "shadowing" the contact. The default is 5 meters.

NM_RADIUS: The distance in meters from the trail point within which the speed will be gradually change from the outer chase speed (max speed) and the speed of the contact, as illustrated in Fig. 39. This parameter should typically be set to several times the value of `RADIUS` to achieve smooth formation flying. Default is 20 meters.

MAX_RANGE: The distance (in meters) that the contact must be within for the behavior to be active and produce an objective function. The default is max_range value is zero meaning it will be active regardless of the distance to the contact.

10 Extended Example Missions with the IvP Helm

This section addresses a number of example mission configurations the user may run in simulation, to explore various aspects of the helm, certain behaviors, and certain tools for configuring, running and analyzing missions. All missions are available in the moos-ivp software tree in the following location:

```
moos-ivp/ivp/missions/
```

Obtaining the moos-ivp software tree from the public server was discussed in Section 1.4.

10.1 Preliminaries

Each mission in the `missions/` directory is contained in a dedicated subdirectory such as `s1.alpha`, or `m2.bertha`. The 's' and 'm' in the prefix indicate whether it is a single-vehicle or multi-vehicle mission. The numbering roughly correlates to an increase in complexity from commonly used bread-and-butter behaviors and configurations to more complex mission configurations.

Each directory contains one or more *mission* files, i.e., files that end in the `.moos` suffix, and one or more *behavior* files, i.e., files that end in the `.bhv` suffix. During the course of running a mission, certain additional temporary files may be created. In all cases, the temporary files may be removed by running the `clean.sh` script included in each directory. The configuration and launching of the missions requires some familiarity with three tools, (a) `pAntler`, for launching multiple MOOS applications, (b) the `nsplug` tool, for building composite `.moos` and `.bhv` files from a template and set of include files, and (c) basics of shell scripts for organizing the overall launch process and cleanup. A brief recap of these three tools is covered next.

10.1.1 Using pAntler to Launch Missions

The `pAntler` utility is a command-line tool used to orchestrate the launching of a group of MOOS processes. A typical invocation is:

```
> pAntler charlie.moos
```

The MOOS file contains a configuration block for each process, and an Antler configuration block which is typically the first block in the file. Each block contains a collection of local “parameter = value” pairs read in by each individual application. There are also typically a number of global parameter=value pairs for possible use by all applications.

10.1.2 Using the nsplug Utility for Configuring Mission and Behavior Files

In multi-vehicle missions, the maintenance of mission and behavior files across multiple vehicles can become cumbersome and user error-prone. Since many of the file components are identical between vehicles, a fair amount of the problem is mitigated by building the files from file template files that include the common components from separate files. The `nsplug` command-line utility is used to expand a template file into a target file, with arguments passed that typically distinguish the produced file from others produced from the same template. For example, two mission files, one for the vehicle “charlie”, and one for the vehicle “frankie” may differ only in their vehicle names and IP Port number, and may be produced from a template file with the following two commands:

```
> nsplug meta_vehicle.moos targ_charlie.moos VNAME=charlie PORT=9201
> nsplug meta_vehicle.moos targ_frankie.moos VNAME=charlie PORT=9202
```

For the multi-vehicle example missions distributed with the moos-ivp tree and described in this section, this use of templates is used in all cases. The mission directories downloaded will not contain the nsplug "output" files such as `targ_charlie.moos` above. Rather, they are built by executing the launch scripts provided in each directory with a command such as:

```
> ./launch.sh
```

The above invocation will both build the mission and behavior files and invoke pAntler for each vehicle to start the simulation. Certain common command-line options such as `./launch --just_build`, to build the mission files without launching, are available in all scripts. The scripts are discussed next in Section 10.1.3. A few conventions with respect to templates and nsplug are used across all example mission directories.

1. Files used as templates have a "meta_" prefix.
2. Files meant to be included or plugged into another template file have a "plug_" prefix.
3. Output files that are built from templates and plug-ins via nsplug have "targ_" prefix.
4. Template or plug-in files that contribute to a target MOOS file have ".moos" suffix.
5. Template or plug-in files that contribute to a target Helm behavior file have ".bhv" suffix.

For example, in the `m2_berta` mission, the following files exist prior to building any target files and launching:

```
> cd missions/m2_berta
> ls
clean.sh*           plug_iMarineSim.moos      plug_pMOOSBridgeV.moos
launch.sh*         plug_origin_warp.moos    plug_pMarinePID.moos
meta_shoreside.moos plug_pBasicContactMgr.moos plug_pNodeReporter.moos
meta_vehicle.bhv   plug_pHelmIvP.moos       plug_uProcessWatch.moos
meta_vehicle.moos  plug_pLogger.moos        plug_uXMS.moos
```

After building all the target files, the following additional `targ_*` files exist:

```
> ./launch.sh --just_build
> ls
clean.sh*           plug_pBasicContactMgr.moos  plug_uXMS.moos
launch.sh*         plug_pHelmIvP.moos         targ_gilda.bhv
meta_shoreside.moos plug_pLogger.moos          targ_gilda.moos
meta_vehicle.bhv   plug_pMOOSBridgeV.moos     targ_henry.bhv
meta_vehicle.moos  plug_pMarinePID.moos       targ_henry.moos
plug_iMarineSim.moos plug_pNodeReporter.moos    targ_shoreside.moos
plug_origin_warp.moos plug_uProcessWatch.moos
```

The mission may be launched, with `MOOSTimeWarp=10`, by:

```
> ./launch.sh 10
```

10.1.3 Shell Scripts

10.2 Mission S3: The Charlie Mission

Overview of Charlie Mission Components and Topics

Mission:	"charlie" in moos-ivp/missions/s3_charlie
Behaviors:	BHV_Loiter, BHV_StationKeep, BHV_Waypoint
MOOS Apps:	pHelmIvP, pLogger, iMarineSim, pMarinePID, pNodeReporter, pMarineViewer, uTimerScript
Primary Topics:	(1) Hierarchical Mode Declarations (2) The Loiter behavior (2a) Loiter traversal - Clockwise vs. counter-clockwise (2b) Loiter polygon shapes, hexagons, ellipses (2c) Loiter dynamic changes to the polygon center position (2d) Loiter robustness to periodic external forces (3) The StationKeep Behavior
Side Topics:	(1) uTimerScript is used to simulate wind gusts, external forces (2) Use of pMarineViewer action buttons and action pull-down menu

Launching the Charlie Mission

The charlie mission may be launched from the command line in the following manner:

```
> cd moos-ivp/missions/s3_charlie/
> ./launch.sh --warp=10
```

This should bring up a pMarineViewer window like that shown in Figure 41 on page 150, with a single vehicle, "henry", initially in the DISENGAGED mode. After hitting the DEPLOY button in the lower right corner, the vehicle enters the "LOITERING" mode and begins to proceed to the polygon shown. To get a quick feel for what's possible in this simulation, the following are some things to try. (a) Click on the "CWISE" and "CCWISE" buttons to change the direction of loitering around the polygon. (b) Click the RETURN and DEPLOY buttons repeatedly to see the vehicle switch between two primary modes. (c) Select the "WIND_GUSTS=true" option in the ACTION pull-down menu to see the vehicle adjust to random periodic external forces. (d) Select the "STATION_KEEP=true" option in the ACTION pull-down menu to see how the vehicle station keeps with simulated wind gust. (e) Let the vehicle return to its return point and watch how it automatically switches to the station keeping mode, and then re-deploy it. (f) Select the ellipse polygon from the ACTION pull-down menu to see a different loiter shape. (g) Select the different center points for the loiter ellipse from the ACTION pull-down menu to see just the location of the loiter polygon change and the vehicle adjust.

10.2.1 Topic #1: Hierarchical Mode Declarations in the Charlie Mission

The Charlie mission is organized by hierarchical mode declarations into four modes: INACTIVE, LOITERING, RETURNING, and STATION-KEEPING. The mode declarations are given at the top of the charlie.bhv file and shown again in Figure 40. The pMarineViewer application by default shows the vehicle's mode alongside the vehicle name, and when the simulation is first launched, the Charlie vehicle is shown on the screen with the mode DISENGAGED.

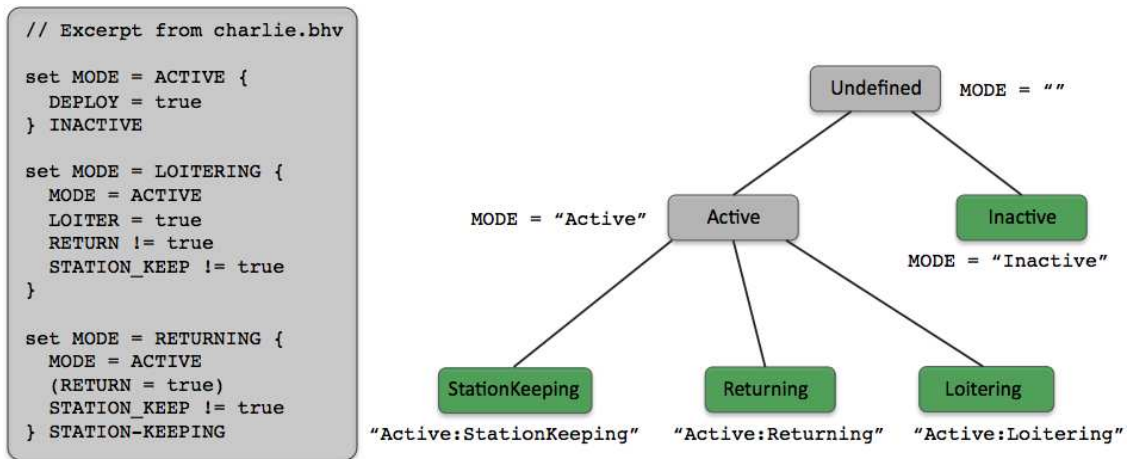


Figure 40: **Charlie Mission Mode Declarations:** The helm, when engaged, will be in one of the four modes indicated by the leaf nodes on the tree. The hierarchical mode structure means, for example, that when the vehicle is in the "RETURNING" mode, it is also considered to be in the "ACTIVE" mode. The vehicle mode, by default, is displayed alongside the vehicle name in the pMarineViewer window.

The "DISENGAGED" mode displayed with the vehicle when the simulation is launched is actually the helm engagement state. As described in Section 5.2, the helm has a higher level state, the engagement state which is either DISENGAGED or ENGAGED, analogous to a car in either the "Park" or "Drive" modes respectively. When the Charlie mission is first launched, the helm is not yet engaged, and is put into the engaged mode when the DEPLOY button is hit. This button is configured in the pMarineViewer configuration block to make several MOOS pokes with a single button click. It posts MOOS_MANUAL_OVERRIDE=false, to put the vehicle in the ENGAGED engagement state. It posts DEPLOY=true to put the helm in the ACTIVE mode, and it posts LOITER=true to put the helm in the ACTIVE:LOITERING mode.

The Charlie mission is configured to allow for easy transition between the other modes via the pMarineViewer interface. The vehicle may be put into the STATION-KEEPING mode at any time via the STATION_KEEP=true option in the ACTION pull-down menu in pMarineViewer. This does nothing more than make the STATION_KEEP=true post to the MOOSDB. The same could have been accomplished by uPokeDB for example:

```

> cd moos-ivp/missions/s3_charlie/
> uPokeDB charlie.moos STATION_KEEP=true

```

Referring to the mode declarations in Figure 40, the LOITERING and RETURNING modes both have the condition STATION_KEEP != true, so both of those mode requirements fail to be satisfied. The STATION-KEEPING mode is the default mode, i.e., the "else" mode when the requirements of the RETURNING mode are not met. The STATION_KEEP=true posting could also have been made by another MOOS process, for example, connected to an acoustic modem, an Iridium satellite, or wifi interface.

The helm mode is communicated to pMarineViewer from the helm via the MOOS variable IVPHELM_SUMMARY. This variable is parsed and the mode is rendered next to the vehicle name in the viewer. This rendering may be turned off by toggling through the "name options", with the 'n'

key, or setting the `vehicles_name_viewable` parameter in the `pMarineViewer` configuration block to one of the values list in Table 25 on page 201.

10.2.2 Topic #2: The Loiter Behavior

The `LOITERING` mode in the Charlie mission is characterized by the `BHV.Loiter` behavior, and we explore some of capabilities and options for this behavior here. The behavior configuration, in file `charlie.bhv` is shown in Listing 17 below. The first configuration block, in lines 3-6, are for parameters defined generally for all IvP Helm behaviors, and the second block, in lines 8-16, are for parameters defined explicitly for the Loiter behavior.

Listing 17 - Configuration of the Loiter behavior in the Charlie mission, from the file `charlie.bhv`.

```

0 //-----
1 Behavior = BHV_Loiter
2 {
3   name      = loiter
4   priority  = 100
5   condition = MODE==LOITERING
6   updates   = UP_LOITER
7
8           speed = 1.3
9           clockwise = false
10  capture_radius = 4.0
11  nm_radius = 15.0
12  polygon = format=radial, x=0, y=-75, radius=40, pts=6, snap=1,
13  visual_hints = nextpt_color=white, nextpt_lcolor=khaki
14  visual_hints = edge_color=blue, vertex_color=yellow
15  visual_hints = edge_size=1, vertex_size=2, label=LOITER_POLYGON
16 }
```

When the vehicle is first deployed, it heads to the hexagon shaped polygon shown in Figure 41, configured in line 12. It traverses the polygon in a counter-clockwise manner due to the configuration in line 9. The Loiter behavior maintains an internal mode, the "`acquire_mode`" which is `true` when the vehicle is not sufficiently close to the polygon, defined by the `acquire_dist` parameter which is by default 10 meters. It also keeps track of how many vertex arrivals come by way of achieving the capture radius, and how many by way of the non-monotonic radius. These internal state variables are summarized by the Loiter behavior by publishing a variable `LOITER_REPORT`. An example might look like:

```
LOITER_REPORT = "index=2,capture_hits=12,nonmono_hits=3,acquire_mode=false"
```

In the Charlie mission, the `pMarineViewer` is configured to scope on this variable by default, and the evolving `LOITER_REPORT` may be monitored as the vehicle progresses around the polygon.

Loiter Traversal - Clockwise vs. Counter-Clockwise

The traversal direction of the Loiter behavior is by default clockwise and can be set to counter-clockwise with the parameter `clockwise=false`. In the Charlie mission, the traversal direction can be changed by selecting `UP_LOITER=clockwise=true` and `UP_LOITER=clockwise=false` from the

ACTION pull-down menu. This is a good way to observe the algorithm used by the behavior to acquire the polygon when sufficiently far inside the polygon. The traversal direction could also have been affected by any other MOOS application capable of executing the above two MOOS pokes, including uPokeDB, or any application connected to a communications device.

Loiter Polygon Shapes, Hexagons, and Ellipses

The only restriction on the shape traversed by the Loiter behavior is that it be a convex polygon. The typical specification of the polygon is shown in line 12, via the "Radial" syntax, which accepts a center position ("x=0, y=-75"), a distance from the center point to each vertex ("radius=40"), the number of points in the polygon, ("pts=6"), and a snap value, which rounds the vertex positions to, in this case, the nearest whole meter ("snap=1"). Ellipse shapes are supported with a string such as:

```
polygon = format=ellipse, x=110, y=-75, degs=150, pts=14, major=80, minor=20
```

The above ellipse specification is selectable in the Charlie mission via the **ACTION** pull-down menu. If selected while in the loiter mode, the vehicle immediately begins traversing to this new polygon, as shown in Figure 42.

Loiter Dynamic Changes to the Polygon Position

In addition to the an outright change to the loiter polygon as described above, which includes shape changes, number of vertices and position, there are a few methods for just changing the polygon position while leaving the other characteristics in tact. The Loiter behavior accepts a parameter for just the center position. The following two such assignments are selectable in the **ACTION** pull-down menu in the pMarineViewer for the Charlie mission:

```
center_assign = 40,-40  
center_assign = x=100, y=-80
```

Try selecting either of these options, with the polygon set to either the hexagon or ellipse and confirm that only the position changes. One other method for affecting the polygon position is via the `center_activate` parameter, which is `false` by default. When set to `true`, the polygon center is set to be the vehicle's present position when the Loiter behavior enters the running state. In the Charlie mission, try selecting `center_activate=true` from the **ACTION** pull-down menu. If already in the `LOITERING` mode, then nothing happens immediately. If and when the helm exits and returns to the `LOITERING` mode, for example after clicking the `RETURN` button, and then the `DEPLOY` button again, note that the loiter polygon is centered on the vehicle's present position. The `center_active` feature is particularly useful when the Loiter behavior is used more or less as a station keeping behavior and one wants to be able to command the vehicle to loiter at the present position at any given time.

Loiter Robustness to Periodic External Forces

When the Loiter behavior is active and the vehicle is proceeding around the polygon vertices, it is proceeding more or less like the Waypoint behavior (both behaviors share the same WaypointEngine

class as a sub-component). Things get interesting when the vehicle is approaching the polygon from the outside or from a distance internally (for example when the `center_activate` parameter set to `true`). To test and demonstrate this robustness, the Charlie mission is configured with the `uTimerScript` utility to generate periodic random forces to simulate wind gusts, to push the vehicle off the loiter polygon in unpredictable ways. An example is shown in Figure 43 on page 151.

The simulated wind gusts may be activated by selecting the `WIND_GUSTS=true` option from the `pMarineViewer` `ACTION` pull-down menu. The details of the simulated forces can be found in the `uTimerScript` configuration block in the `charlie.moos` file. The script works by posting external force vectors to the MOOS variable `IMS_FORCE_VECTOR_ADD`, which is read by the `iMarineSim` application to alter the prevailing external force vector, which by default has a magnitude of zero. The syntax of the `uTimerScript` script to implement the forces in this example are described in more detail in Section 14.7.2 on page 219.

10.2.3 Topic #3: The StationKeep Behavior

The `STATION-KEEPING` mode in the Charlie mission is characterized by the `BHV_StationKeep` behavior, and we explore some of capabilities and options for this behavior here. The behavior configuration, in file `charlie.bhv` is shown in Listing 18 below. The first configuration block, in lines 3-5, are for parameters defined generally for all IvP Helm behaviors, and the second block, in lines 7-11, are for parameters defined explicitly for the Loiter behavior.

Listing 18 - Configuration of the StationKeep behavior in the Charlie mission, from the file `charlie.bhv`.

```

0 //-----
1 Behavior = BHV_StationKeep
2 {
3     name      = station-keep
4     priority  = 100
5     condition = MODE==STATION-KEEPING
6
7     center_activate = true
8     inner_radius   = 5
9     outer_radius   = 10
10    outer_speed    = 1.0
11    swing_time     = 0
12 }
```

Putting the Vehicle into the Station Keeping Mode

The vehicle is put into the station keeping mode by posting `STATION_KEEP=true` to the MOOSDB. This results in the helm mode, represented by the MOOS variable `MODE`, being set to station keeping. The hierarchical mode declarations used in the Charlie mission are declared in the top of the `charlie.bhv` file and were shown in Figure 40. The `StationKeep` behavior is conditioned on `MODE==STATION-KEEPING`, on line 5 above. The `StationKeep` behavior may be configured to station keep at a specified point in water (with the `station_pt` parameter), or it may be configured to station keep wherever it happens to be when it enters or re-enters the running state, as it is configured in the Charlie mission by virtue of line 7 above. In the Charlie mission, `pMarineViewer` is configured

with two on-screen buttons (Section 13.5.2). Two of them are used for toggling the `STATION_KEEP` variable to the MOOSDB.

What is Happening in the Station Keeping Mode

The station keeping behavior (the only running behavior in this mode) attempts to keep the vehicle within a certain distance, given by the `inner_radius` parameter, to a center point. Inside this radius, it simply lets the vehicle drift. Outside the radius it sets a heading and speed to drive the vehicle back to the center point. The speed decreases as it approaches the inner circle, and is at its highest speed (set by the `outer_speed` parameter on line 10 above) when its range to the center point is greater than that given by the `outer_radius` distance. It also makes two postings to the `VIEW_POLYGON` object to represent the circles implied by the `inner_radius` and `outer_radius` parameters, as shown in Figure 44.

Suggestions for Tinkering in the Charlie Mission

- Station keeping is trivial if the vehicle doesn't drift. Try turning on the artificial wind gusts available in the Charlie mission, courtesy of the `uTimerScript` script, available by selecting `WIND_GUSTS=true` from the Action pull-down menu. The vehicle performance is a bit more interesting now in the station keeping mode.
- Try configuring the simulator, `iMarineSim`, to reflect a vehicle that takes much more time to come to a full stop in the water. This can be done by setting `DECELERATION=0.1` in the `iMarineSim` configuration block, or by posting `IMS_DECELERATION=0.1` to the MOOSDB once the mission is running. Note that when the vehicle is put into station keeping mode, its station point is set to the point where it is when it enters this mode. Since the vehicle takes so long to slow down, it immediately drifts out of the inner radius and turns around 180 degrees. This is a typical situation seen in the field. This can be countered a bit by setting the `swing_time` parameter in the `StationKeep` behavior. This parameter is the number of elapsed seconds after the vehicle enters the station keeping mode before the station keeping behavior marks its present position as the point to station keep around. Try setting `swing_time=5` and re-running the above to see the difference.

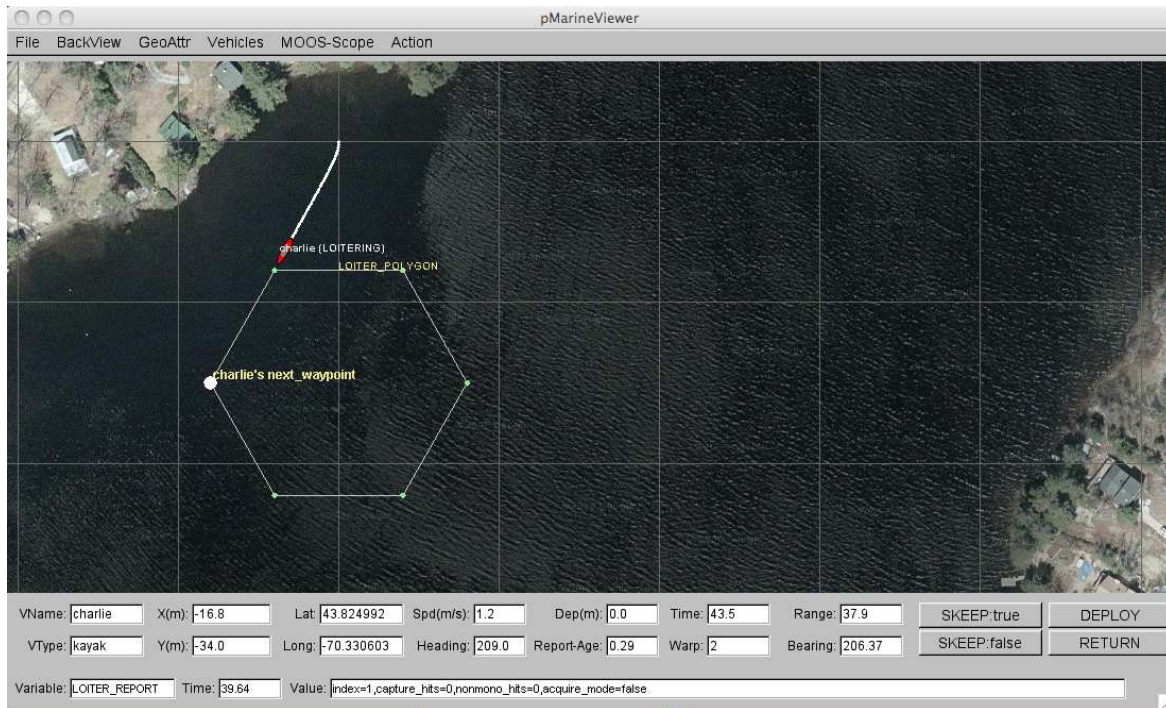


Figure 41: **The Charlie Mission (1):** The vehicle "charlie" proceeds to a loiter polygon, traversing in a counter-clockwise manner to the first waypoint labelled "charlie's next waypoint".

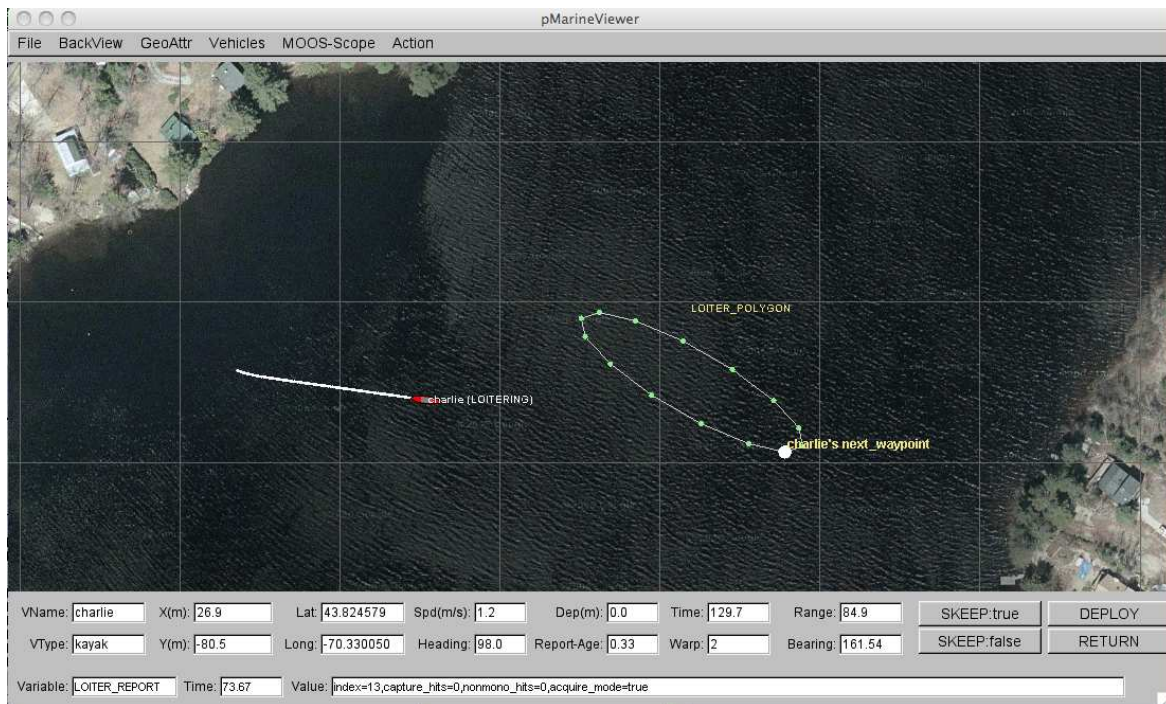


Figure 42: **The Charlie Mission (2):** The loiter traversal polygon for the vehicle "charlie" has been dynamically changed to an ellipse via a selection from the ACTION pull-down menu.

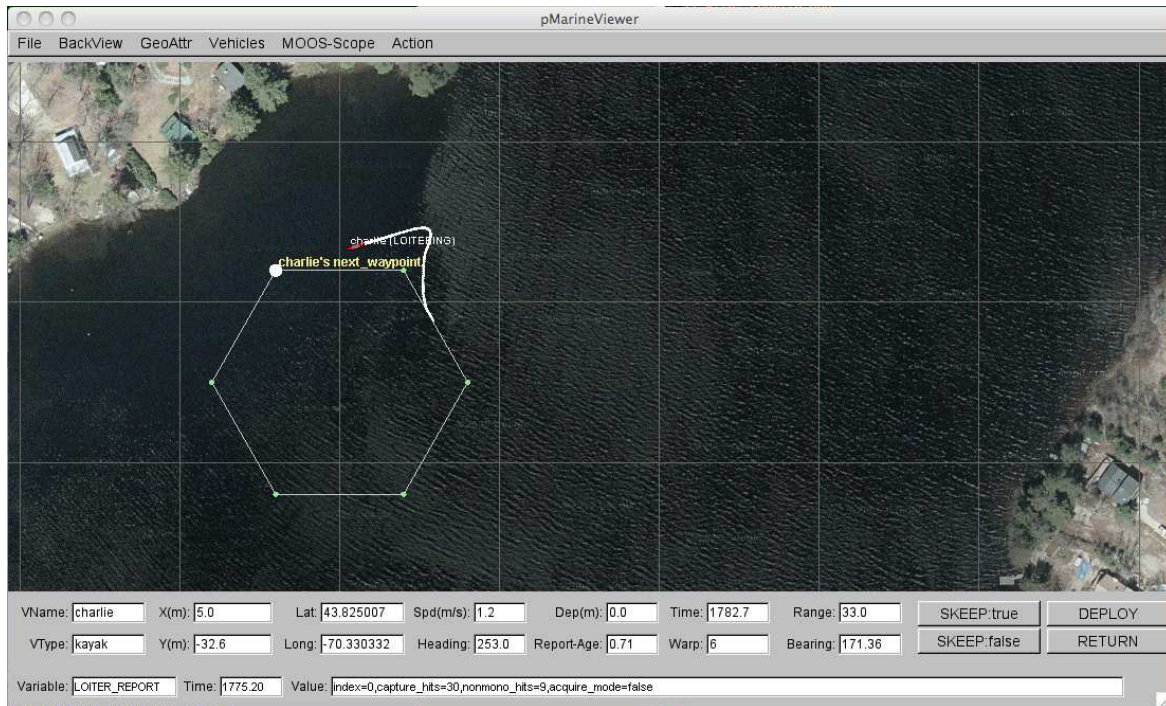


Figure 43: **The Charlie Mission (3):** The vehicle, "charlie" recovers from a wind gust and proceeds to re-enter the polygon trajectory at the tangential vertex labelled "charlie's next waypoint".

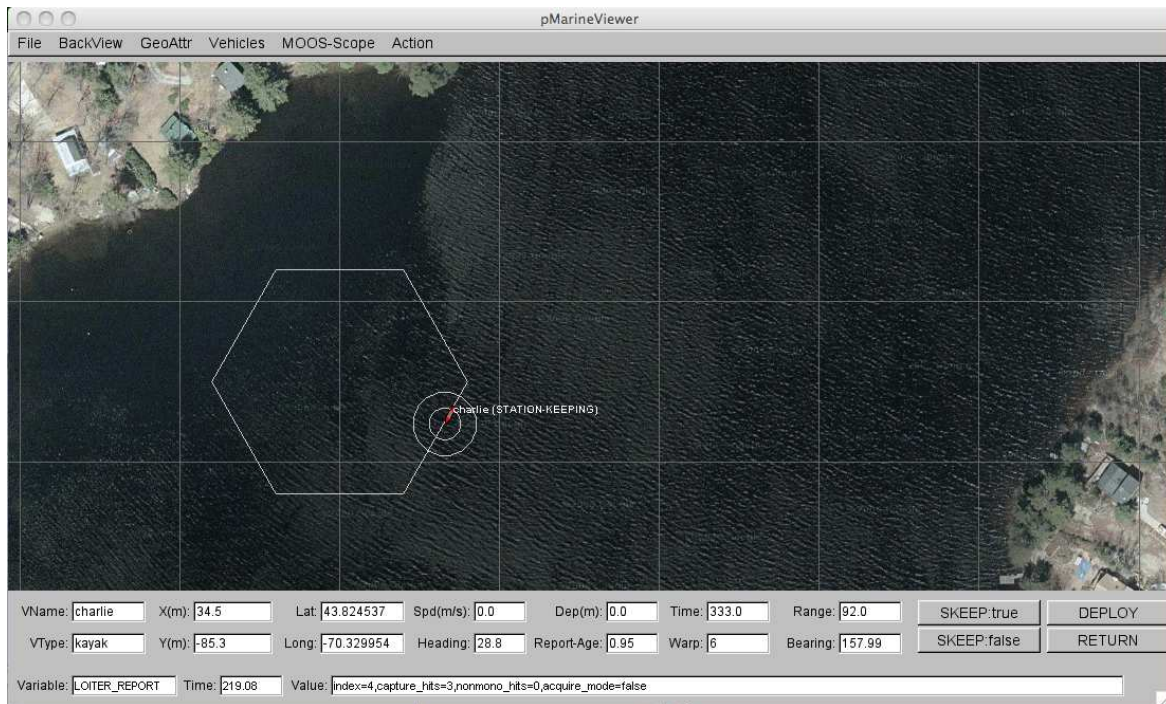


Figure 44: **The Charlie Mission (4):** The vehicle "charlie" is put into the station keeping mode. The two rings around the vehicle are the inner_radius and outer_radius parameters.

10.3 Mission S4: The Delta Mission

The Delta example mission is used to illustrate the operation of a a vehicle in the depth plane (an underwater as opposed to surface vehicle), the illustration of the PeriodicSurface behavior, the use of the Waypoint behavior with survey patterns, and the use of the pMarineViewer application to send field-control commands to alter the mission as it unfolds. The vehicle will initially deploy using the Loiter behavior, and will periodically come to the surface. If commanded by the user, the vehicle will break off from the Loiter behavior to execute a survey pattern, after which it will resume loitering at its original location.

Overview of the Delta Mission Components and Topics

Mission:	"delta" in moos-ivp/missions/s4_delta
Behaviors:	BHV_Waypoint, BHV_Loiter, PeriodicSurface, BHV_ConstantDepth
MOOS Apps:	pHelmIvP, pLogger, iMarineSim, pMarinePID, pNodeReporter, pMarineViewer uTimerScript
Primary Topics:	(1) Configuring the Helm for operation at depth (2) The ConstantDepth behavior (3) The PeriodicSurface behavior (4) The Waypoint behavior with survey patterns (5) Using pMarineViewer with Geo-referenced mouse clicks
Side Topics:	(1) uTimerScript is used to simulate a UUV receiving a GPS update.

Launching the Delta Mission

The delta mission may be launched from the command line:

```
> cd moos-ivp/missions/s4_delta/
> ./launch.sh --warp=10
```

This should bring up a pMarineViewer window like that shown in Figure 45 on page 158, with a single vehicle, "dudley", initially in the DISENGAGED engagement state. See Section 5.2 for more on the helm engagement state. After hitting the DEPLOY button in the lower right corner, the vehicle enters the ENGAGED engagement state, and the LOITERING helm mode, and begins to proceed along the waypoints as shown. See Section 6.4 for more on more on the helm mode, vs. the helm engagement state. The mode declarations for the Delta mission are defined at the top of the delta.moos file, and amount to the following simple hierarchy:

```
o ROOT
|--o INACTIVE
|--o ACTIVE
    |--o RETURNING
    |--o SURVEYING
    |--o LOITERING
```

In the initial helm mode after deployment, the LOITERING mode, the helm is running the Loitering behavior, Section 8.3, the ConstantDepth behavior, Section 8.6, and the PeriodicSurface behavior, Section 8.5. It will stay in this mode indefinitely until it is either commanded to return or break off

to another region to conduct a survey pattern. In the LOITERING mode the vehicle will periodically come to the surface for a GPS fix, presumably to correct for accumulated navigation error. The `uTimerScript` utility is used to simulate the event of receiving a GPS fix. This is described in more detail in Section 14.7.1.

In the SURVEYING mode, the Waypoint behavior becomes active and will execute a survey lawnmower type pattern, as shown in Figures 46 and 48. In this mode, the periodic surfacing for GPS fixes is suppressed until the pattern is completed. The SURVEYING mode is entered whenever the MOOS variable SURVEY is set to true. In this mission, `pMarineViewer` is configured to toggle the SURVEY MOOS variable with on-screen buttons, and it is configured to accept mouse clicks which not only put the vehicle into the SURVEYING mode, but also accept the location of the mouse click as the center location of a predefined survey pattern. This kind of `pMarineViewer` configuration is discussed in Section 10.3.5.

10.3.1 Topic #1: Configuring the Helm for Operation at Depth

The Delta mission is configured to simulate a UUV and the helm is configured to produce decisions about the decision variables *heading*, *speed*, as well as *depth*. Adding *depth* to the helm decision space is done in the helm configuration block as shown below in Listing 19, taken from the `delta.moos` mission file. In this case, the *depth* decision space is defined on line 13 with a range from 0 to 500 meters, with a resolution of 1 meter. See Section 5.4 for more on configuring the helm decision space with the `domain` parameter.

Listing 19 - Configuring `pHelmIvP` in the Delta mission to use behaviors concerning vehicle depth.

```

1 //-----
2 // pHelmIvP config block
3
4 ProcessConfig = pHelmIvP
5 {
6   AppTick      = 4
7   CommsTick    = 4
8
9   Behaviors    = delta.bhv
10  Verbose      = quiet
11  Domain       = course:0:359:360
12  Domain       = speed:0:4:21
13  Domain       = depth:0:500:501
14 }
```

In this example, the *depth* decision variable is a mandatory variable, along with *heading* and *speed*. This means that, on any given helm iteration, there *must* be a decision made about depth, or else the helm will post a helm error. How does the helm ensure that a depth decision is always part of any decision? The helm must be configured such that a behavior that reasons about *depth* is always active regardless of the helm mode. In the Delta mission, the three primary modes, LOITERING, SURVEYING, RETURNING, are all sub-modes of the ACTIVE mode, as shown above. The ConstantDepth behavior is configured to be running whenever the helm is in the Active mode.

10.3.2 Topic #2: The ConstantDepth Behavior

The ConstantDepth behavior is used in the Delta mission to keep the vehicle a prescribed depth while it is transiting, surveying, and loitering. For simplicity a single ConstantDepth behavior is used, but a different behavior instance could also be used for each vehicle mode. The behavior configuration, in file `delta.bhv` is shown in Listing 20 below. The first part of the configuration block, in lines 3-6, are for parameters defined generally for all IvP Helm behaviors, and the second part, on line 8, is a parameter defined for the ConstantDepth behavior.

Listing 20 - The ConstantDepth behavior in the Delta mission, from the file delta.bhv.

```

0 //-----
1 Behavior = BHV_ConstantDepth
2 {
3     name      = bhv_const_depth
4     pwt       = 100
5     duration  = no-time-limit
6     condition = MODE==ACTIVE
7
8     depth = 15
9 }
```

The ConstantDepth behavior's primary parameter is the `depth` parameter on line 8. This behavior does make provisions for providing a range of depths, or a more gradually degrading utility function when this behavior is used to work with other behaviors reasoning about depth. In this mission however, the depth is mostly non-contentious between behaviors. The exception is when the PeriodicSurface behavior is active, in which case the priority weight for the PeriodicSurface behavior is simply set to suppress the ConstantDepth behavior.

10.3.3 Topic #3: The PeriodicSurface Behavior

The PeriodicSurface behavior, described generally in Section 8.5, is used in the Delta mission to bring the vehicle to the surface for GPS fixes periodically, to simulate the need for occasional navigation corrections. The behavior configuration, in file `delta.bhv` is shown in Listing 21 below. The first part of the configuration block, in lines 3-6, is for parameters defined generally for all IvP Helm behaviors, and the second part, in lines 8-13, is for parameters defined for the PeriodicSurface behavior.

Listing 21 - The PeriodicSurface behavior in the Delta mission, from the file delta.bhv.

```

0 //-----
1 Behavior = BHV_PeriodicSurface
2 {
3     name          = bhv_periodic_surface
4     pwt           = 1000
5     condition     = (MODE == LOITERING) or (MODE == RETURNING)
6     condition     = PSURFACE = true
7
8     period        = 120
9     zero_speed_depth = 2
10    max_time_at_surface = 60
11    ascent_speed   = 1.0
```

```

12         ascent_grade = fullspeed
13         mark_variable = GPS_UPDATE_RECEIVED
14     }

```

The PeriodicSurface behavior outputs an objective function solely on the *depth* decision variable. Note the priority weight in line 4 in Listing 21 is set to 1000, in comparison to the priority weight set for the ConstantDepth behavior on line 4 in Listing 20. When the PeriodicSurface behavior is running, it may or may not be active and producing an objective function over the *depth* decision variable. When it *is* active, the influence on *depth* simply overrules the influence from the ConstantDepth behavior due to these relative priority weights. For this reason, the ConstantDepth behavior may be conditioned on all active modes as in line 6 of Listing 20.

Note the parameter setting on line 13 above, setting the "mark variable" to GPS_UPDATE_RECEIVED. This is the default value, and the line could be safely be removed from the configuration block, but it is included anyway to be clear. The PeriodicSurface behavior, once it has noted that the vehicle has reached the surface, will wait until a value has been posted to GPS.UPDATE.RECEIVED that is different than its previous posting. Usually a timestamp suffices. The configuration of uTimerScript to achieve simulated GPS updates is discussed in more detail in Section 14.7.1.

10.3.4 Topic #4: The Waypoint Behavior with Survey Patterns

The Waypoint behavior, described generally in Section 8.1, is used in the Delta mission to conduct survey patterns like that shown in Figure 46. The behavior configuration, in file `delta.bhv` is shown in Listing 22 below. Note the survey pattern, described on line 15, does not list a set of points, but instead describes the pattern in terms of its properties such as the lane width and pattern orientation. This format is supported generally for building SegList objects from string specifications, discussed in Section 12.4.

Listing 22 - The Waypoint behavior in the Delta mission, from the file delta.bhv.

```

0 //-----
1 Behavior = BHV_Waypoint
2 {
3     name      = waypt_survey
4     pwt       = 100
5     condition = MODE==SURVEYING
6     perpetual = true
7     updates   = SURVEY_UPDATES
8     endflag   = SURVEY = false
9
10         lead = 8
11     lead_damper = 1
12     speed = 2.0 // meters per second
13     radius = 8.0
14     points = format=lawnmower, label=dudley_survey, x=80, y=-80, \
                width=70, height=30, lane_width=8, rows=north-south, \
                degs=30
15 }

```

The waypoint behavior is configured to execute the survey pattern once, since the `repeat` parameter is not set and defaults to zero. Upon completion, it posts an end flag, configured on line 8, `SURVEY=false` to the MOOSDB. This immediately moves the vehicle out of the `SURVEYING` and into

either the `LOITERING` or `RETURNING` mode depending on what it was doing when it was commanded to begin the survey. See the hierarchical mode declarations at the top of the `delta.bhv` file. Since the behavior is set with `perpetual=true` on line 6, completion of the survey pattern merely puts the behavior in a virtual stand-by mode until it is given a new set of waypoints and it once again meets its run conditions.

The waypoint behavior is configured to accept dynamic parameter updates on line 7 through the MOOS variable `SURVEY_UPDATES`. In the Delta mission, updates are initiated by a mouse click in the `pMarineViewer` window, with the result being a post to the MOOSDB of the `SURVEY_UPDATES` variable. Such a posting would consist of a new value for the `points` parameter, replacing the initial configuration on line 14. This is discussed next.

10.3.5 Topic #4: Using pMarineViewer with Geo-referenced Mouse Clicks

In the Delta mission, the `pMarineViewer` application is used to post messages to the MOOSDB to (a) put the vehicle into the `SURVEYING` mode from either the `LOITERING` or `RETURNING` modes and (b) grab a user specified point in the operation area, from the user's mouse click, to be used as the center point of the commanded survey pattern. This situation is shown in Figure 46. This is achieved by utilizing the Mouse Context feature of `pMarineViewer`, discussed in Section 13.3.6. The below two lines are inserted into the `pMarineViewer` configuration block in `delta.moos`:

```
left_context[survey-point] = SURVEY = true
left_context[survey-point] = SURVEY_UPDATES = points = vname=$(VNAME), \
    x=$(XPOS), y=$(YPOS), format=lawnmower, label=delta, width=70, \
    height=30, lane_width=8, rows=north-south, degs=80
```

Both lines declare that a MOOS variable-value pair is to be posted whenever a left mouse click is generated by the user. The first line sets `SURVEY=true`, in an attempt to put the helm into the `SURVEYING` mode. This alone will not suffice to switch modes if the current value of the MOOS variable `RETURN` is set to `true`. See the mode declarations near the top of the `delta.bhv` file for this mission - a command to return overrides a command to perform a survey. The second line above associates with a left-mouse click a posting to the `SURVEY_UPDATES` variable. Recall from Listing 22 that this is the very variable through which the surveying waypoint behavior is configured to receive dynamic parameter updates. This posting is configured with a few macros, `$(VNAME)`, `$(XPOS)`, `$(YPOS)`, which are filled in with the name and position of the current vehicle in the `pMarineViewer` window. Each user left-mouse click thus re-assigns the vehicle to a new survey pattern, and switches the helm mode, unless it has been commanded to return.

10.3.6 Suggestions for Further Experimenting with the Delta Mission

Failing to Reason about Depth

In this mission, `depth` is a mandatory helm decision variable, along with `course` and `speed`, as configured in `delta.moos` and shown in Listing 19. If a mission is not configured properly it's possible to bring about a helm mode where no behavior is reasoning about depth. Declaring `depth` to mandatory is equivalent to declaring that a situation where a helm iteration with no decision on `depth` is an error condition worth of an all-stop.

One way to bring this about in this mission, is to reconfigure the ConstantDepth behavior configuration in `delta.bhv` to replace line 6 in Listing 20 with the following

```
condition = (MODE==LOITERING)
```

By doing this, there will be no *depth* related behavior when the vehicle is in the RETURNING mode. Try re-running the mission. Note when the mission is first launched, the label next to the vehicle in `pMarineViewer` reads "dudley (DISENGAGED)(ManualOverride)". This is normal and indicates that the helm engagement mode is DISENGAGED, simply because the operator retains manual control. In addition to seeing this in the `pMarineViewer` window, this can also be confirmed by scoping on a few key helm variables including IVPHELM_ENGAGED and IVPHELM_ALLSTOP:

```
$ uXMS delta.moos IVPHELM_ENGAGED IVPHELM_ALLSTOP BHV_ERROR --show=source,time,community
```

VarName	(S)ource	(T)ime	(C)ommunity	VarValue (MODE = SCOPE:PAUSED)
-----	-----	-----	-----	----- (61)
IVPHELM_ENGAGED	pHelmIvP	81.86	dudley	"DISENGAGED"
IVPHELM_ALLSTOP	pHelmIvP	1.69	dudley	"ManualOverride"
BHV_ERROR	n/a	n/a	n/a	n/a
MODE	n/a	n/a	n/a	n/a

Note that the IVPHELM_ALLSTOP value is posted once, until its value changes, and IVPHELM_ENGAGED posts its value on every helm iteration regardless of the value. The latter variable also serves the purpose of a helm heartbeat indicator.

After noting the above, launch the mission by hitting the DEPLOY button, and note that the label next to the vehicle has changed to "dudley (LOITERING)". The four MOOS variables from above have also changed to:

VarName	(S)ource	(T)ime	(C)ommunity	VarValue (MODE = SCOPE:PAUSED)
-----	-----	-----	-----	----- (103)
IVPHELM_ENGAGED	pHelmIvP	109.56	dudley	"ENGAGED"
IVPHELM_ALLSTOP	pHelmIvP	98.07	dudley	"clear"
BHV_ERROR	n/a	n/a	n/a	n/a
MODE	pHelmIvP	98.07	dudley	"ACTIVE:LOITERING"

After the vehicle has been running a bit, try hitting the RETURN button which changes the helm to the RETURNING mode. In this case, due to our tinkering with the mission above, there is no behavior reasoning about depth, and the following message appears next to the vehicle on the screen: "dudley (Returning)(MissingDecVars:depth)". The four scoped MOOS variables also change to the following:

VarName	(S)ource	(T)ime	(C)ommunity	VarValue (MODE = SCOPE:PAUSED)
-----	-----	-----	-----	----- (134)
IVPHELM_ENGAGED	pHelmIvP	621.34	dudley	"ENGAGED"
IVPHELM_ALLSTOP	pHelmIvP	617.09	dudley	"MissingDecVars:depth"
BHV_ERROR	pHelmIvP	621.59	dudley	"MissingDecVars:depth"
MODE	pHelmIvP	617.09	dudley	"ACTIVE:RETURNING"

Note that, despite the error and all-stop event, the helm remains engaged, and may return to loitering or surveying at any time. Try configuring the helm in `delta.moos` to contain the line `DISENGAGE_ON_ALLSTOP=true` and note the difference in the above experiment. The generated error will bump the helm into the DISENGAGED helm engagement mode.

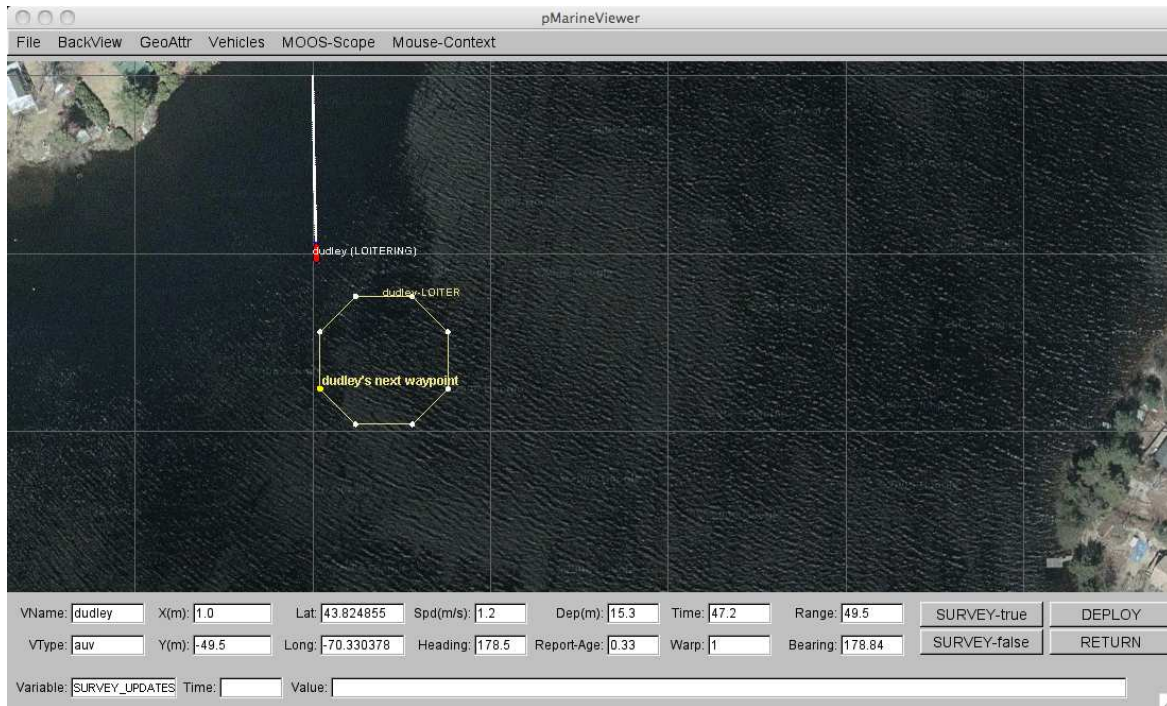


Figure 45: **The Delta Mission (1):** The vehicle "dudley" heads to its loiter region where it will remain indefinitely until it is commanded to return or perform a survey pattern. It will periodically surface for a GPS fix.

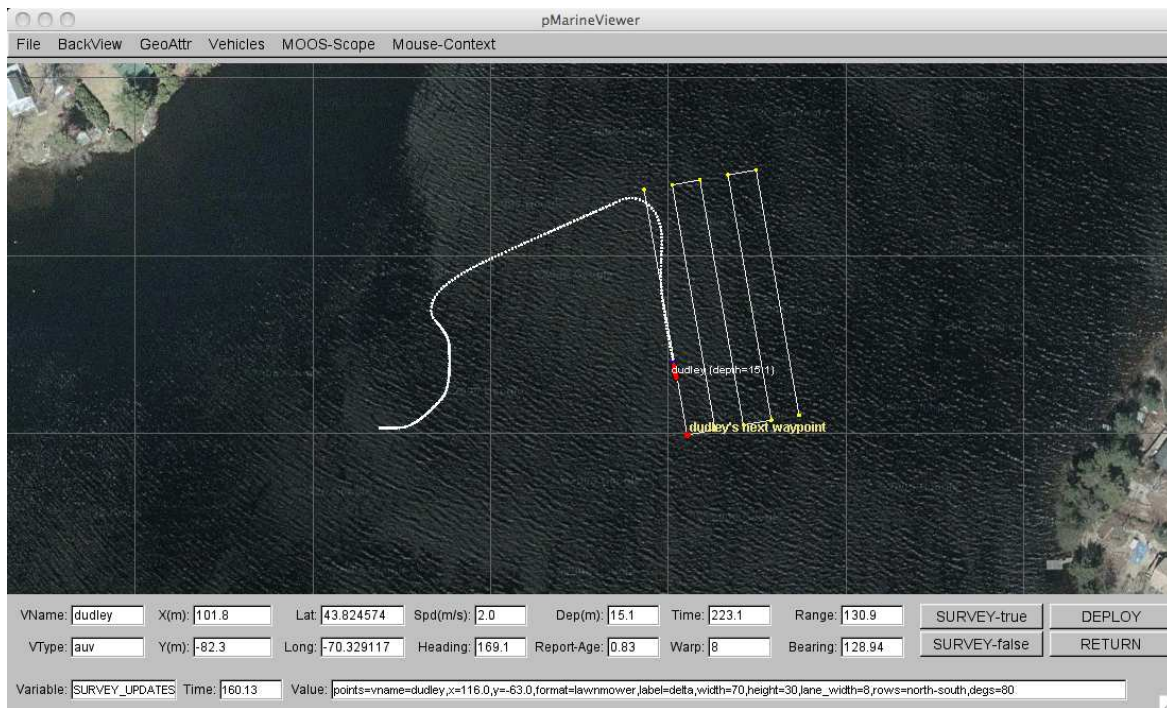


Figure 46: **The Delta Mission (2):** The user has clicked a point in the viewer around which a survey pattern is built. The vehicle exits the loitering mode and begins to execute the survey pattern.



Figure 47: **The Delta Mission (3)**: Once the vehicle has finished the survey pattern, it re-enters the loiter mode returning to its loiter region. It resumes periodic surfacing and immediately surfaces for a GPS fix.

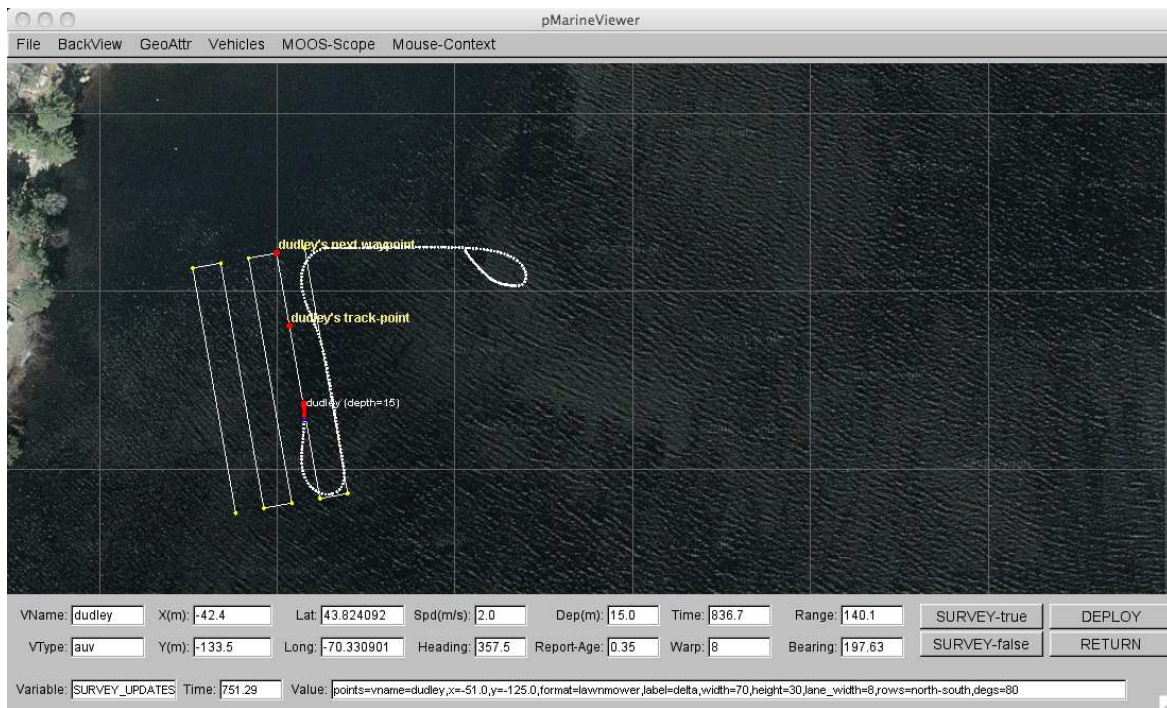


Figure 48: **The Delta Mission (4)**: After resumption of loitering, the user clicks in the viewer a new point around which a new survey pattern is built. The entry point of the survey pattern automatically accommodates the vehicle.

10.4 Mission S5: The Echo Mission

The primary purpose of the Echo example mission is to illustrate the use of dynamically spawned behaviors. A simple behavior, the BearingLine behavior, is used to illustrate the idea. The BearingLine behavior simply posts a viewable point and viewable line segment representing the bearing from the present position of the vehicle to a fixed point in the operation area. Each new “bearing point” posted to the MOOSDB results in a newly spawned BearingLine behavior in the helm.

Overview of the Echo Mission Components and Topics

Mission:	"echo" in moos-ivp/missions/s5_echo
Behaviors:	BHV_Waypoint, BHV_BearingLine
MOOS Apps:	pHelmIvP, pLogger, iMarineSim, pMarinePID, pNodeReporter, pMarineViewer
Primary Topics:	(1) The BearingLine behavior. (2) Dynamic behavior spawning. (3) Sending updates to the original and spawned behaviors.
Side Topics:	(1) uTimerScript is used to auto-generate events with random components that lead to behavior spawning. (2) uHelmScope may be used to monitor the spawning and death of behaviors in the helm.

Launching the Echo Mission

The echo mission may be launched from the command line:

```
> cd moos-ivp/missions/s5_echo/
> ./launch.sh --warp=10
```

This should bring up a pMarineViewer window like that shown in Figure 49 on page 165, with a single vehicle, "henry", initially in the "DISENGAGED" mode. After hitting the DEPLOY button in the lower right corner, the vehicle enters the "SURVEYING" mode and begins to proceed along the waypoints as shown.

10.4.1 Topic #1: The BearingLine Behavior

In Figure 49, note the line segment rendered from the vehicle in the direction of point (100, -100). This line segment is posted to the MOOSDB by the IvP Helm on behalf of the BearingLine behavior. This behavior does not influence the trajectory of the vehicle at all. The line segment acts as an easy visual confirmation that the behavior is instantiated and running properly. In the Echo mission this behavior is configured as in Listing 23. The bearing line originates from the present vehicle position toward the point specified on line 8. The length of the line is 50% of the present distance between the vehicle and the bearing point, as specified on line 7. The bearing point is also configured to be rendered by the configuration on line 9.

Listing 23 - Configuration of the BearingLine behavior in the Echo example mission.

```
0 //-----
1 Behavior = BHV_BearingLine
2 {
```

```

3   name      = bng-line
4   templating = clone
5   updates   = BEARING_POINT
6
7       line_pct = 50
8   bearing_point = 100,-100
9       show_pt = true
10 }
```

The BearingLine behavior produces no (IvP) objective function, so by the definition of the behavior run states (Section 6.5.3), it is never in the *active* state. In the Echo mission, the BearingLine behavior is in the *running* state when the vehicle is surveying the five waypoints shown in Figure 49. This can be confirmed by launching a uHelmScope window:

```
uHelmScope moos-ivp/ivp/missions/s5_echo/echo.moos -x -p
```

The output should be similar to that shown in Listing 24 below. Note the Waypoint behavior is active, line 12, and the BearingLine behavior is in the running state, line 14.

Listing 24 - Output of the uHelmScope tool during the execution of the Echo mission.

```

0  ===== uHelmScope Report ===== ENGAGED (8)
1  Helm Iteration: 173 (hz=0.25)(5) (hz=0.25)(100) (hz=0.26)(max)
2  IvP functions: 1
3  Mode(s):
4  SolveTime: 0.00 (max=0.01)
5  CreateTime: 0.00 (max=0.01)
6  LoopTime: 0.00 (max=0.01)
7  Halted: false (0 warnings)
8  Helm Decision: [speed,0,4,21] [course,0,359,360]
9  course = 189.0
10 speed = 2.0
11 Behaviors Active: ----- (1)
12   waypt_survey (43.0) (pwt=100.00) (pcs=6) (cpu=0.17)
13 Behaviors Running: ----- (1)
14   bng-line (43.0) (upd=0/0)
15 Behaviors Idle: ----- (1)
16   waypt_return
17 Behaviors Completed: ----- (0)
18
19 # MOOSDB-SCOPE ----- (Hit '#' to en/disable)
20 @ BEHAVIOR-POSTS TO MOOSDB ----- (Hit '@' to en/disable)
```

10.4.2 Topic #2 Dynamic Behavior Spawning

The Echo mission is configured to allow dynamic behavior spawning for the BearingLine behavior. Lines 4 and 5 in Listing 23 allow the spawning by configuring templating to be enabled on line 4, and specifying the MOOS variable through which spawning requests are received on line 5. Recall that templating can be enabled with either the "clone" or "spawn" options. In this case, "clone" option was chosen to allow the instantiation of one initial instance upon helm start-up, with the parameter configuration shown.

In this example, the pMarineViewer is configured to convert left-mouse clicks into posts of the BEARING_POINT variable to the MOOSDB, triggering the spawning of new BearingLine instances. A mouse click over the point (-5, -58) results in the post:

```
BEARING_POINT = "name=bng-line-5.0--158.0, bearing_point=-5.0,-158.0"
```

The helm receives mail for the BEARING_POINT variable since it registers automatically for each variable specified in any behavior configured with the UPDATES parameter. The helm examines this string before applying the update, and notes that the behavior name specified is unique (not currently instantiated) and rather than interpreting this as a request to update the existing BearingLine behavior already instantiated, interprets it as a request to spawn a new BearingLine instance if templating is enabled (which it is). The new behavior is spawned, with the behavior name specified. In this case the behavior name is based on the coordinates of the point clicked by the user. Two successive clicks on the same point will result in two posts to BEARING_POINT by pMarineViewer, but the second post will be effectively ignored by the helm. (It is read by the helm, but since the behavior name is one that is already known to the helm, the update is applied to that existing behavior instance. In this case such an update to the bearing_point parameter would be redundant.

After two such user mouse clicks, there will be two new BearingLine behaviors instantiated, and the situation would look similar to that shown in Figure 50. If the uHelmScope tool is still connected as above, the output would look similar to that shown in Listing 25. Note the existence of three running BearingLine behavior instances reported in lines 14-16. The instance on line 14 was created upon helm startup, and the instances on lines 15-16 were created upon the user mouse clicks.

Listing 25 - Output of the uHelmScope tool during the later execution of the Echo mission.

```
0 ===== uHelmScope Report ===== ENGAGED (12)
1 Helm Iteration: 279 (hz=0.25)(5) (hz=0.25)(100) (hz=0.26)(max)
2 IvP functions: 1
3 Mode(s): ACTIVE:SURVEYING
4 SolveTime: 0.00 (max=0.01)
5 CreateTime: 0.00 (max=0.01)
6 LoopTime: 0.00 (max=0.01)
7 Halted: false (0 warnings)
8 Helm Decision: [speed,0,4,21] [course,0,359,360]
9 course = 180.0
10 speed = 2.0
11 Behaviors Active: ----- (1)
12 waypt_survey (69.6) (pwt=100.00) (pcs=4) (cpu=0.28)
13 Behaviors Running: ----- (3)
14 bng-line (69.6) (upd=0/0)
15 bng-line-5--58 (66.1) (upd=1/1)
16 bng-line13--124 (56.8) (upd=1/1)
17 Behaviors Idle: ----- (1)
18 waypt_return
19 Behaviors Completed: ----- (0)
20
21 # MOOSDB-SCOPE ----- (Hit '#' to en/disable)
22 @ BEHAVIOR-POSTS TO MOOSDB ----- (Hit '@' to en/disable)
```

10.4.3 Topic #3: Sending Updates to the Original and Spawned Behaviors

The action associated with the left-mouse click in the Echo mission is configured in the pMarineViewer configuration block in `echo.moos` by:

```
left_context[bng_point] = BEARING_POINT = name=bng-line$(X)-$(Y) # bearing_point=$(X),$(Y)
```

Setting the context for the left and right mouse clicks in pMarineViewer is discussed in Section 13.3.6 on page 192. With the above configuration a left-mouse click may result in the following if clicked at the point (-5, -58):

```
BEARING_POINT = name=bng-line-5--58 # bearing_point=-5,-58
```

Updating or changing the prevailing parameters for existing behaviors is possible via the use of the MOOS variable specified in the `UPDATES` parameter for each behavior. The only difference between an update that changes parameters of an existing behavior, and an update that spawns a new behavior is the inclusion of a `name=<behavior-name>` as above. If this component is present in the string posted to the MOOSDB and the `<behavior-name>` specifies an existing behavior, then that behavior only will have its parameters updated. If it does not specify an existing behavior, a new behavior will be spawned with the specified name. If the `name=<behavior-name>` component is not included in the posting, then the update will be applied to all behaviors configured to receive updates via that particular MOOS variable.

This case is a bit interesting since all newly spawned behaviors specify the same MOOS variable for receiving updates. Indeed a single poke to the MOOS variable `BEARING_POINT` could result in the simultaneous configuration modification of all instantiated `BearingLine` behaviors. In the Echo mission, pMarineViewer is configured to make the following pokes to the MOOSDB via the `ACTION` pull-down menu:

```
BEARING_POINT = show_pt=true
BEARING_POINT = show_pt=false
BEARING_POINT = line_pct=0
BEARING_POINT = line_pct=25
BEARING_POINT = line_pct=50
BEARING_POINT = line_pct=75
BEARING_POINT = line_pct=100
BEARING_POINT = "name=bng-line # line_pct=0"
BEARING_POINT = "name=bng-line # line_pct=50"
BEARING_POINT = "name=bng-line # line_pct=100"
```

The first two actions will turn on or off the rendering of the bearing points posted by each behavior. The next five actions will adjust the rendering length of the posted bearing line by each behavior. The last two actions will adjust the rendering length of the posted bearing line only for the behavior named "bng-line", the behavior spawned at the time of helm start-up.

Suggestions for Tinkering

- After the mission is launched, use the `ACTION` pull-down menu in pMarineViewer to select `AUTO_SPAWN=true`. This enables a script via `uTimerScript` that automatically generates new bearing points, spawning new behaviors. These behaviors have their durations set randomly

by the script to be in range [5, 10] seconds. Note the new bearing lines emerging and moving with the vehicle until the behavior dies. The script will lead to the spawning (and death) of 5000 behaviors over the course of about two hours of simulation at `MOOSTimeWarp=1`.

- With `AUTO_SPAWN=true` as above, let the vehicle return to the launch point (by clicking the `RETURN` button in the `pMarineViewer` window. After it reaches the return point and perhaps sits for a bit, hit the `DEPLOY` button once again to return the vehicle into its `SURVEYING` mode. Notice that initially there are many bearing lines rendered before returning to only a handful of bearing lines after a few seconds of simulation. This is because newly spawned behaviors do not start their duration clock until the first time the behavior enters the running state. All behaviors spawned while returning to the start point are effectively put on hold until the vehicle is re-deployed. Then they all start their duration clocks simultaneously and all die off 5-10 seconds later.

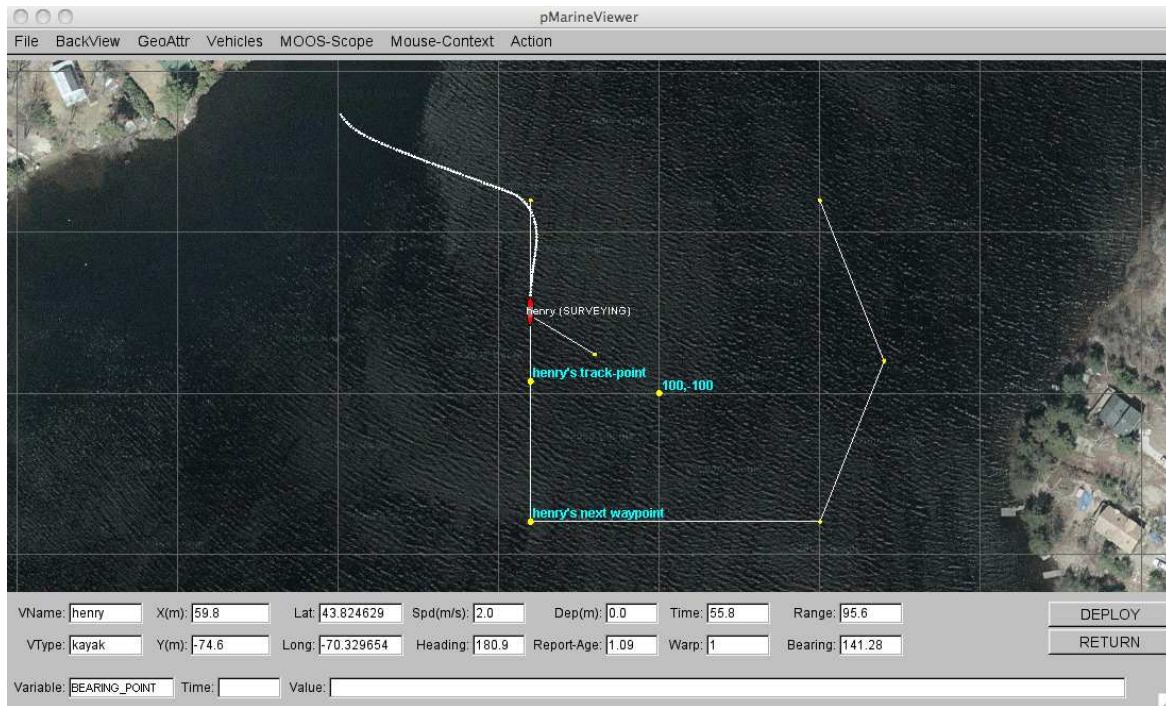


Figure 49: **The Echo Mission (1)**: The vehicle "henry" traverses waypoints with the Waypoint behavior. The BearingLine behavior generates a viewable "bearing point" at (100, -100), and a viewable "bearing line".

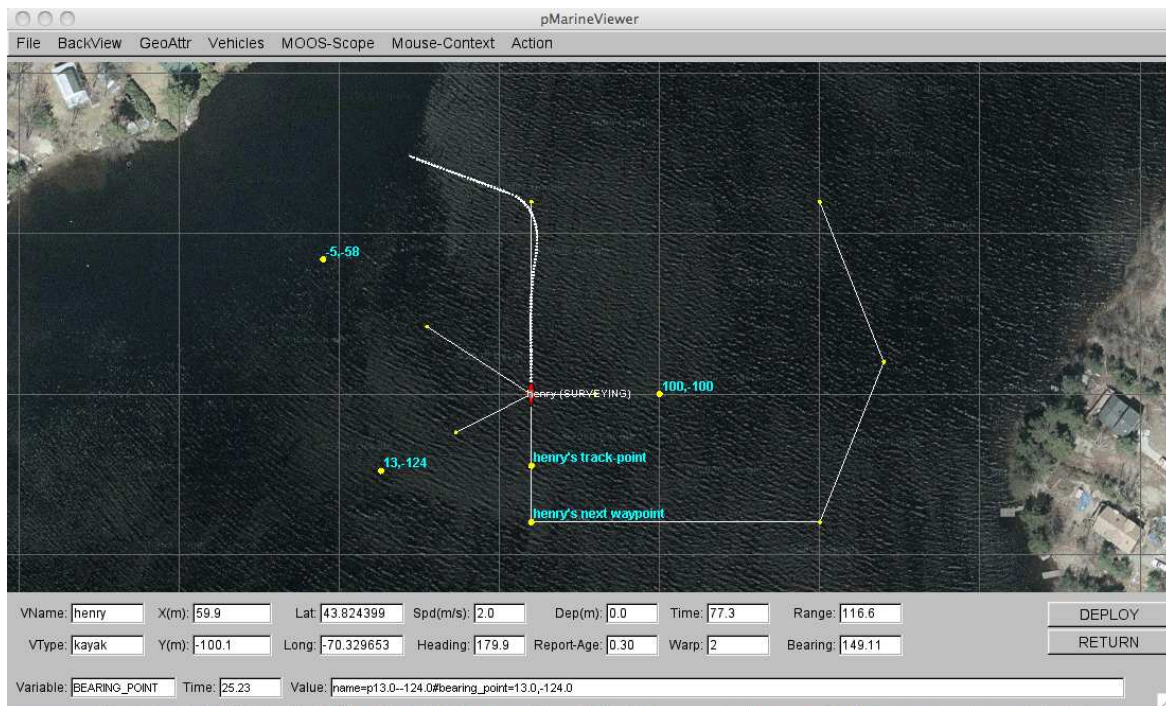


Figure 50: **The Echo Mission (2)**: The user has clicked two new bearing points, (-5, -58), and (13, -124), and two new BearingLine behaviors have been spawned, each generating bearing line and bearing point visual outputs.

10.5 Mission M1: The Multi-Loiter Mission

10.6 Mission M2: The Berta Mission

The Berta mission involves two vehicles repeatedly performing collision avoidance with one another. The primary capabilities highlighted are the helm's collision avoidance behavior, the basic contact manager (`pBasicContactMgr`), and the dynamic spawning and removal of behaviors related to contacts from the helm.

Overview of the Berta Mission Components and Topics

Mission:	"Berta" in <code>moos-ivp/missions/m2_berta</code>
Vehicles:	<code>henry</code> , <code>gilda</code>
Behaviors:	<code>BHV_Loiter</code> , <code>BHV_AvoidCollision</code>
MOOS Apps:	<code>pHelmIvP</code> , <code>pLogger</code> , <code>iMarineSim</code> , <code>pBasicContactMgr</code> , <code>pMarinePID</code> , <code>pNodeReporter</code> , <code>pMarineViewer</code> , <code>uTimerScript</code> , <code>pMOOSBridge</code>
Primary Topics:	(1) The IvP Helm <code>AvoidCollision</code> behavior / Dynamic behavior spawning. (2) Contact management with the <code>pBasicContactMgr</code> application.
Side Topics:	(1) <code>uTimerScript</code> is used in a command and control role for random permuting of vehicle loiter assignments. (2) <code>pMOOSBridge</code> is used for connecting one shoreside command and control community to two simulated vehicle communities. (3) The <code>Loiter</code> behavior is configured to receive dynamic updates on its loiter position.

Launching the Berta Mission

The *Berta* mission may be launched from the command line:

```
> cd moos-ivp/missions/m2_berta/
> ./launch.sh --warp=10
```

This should bring up a `pMarineViewer` window like that shown in Figure 51 on page 171, with two vehicles, "henry" and "gilda", each initially in the "DISENGAGED" mode. After hitting the DEPLOY button in the lower right corner, the vehicle enters the "LOITERING" mode and begins to proceed along the loiter pattern as shown. The example mission is configured to periodically alter the position of each vehicle's loiter pattern, alternating between a random point in Region-A and Region-B shown in Figure 51. The user may click the PERMUTE-NOW button to immediately cause a new permutation and command sent to the vehicle, which otherwise happens automatically every three minutes.

10.6.1 Topic #1: The AvoidCollision Behavior and Dynamic Behavior Spawning

The `AvoidCollision` behavior runs on both vehicles and is configured identically on each vehicle in this mission. Its configuration is shown in Listing 26. When the helm first launches on each vehicle this behavior is not present. It is configured to be a dynamically spawned behavior - one for each known contact within a certain range of the vehicle. In this regard it depends on alerts from a contact manager running separately on each vehicle that posts the MOOS variable `CONTACT_INFO`, with the name of the new contact for which to spawn a new behavior.

The `CONTACT_INFO` variable is the variable for which the behavior is configured to receive dynamic updates, on line 6. The behavior is configured to allow dynamic instantiations in line 7 with `templating = spawn`. The choice of `spawn` (vs. `clone`) means that a behavior of this configuration is not initially present unless cued via the updates interface. See the discussion on dynamic behavior spawning in Section 7.7, on page 89.

Listing 26 - Configuration of the AvoidCollision behavior in the Berta example mission.

```

0 //-----
1 Behavior = BHV_AvoidCollision
2 {
3     name          = avd_collision
4     pwt           = 200
5     condition     = AVOID=true
6     updates       = CONTACT_INFO
7     endflag       = CONTACT_RESOLVED = ${CONTACT}
8     templating    = spawn
9
10                 contact = to-be-set
11     active_outer_distance = 50
12     active_inner_distance = 20
13         active_grade = linear
14     collision_distance = 8
15     all_clear_distance = 25
16     completed_distance = 75
17     on_no_contact_ok = true
18     extrapolate = true
19         decay = 30,60
20     bearing_lines = white:0, green:0.65, yellow:0.8, red:1.0
21 }
```

The parameters in lines 11-13 determine the level of activity of the behavior based on the range to the contact. The parameters in lines 11, 12 refer to the priority weight of the behavior. Beyond 50 meters in range the weight will be 0% of its static weight of 200 assigned on line 4. (A weight of zero means that no objective function will be produced and the behavior is in the running state, but not the active state.) At 20 meters range, it will be at 100% of its static priority weight. The grade in priority between outer and inner distances is linear, due to the setting on line 13. The `collision_distance`, and `all_clear_distance` on lines 14 and 15 refer to the utilities assigned to candidate maneuvers in the objective function output by the behavior. Any candidate maneuver whose CPA is less than 8 meters will be given the lowest utility rating, equivalent to an actual collision. Likewise, any candidate maneuver whose CPA is greater than 25 will be given the highest utility rating, equivalent to missing the contact by infinite distance.

The `completed_distance`, on line 16, refers to the range to the contact beyond which the behavior will declare itself to be complete. Once completed, the behavior will post its end flags (none in this case), and will remove itself from the helm. In this regard, some coordination with the contact manager is needed. At the very least, the contact manager must be configured to post alerts to the mutually configured MOOS variable, `CONTACT_INFO`, on line 6 in Listing 26 and on line 16 in Listing 27. Note also that the `completed_distance` is set to 75 meters, which is higher than the 55 meters set for the `alert_range` in the contact manager. This means that, after the avoid collision behavior dies, the contact must come back within 55 meters before the contact manager

generates another alert, triggering the helm to once again spawn a behavior for the contact.

Once a contact has gone out of range to the point where the `AvoidCollision` behavior dies, it typically never returns, in practice. There is no guarantee of this however, since the future maneuvers of either the contact or ownship may once again put them on a collision course. The Berta mission tests this scenario repeatedly. The two vehicles are configured to loiter in a loiter pattern that keeps them out range from each other in terms of triggering an `AvoidCollision` behavior in each of their helms (as in Figure 51). In this mission, a `uTimerScript` script is running in the shoreside community that periodically picks a new loiter location within one of the two regions shown in Figure 51. It picks a new location once every three minutes, alternating between the two regions for each vehicle each time. This ensures that there will be a reasonably unpredictable collision avoidance situation each time the vehicles transit to their new loiter locations. The permutations happen automatically once every three minutes, but the user may jump to the next permutation by clicking on the `PERMUTE-NOW` button.

In Figure 52, note the line segment rendered between the two vehicles. This line segment is posted to the MOOSDB by the IvP Helm on behalf of the `AvoidCollision` behavior. A white line is drawn between the two vehicles as soon as the `AvoidCollision` behavior is spawned. The line turns a non-white color as soon as the behavior begins to generate an objective function, thus actively influencing the helm to prefer maneuvers with a lower expected CPA. The line is initially green to indicate a lower behavior priority. As the priority grows, the line turns yellow and finally red when it is at the higher priorities. The behavior posting of these line segments is optional and configurable. The configuration on line 20 in Listing 26 is responsible for the postings in this mission.

In this example, the `extrapolate` option is turned on for the `AvoidCollision` behavior (line 18 in Listing 26). Extrapolation is typically enabled when long durations are experienced between updates on contact position (which is not the case here in simulation). The behavior will automatically use the linear extrapolated position given the contact's last known position, trajectory and time-stamp. The linear extrapolation will decay down to a zero speed (stationary solution) beginning at 30 seconds and coming to a complete stop at 60 seconds, due to the decay specification on line 19 of Listing 26.

10.6.2 Topic #2: Contact Management with `pBasicContactMgr`

In the Berta mission, the `pBasicContactMgr` is running on both simulated vehicles, configured identically with the configuration block shown in Listing 27. Both the contact manager and the helm are receiving `NODE_REPORT` messages containing information about contacts. The helm stores this information in its information buffer for any behavior that requests it during normal operation. The contact manager uses contact information to generate alerts, which potentially cues the helm to spawn new contact-related behaviors.

The contact manager may be configured to generate more than one alert. However, in the Berta mission, a single alert, on line 15 in Listing 27 is sufficient for spawning collision avoidance behaviors. Note the alert specifies a variable name, and variable value. The variable name, (`CONTACT_INFO`), is set to be the variable used for updates in the `AvoidCollision` behavior, on line 6 in Listing 26. The variable value is configured to be #-separated list of parameter-value pairs suitable as input to any behavior receiving updates. (See Section 7.2.2 on behavior updates.) In this case, the

alert is configured to “update” the AvoidCollision behavior parameters `name`, and `contact`. Both parameter values are comprised, in part, of the name of the contact, `#[VNAME]`. In the case of the behavior name, this is to ensure that the behavior name is unique, a condition for spawning a new behavior. It also ensures that multiple AvoidCollision behaviors will not be spawned for the same contact. In the case of the contact name, the behavior simply must know the name of the contact for which it avoiding a collision.

In the unlikely event that two distinct contacts are present in the field, and reporting the same vehicle name, it would be up to the contact manager to discern that these are indeed two contacts and not one. Currently this is beyond the algorithms implemented in `pBasicContactMgr`.

Listing 27 - Configuration of the pBasicContactMgr application in the Berta example mission.

```

0 //-----
1 // pBasicContactMgr MOOS Configuration Block
2
3 ProcessConfig = pBasicContactMgr
4 {
5     AppTick    = 2
6     CommsTick = 2
7
8     ALERT_RANGE    = 55
9     ALERT_CPA_RANGE = 70
10    ALERT_CPA_TIME = 30
11    CONTACT_MAX_AGE = 3600
12    DISPLAY_RADII   = false
13    VERBOSE         = true
14
15    ALERT = var=CONTACT_INFO, val="name=avd_#[VNAME] # contact=#[VNAME]"
16 }
```

In the Berta example mission, the contact manager is configured to generate alerts when a know contact comes within 55 meters of the vehicle (line 8 of Listing 27). The contact manager also is configured to generate alerts when a contact comes within 70 meters (line 9) *and* its calculated CPA over next 30 seconds (line 10) falls within the alert range (again line 8). See Figure 71 on page 224 for more on the relationship between these two ranges.

The contact manager is capable of optionally posting to the MOOSDB two circles rendering the two ranges, the `ALERT_RANGE` and `ALERT_CPA_RANGE`. The rendering is turned off and on with the setting on line 12. The circles are posted under the variable `VIEW_POLYGON` in the local MOOSDBs on each vehicle, and each vehicle is configured to bridge this variable (via `pMOOSBridge`) to the shoreside community running the `pMarineViewer`.

Suggestions for Tinkering in the Berta Mission

- Alter the alert ranges in the contact manager, and enable the displaying of range radii (line 12 in Listing 27) and notice when the AvoidCollision behavior is spawned, by the presence of the bearing lines between the two contacts.
- Alter the `active_*_distance` parameters in the AvoidCollision behavior (lines 10-11 in Listing 26) and check how this affects the ranges between the vehicles as they avoid collisions.

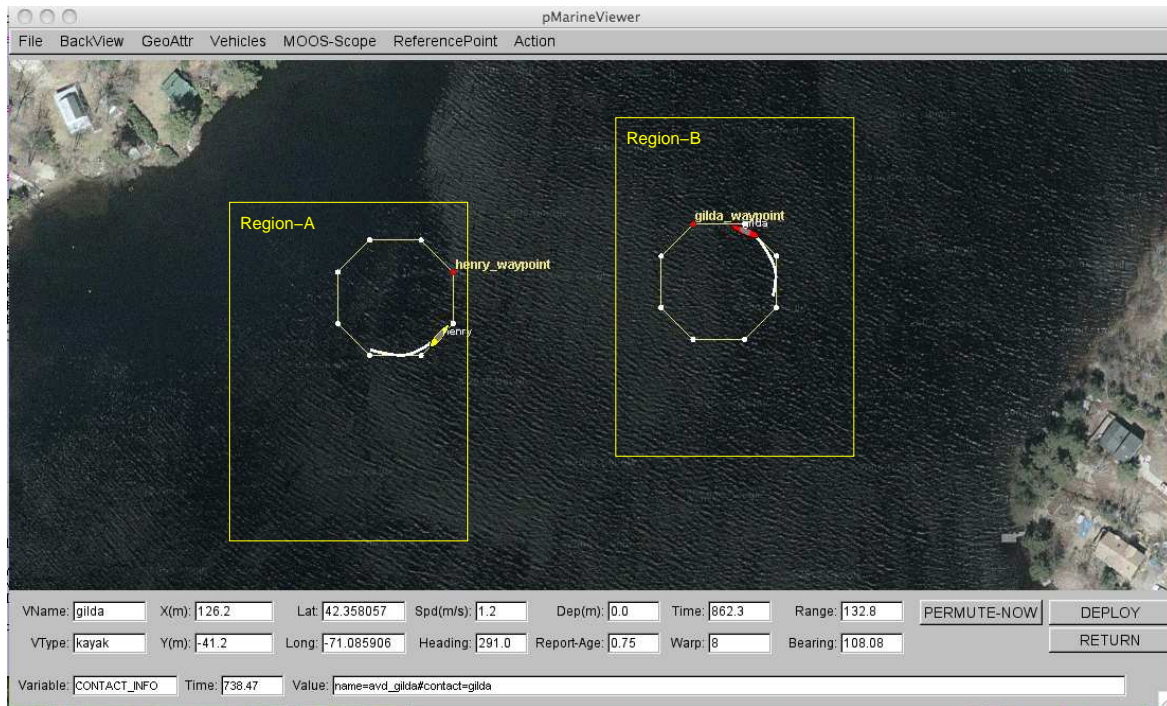


Figure 51: **The Berta Mission (1)**: The two vehicles, "henry" and "gilda", initially transit to their respective loiter stations and await further random location changes between the shown boxes.



Figure 52: **The Berta Mission (2)**: The vehicles have changed their loiter stations and this puts them at risk for collision. The green bearing line between the vehicle indicates the presence of the AvoidCollision behavior.

Part III

Autonomy Utilities

11 The uHelmScope Utility: Scoping on the IvP Helm

11.1 Brief Overview

The uHelmScope application is a console based tool for monitoring output of the IvP helm, i.e., the pHelmIvP process. The helm produces a few key MOOS variables on each iteration that pack in a substantial amount of information about what happened during a particular iteration. The helm scope subscribes for and parses this information, and writes it to standard output in a console window for the user to monitor. The user can dynamically pause or alter the output format to suit one's needs, and multiple scopes can be run simultaneously. The helm scope in no way influences the performance of the helm - it is strictly a passive observer.

11.2 Console Output of uHelmScope

The example console output shown in Listing 28 is used for explaining the uHelmScope fields.

Listing 28 - Example uHelmScope output.

```

1  ===== uHelmScope Report ===== ENGAGED (17)
2  Helm Iteration: 66 (hz=0.38)(5) (hz=0.35)(66) (hz=0.56)(max)
3  IvP functions: 1
4  Mode(s): Surveying
5  SolveTime: 0.00 (max=0.00)
6  CreateTime: 0.02 (max=0.02)
7  LoopTime: 0.02 (max=0.02)
8  Halted: false (0 warnings)
9  Helm Decision: [speed,0,4,21] [course,0,359,360]
10 speed = 3.00
11 course = 177.00
12 Behaviors Active: ----- (1)
13 waypt_survey (13.0) (pwt=100.00) (pcs=1227) (cpu=0.01) (upd=0/0)
14 Behaviors Running: ----- (0)
15 Behaviors Idle: ----- (1)
16 waypt_return (22.8)
17 Behaviors Completed: ----- (0)
18
19 # MOOSDB-SCOPE ----- (Hit '#' to en/disable)
20 #
21 # VarName Source Time Community VarValue
22 # -----
23 # BHV_WARNING n/a n/a n/a n/a
24 # NODE_REPORT_LOCAL pNode..rter 24.32 alpha "NAME=alpha,TYPE=KAYAK,MOOSDB"+
25 # DEPLOY* iRemote 11.25 alpha "true"
26 # RETURN* pHelmIvP 5.21 alpha "false"
27
28 @ BEHAVIOR-POSTS TO MOOSDB ----- (Hit '@' to en/disable)
29 @
30 @ MOOS Variable Value
31 @ ----- (BEHAVIOR=waypt_survey)
32 @ PC_waypt_survey -- ok --
33 @ WPT_STAT_LOCAL vname=alpha,index=1,dist=80.47698,eta=26.83870
34 @ WPT_INDEX 1
35 @ VIEW_SEGLIST label,alpha_waypt_survey : 30,-20:30,-100:90,-100: +
36 @ ----- (BEHAVIOR=waypt_return)
37 @ PC_waypt_return RETURN = true
38 @ VIEW_SEGLIST label,alpha_waypt_return : 0,0
39 @ VIEW_POINT 0,0,0,waypt_return

```

There are three groups of information in the uHelmScope output on each report to the console - the general helm overview (lines 1-17), a MOOSDB scope for a select subset of MOOS variables (lines

19-26), and a report on the MOOS variables published by the helm on the current iteration (lines 28-39). The output of each group is explained in the next three subsections.

11.2.1 The General Helm Overview Section of the uHelmScope Output

The first block of output produced by uHelmScope provides an overview of the helm. This is lines 1-17 in Listing 28, but the number of lines may vary with the mission and state of mission execution. The integer value at the end of line 1 indicates the number of uHelmScope reports written to the console. This can confirm to the user that an action that should result in a new report generation has indeed worked properly. The integer on line 2 is the counter kept by the helm, incremented on each helm iteration. The three sets of numbers that follow indicate the observed time between helm iterations. These numbers are reported by the helm and are not inferred by the scope. The first number is the average over the most recent five iterations. The second is the average over the most recent 58 iterations. The last is the maximum helm-reported interval observed by the scope. The number of iterations used to generate the first two numbers can be set by the user in the uHelmScope configuration block. The default is 5 and 100 respectively. The number 58 is shown in the second group simply because 100 iterations hadn't been observed yet. The helm is apparently only on iteration 66 in this example and uHelmScope apparently didn't start and connect to the MOOSDB until the helm was on iteration 8.

The value on Line 3 represents the the number of IvP functions produced by the active helm behaviors, one per active behavior. The solve-time on line 5 represents the time, in seconds, needed to solve the IvP problem comprised the n IvP functions. The number that follows in parentheses is the maximum solve-time observed by the scope. The create-time on line 6 is the total time needed by all active behaviors to produce their IvP function output. The loop time on line 7 is simply the sum of lines 5 and 6. The Boolean on line 8 is true only if the helm is halted on an emergency or critical error condition. Also on line 8 is the number of warnings generated by the helm. This number is reported by the helm and *not* simply the number of warnings observed by the scope. This number coincides with the number of times the helm writes a new message to the variable BHV_WARNING.

The helm decision space (i.e., IvP domain) is displayed on line 9, with the following lines used to display the actual helm decision. Following this is a list of all the active, running, idle and completed behaviors. At any point in time, each instantiated IvP behavior is in one of these four states and each behavior specified in the behavior file should appear in one of these groups. Technically all *active* behaviors are also *running* behaviors but not vice versa. So only the running behaviors that are not active (i.e., the behaviors that could have, but chose not to produce an objective function), are listed in the “Behaviors Running:” group. Immediately following each behavior the time, in seconds, that the behavior has been in the current state is shown in parentheses. For the active behaviors (see line 13) this information is followed by the priority weight of the behavior, the number of pieces in the produced IvP function, and the amount of CPU time required to build the function. If the behavior also is accepting dynamic parameter updates the last piece of information on line 13 shows how many successful updates where made against how many attempts. A failed update attempt also generates a helm warning, counted on line 8. The idle and completed behaviors are listed by default one per line. This can be changed to list them on one long line by hitting the 'b' key interactively. Insight into why an idle behavior is not in the running state can be found in the another part of the report (e.g., line 37) described below in Section 11.2.3.

11.2.2 The MOOSDB-Scope Section of the uHelmScope Output

Part of understanding what is happening in the helm involves the monitoring of variables in the MOOSDB that can either affect the helm or reveal what is being produced by the helm. Although there are other MOOS scope tools available (e.g., uXMS or uMS), this feature does two things the other scopes do not. First, it is simply a convenience for the user to monitor a few key variables in the same screen space. Second, uHelmScope automatically registers for the variables that the helm reasons over to determine the behavior activity states. It will register for all variables appearing in behavior conditions, runflags, activeflags, inactiveflags, endflags and idleflags. Variables that are registered for by this criteria are indicated by an asterisk at the end of the variable name. If the output resulting from these automatic registrations becomes unwanted, it can be toggled off by typing 's'.

The lines comprising the MOOSDB-Scope section of the uHelmScope output are all preceded by the '#' character. This is to help discern this block from the others, and as a reminder that the whole block can be toggled off and on by typing the '#' character. The columns in Listing 28 are truncated to a set maximum width for readability. The default is to have truncation turned off. The mode can be toggled by the console user with the 't' character, or set in the MOOS configuration block or with a command line switch. A truncated entry in the VarValue column has a '+' at the end of the line. Truncated entries in other columns will have "." embedded in the entry. Line 24 shows an example of both kinds of truncation.

The variables included in the scope list can be specified in the uHelmScope configuration block of a MOOS file. In the MOOS file, the lines have the form:

```
VAR = VARIABLE_1, VARIABLE_2, VARIABLE_3, ...
```

An example configuration is given in Listing 31. Variables can also be given on the command line. Duplicates requests, should they occur, are simply ignored. Occasionally a console user may want to suppress the scoping of variables listed in the MOOS file and instead only scope on a couple variables given on the command line. The command line switch -c will suppress the variables listed in the MOOS file - unless a variable is also given on the command line. In line 23 of Listing 28, the variable BHV_WARNING is a *virgin* variable, i.e., it has yet to be written to by any MOOS process and shows n/a in the four output columns. By default, virgin variables are displayed, but their display can be toggled by the console user by typing '-v'.

11.2.3 The Behavior-Posts Section of the uHelmScope Output

The Behavior-Posts section is the third group of output in uHelmScope lists MOOS variables and values posted by the helm on the current iteration. Each variable was posted by a particular helm behavior and the grouping in the output is accordingly by behavior. Unlike the variables in the MOOSDB-Scope section, entries in this section only appear if they were written to on the current iteration. The lines comprising the Behavior-Posts section of the uHelmScope output are all preceded by the '@' character. This is to help discern this block from the others, and as a reminder that the whole block can be toggled off and on by typing the '@' character. As with the output in the MOOSDB-Scope output section, the output may be truncated. A trailing '+' at the end of the line indicates the variable value has been truncated.

There are a few switches for keeping the output in this section concise. A behavior posts a few standard MOOS variables on every iteration that may be essentially clutter for users in most cases. A behavior F00 for example produces the variables PWT_F00, STATE_F00, and UH_F00 which indicate the priority weight, run-state, and tally of successful updates respectively. Since this information is present in other parts of the uHelmScope output, these variables are by default suppressed in the Behavior-Posts output. Two other standard variables are PC_F00 and VIEW_* which indicate the precondition keeping a behavior in an idle state, and standard viewing hints to a rendering engine. Since this information is not present elsewhere in the uHelmScope output, it is not masked out by default. A console user can mask out the PWT, STATE_* and UH_* variables by typing 'm'. The PC_* and VIEW_* variables can be masked out by typing 'M'. All masked variables can be unmasked by typing 'u'.

11.3 Stepping Forward and Backward Through Saved Scope History

The user has the option of pausing and stepping forward or backward through helm iterations to analyze how a set of events may have unfolded. Stepping one event forward or backward can be done with the '[' and ']' keys respectively. Stepping 10 or 100 events can be done with the '{' and '}', and '(' and ')' keys respectively. The current helm iteration being displayed is always shown on the second line of the output. For each helm iteration, the uHelmScope process stores the information published by the helm (Section 11.5), and thus the memory usage of uHelmScope would grow unbounded if left unchecked. Therefore information is kept for a maximum of 2000 helm iterations. This number is *not* a configuration parameter - to preclude a user from inadvertently setting this too high and inducing the system maladies of a single process with runaway memory usage. To change this number, a user must change the source code (in particular the variable `m_history_size_max` in the file `HelmScope.cpp`). The uHelmScope history is therefore a moving window of fixed size that continues to shift right as new helm information is received. Stepping forward or backwards therefore is subject to the constraints of this window. Any steps backward or forward will in effect generate a new *requested* helm index for viewing. The requested index, if older than the oldest stored index, will be set exactly to the oldest stored index. Similarly in the other direction. It's quite possible then to hit the '[' key to step left by one index, and have the result be a report that is not one index older, but rather some number of indexes newer. Hitting the space bar or 'r' key always generates a report for the very latest helm information, with the 'r' putting the scope into streaming, i.e., continuous update, mode.

11.4 Console Key Mapping and Command Line Usage Summaries

The uHelmScope has a separate thread to accept user input from the console to adjust the content and format of the console output. It operates in either the *streaming mode*, where new helm summaries are displayed as soon as they are received, or the *paused mode* where no further output is generated until the user requests it. The key mappings can be summarized in the console output by typing the 'h' key, which also sets the mode to *paused*. The key mappings shown to the user are shown in Listing 29.

Listing 29 - Key mapping summary shown after hitting 'h' in a console.

```

1 KeyStroke  Function
2 -----  -----
```

```

3   Spc      Pause and Update latest information once - now
4   r/R      Resume information refresh
5   h/H      Show this Help msg - 'r' to resume
6   b/B      Toggle Show Idle/Completed Behavior Details
7   t/T      Toggle truncation of column output
8   m/M      Toggle display of Hierarchical Mode Declarations
9   f        Filter PWT_* UH_* STATE_* in Behavior-Posts Report
10  F        Filter PC_* VIEW_* in Behavior-Posts Report
11  s/S      Toggle Behavior State Vars in MOOSDB-Scope Report
12  u/U      Unmask all variables in Behavior-Posts Report
13  v/V      Toggle display of virgins in MOOSDB-Scope output
14  [/]     Display Iteration 1 step prev/forward
15  {/}     Display Iteration 10 steps prev/forward
16  (/)     Display Iteration 100 steps prev/forward
17  #       Toggle Show the MOOSDB-Scope Report
18  @       Toggle Show the Behavior-Posts Report
19
20 Hit 'r' to resume outputs, or SPACEBAR for a single update

```

Several of the same preferences for adjusting the content and format of the uHelmScope output can be expressed on the command line, with a command line switch. The switches available are shown to the user by typing uHelmScope -h. The output shown to the user is shown in Listing 30.

Listing 30 - Command line usage of the uHelmScope application.

```

1 > uHelmScope -h
2 Usage: uHelmScope moosfile.moos [switches] [MOOSVARS]
3   -t: Column truncation is on (off by default)
4   -c: Exclude MOOS Vars in MOOS file from MOOSDB-Scope
5   -x: Suppress MOOSDB-Scope output block
6   -p: Suppress Behavior-Posts output block
7   -v: Suppress display of virgins in MOOSDB-Scope block
8   -r: Streaming (unpaused) output of helm iterations
9   MOOSVAR_1 MOOSVAR_2 .... MOOSVAR_N

```

The command line invocation also accepts any number of MOOS variables to be included in the MOOSDB-Scope portion of the uHelmScope output. Any argument on the command line that does not end in .moos, and is not one of the switches listed above, is interpreted to be a requested MOOS variable for inclusion in the scope list. Thus the order of the switches and MOOS variables do not matter. These variables are added to the list of variables that may have been specified in the uHelmScope configuration block of the MOOS file. Scoping on *only* the variables given on the command line can be accomplished using the -c switch. To support the simultaneous running of more than one uHelmScope connected to the same MOOSDB, uHelmScope generates a random number N between 0 and 10,000 and registers with the MOOSDB as uHelmScope.N.

11.5 IvPHelm MOOS Variable Output Supporting uHelmScope Reports

There are six variables published by the pHelmIvP MOOS process, and registered for by the uHelmScope process, that provide critical information for generating uHelmScope reports. They are: IVPHELM_SUMMARY, IVPHELM_POSTINGS, IVPHELM_ENGAGED, IVPHELM_STATEVARS, IVPHELM_DOMAIN, IVPHELM_LIFE_EVENT and IVPHELM_MODESET. The first three are produced on each iteration of the helm, and the last three are typically only produced once when the helm is launched.

```

IVPHELM_SUMMARY = "iter=66,ofnum=1,warnings=0,utc_time=1209755370.74,solve_time=0.00,
  create_time=0.02,loop_time=0.02,var=speed:3.0,var=course:108.0,halted=false,
  running_bhvs=none,active_bhvs=waypt_survey$6.8$100.00$1236$0.01$0/0,
  modes=MODE@ACTIVE:SURVEYING,idle_bhvs=waypt_return$55.3$n/a,completed_bhvs=none"

IVPHELM_POSTINGS = "waypt_return$@$66$@$PC_waypt_return=RETURN = true$@$VIEW_SEGLIST=label,
  alpha_waypt_return : 0,0$@$VIEW_POINT=0,0,0,waypt_return$@$PWT_BHV_WAYPT_RETURN=0
  $@$STATE_BHV_WAYPT_RETURN=0"

IVPHELM_POSTINGS = waypt_survey$@$66$@$PC_waypt_survey=-- ok --$@$WPT_STAT_LOCAL=vname=alpha,
  index=1,dist=80.47698,eta=26.83870$@$WPT_INDEX=1$@$VIEW_SEGLIST=label,
  alpha_waypt_survey:30,-20:30,-100:90,-100:110,-60:90,-20$@$PWT_BHV_WAYPT_SURVEY=100$@$
  STATE_BHV_WAYPT_SURVEY=2

IVPHELM_DOMAIN = "speed,0,4,21:course,0,359,360"

IVPHELM_STATEVARS = "RETURN,DEPLOY"

IVPHELM_MODESET = "---,ACTIVE#---,INACTIVE#ACTIVE,SURVEYING#ACTIVE,RETURNING"

IVPHELM_ENGAGED = "ENGAGED"

```

The IVPHELM_SUMMARY variable contains all the dynamic information included in the general helm overview (top) section of the uHelmScope output. It is a comma-separated list of var=val pairs. The IVP_DOMAIN variable also contributes to this section of output by providing the IvP domain used by the helm. The IVPHELM_POSTINGS variable includes a list of MOOS variables and values posted by the helm for a given behavior. The helm writes to this variable once per iteration *for each behavior*. The IVPHELM_STATEVARS variable affects the MOOSDB-Scope section of the uHelmScope output by identifying which MOOS variables are used by behaviors in conditions, runflags, endflags and iddeflags.

11.6 Configuration Parameters for uHelmScope

Configuration for uHelmScope amounts to specifying a set of parameters affecting the terminal output format. An example configuration is shown in Listing 31, with all values set to the defaults. Launching uHelmScope with a MOOS file that does not contain a uHelmScope configuration block is perfectly reasonable.

Listing 31 - An example uHelmScope configuration block.

```

1 //-----
2 // uHelmScope configuration block
3
4
5 ProcessConfig = uHelmScope
6 {
7   AppTick      = 1
8   CommsTick    = 1
9
10  PAUSED          = true      // All Parameters and Parameter-Values
11  HZ_MEMORY       = 5, 100   // are __NOT__ Case Sensitive
12  DISPLAY_MOOS_SCOPE = true
13  DISPLAY_BHV_POSTS  = true
14  DISPLAY_VIRGINS   = true

```

```
15  DISPLAY_STATEVARS = true
16  TRUNCATED_OUTPUT  = false
17  BEHAVIORS_CONCISE = false
18
19  VAR = BHV_WARNING, AIS_REPORT_LOCAL // MOOS Variable names
20 } // __ARE__ Case Sensitive
```

Each of the parameters, with the exception of `HZ_MEMORY` can also be set on the command line, or interactively at the console, with one of the switches or keyboard mappings listed in Section 11.4. A parameter setting in the MOOS configuration block will take precedence over a command line switch. The `HZ_MEMORY` parameter takes two integer values, the second of which must be larger than the first. This is the number of samples used to form the average time between helm intervals, displayed on line 2 of the `uHelmScope` output.

11.7 Publications and Subscriptions for `uHelmScope`

Variables published by the `uHelmScope` application

- NONE

Variables subscribed for by the `uHelmScope` application

- `<USER-DEFINED>`: Variables identified for scoping by the user in the `uHelmScope` will be subscribed for. See Section 11.2.2.
- `<HELM-DEFINED>`: As described in Section 11.2.2, the variables scoped by `uHelmScope` include any variables involved in the preconditions, runflags, idleflags, activeflags, inactiveflags, and endflags for any of the behaviors involved in the current helm configuration.
- `IVPHELM_SUMMARY`: See Section 11.5.
- `IVPHELM_POSTINGS`: See Section 11.5.
- `IVPHELM_STATEVARS`: See Section 11.5.
- `IVPHELM_DOMAIN`: See Section 11.5.
- `IVPHELM_MODESET`: See Section 11.5.
- `IVPHELM_ENGAGED`: See Section 11.5.

12 Geometry Utilities

12.1 Brief Overview

This section discusses a few geometry data structures often used by the `helm` and the `pMarineViewer` application - convex polygons, lists of line segments, and points. These data structures are implemented by the classes `XYPolygon`, `XYSegList`, `XYPoint` respectively in the `lib_geometry` module distributed with the MOOS-IvP software bundle. The implementation of these class definitions is somewhat shielded from the `helm` user's perspective, but they are often involved in parameter settings of for behaviors. So the issue of how to specify a given geometric structure with a formatted string is discussed here.

Furthermore, the `pMarineViewer` application accepts these data structures for rendering by subscribing to three MOOS variables `VIEW_POLYGON`, `VIEW_SEGLIST`, and `VIEW_POINT`. These variables contain a string format representation of the structure, often with further visual hints on the color or size of the edges and vertices for rendering. These variables may originate from any MOOS application, but are also often posted by `helm` behaviors to provide visual clues about what is going on in the vehicle. In the Alpha mission described in Section 4 for example, the waypoint behavior posted a seglist representing the set of waypoints for which it was configured, as well as posting a point indicating the next point on the behavior's list to traverse.

12.2 Points

Points are implemented in the `XYPoint` class, and minimally represent a point in the x-y plane. These objects are used internally for applications and behaviors, and may also be involved in rendering in a GUI and therefore may have additional fields to support this.

12.2.1 String Representations for Points

The only required information for a point specification is its position in the x-y plane. A third value may optionally be specified in the z-plane. All four of the below string representations correspond to the very same data structure:

```
point = 60,-40
point = 60, -40, 0
point = x=60, y=-40
point = x=60, y=-40, z=0
```

12.2.2 Optional Point Parameters

Points also may have several optional fields associated with them. The `label` field is string that is often rendered with a point in MOOS GUI applications such as the `pMarineViewer`. The `label_color` field represents a color preference for the label rendering. The `type` and `source` fields are additional string fields for further distinguishing a point in applications that handle them. The `active` field is a Boolean that is used in the `pMarineViewer` application to indicate whether the the point should be rendered. The `time` field is a double that may optionally be set to indicate when the point was generated, or how long it should exist before “expiring”, or however an application may wish to

interpret it. The `vertex_color` and `vertex_size` field represent further rendering preferences. The following are two equivalent further string representations:

```
point = x=60, y=-40, label=home, label_color=red, source=henry, type=waypoint,
      time=30, active=true, vertex_color=white, vertex_size=5
point = 60,-40:label,home:label_color,red:source,henry:type,waypoint
      time,30:active,true:vertex_color,white:vertex_size,5
```

The former is a more user-friendly format for specifying a point, perhaps found in a configuration file for example. The latter is the string representation passed around internally when `XYPoint` objects are automatically converted to strings and back again in the code. This format is more likely to be found in log files or seen when scoping on variables with one of the MOOS scoping tools.

12.3 Polygons

Polygons are implemented in the `XYPolygon` class. This implementation accepts as a valid construction only specifications that build a convex polygon. Common operations used internally by behaviors and other applications, such as intersection tests, distance calculations etc, are greatly simplified and more efficient when dealing with convex polygons.

12.3.1 String Representations for Polygons

Polygons are defined by a set of vertices and the simplest way to specify the points is with a line comprised of a sequence of colon-separated pairs of comma-separated x-y points in local coordinates such as:

```
polygon = 60,-40:60,-160:150,-160:180,-100:150,-40:label,foxtrot
```

If one of the pairs, such as the last one above, contains the keyword `label` on the left, then the value on the right, e.g., `foxtrot` as above, is the label associated with the polygon. An alternative notation for the same polygon is given by the following:

```
polygon = label=foxtrot, pts="60,-40:60,-160:150,-160:180,-100:150,-40"
```

This is an comma-separated list of equals-separated pairs. The ordering of the comma-separated components is insignificant. The points describing the polygon are provided in quotes to signify to the parser that everything in quotes is the right-hand side of the `pts=` component. Both formats are acceptable specifications of a polygon in a behavior for which there is a `polygon` parameter.

12.3.2 A Polygon String Representation using the Radial Format

Polygons may also be specified by their shape and the shape parameters. For example, a commonly used polygon is formed by points of an equal radial distance around a center point. The following is an example:

```
polygon = format=radial, label=foxtrot, x=0, y=40, radius=60, pts=6, snap=1
```

The `snap` component in the above example signifies that the vertices should be rounded to the nearest 1-meter value. The `x`, `y` parameters specify the middle of the polygon, and `radius` parameters specify the distance from the center for each vertex. The `pts` parameters specifies the number of vertices used, as shown in Figure 53.

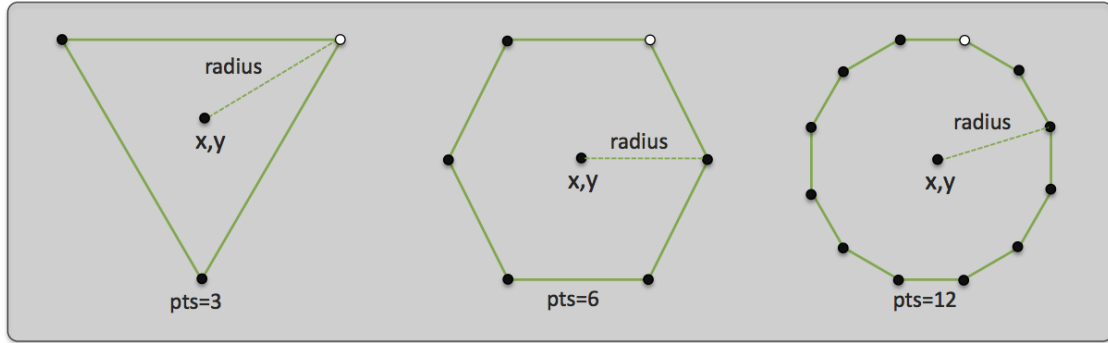


Figure 53: **Polygons built with the radial format:** Radial polygons are specified by (a) the location of their center, (b) the number of vertices, and (c) the radial distance from the center to each vertex. The lighter vertex in each polygon indicates the first vertex if traversing in sequence, proceeding clockwise.

12.3.3 A Polygon String Representation using the Ellipse Format

Polygons may also be built using the `ellipse` format. The following is an example:

```

polygon = label=golf, format=ellipse, x=0, y=40, degs=45, pts=14, snap=1,
        major=100, minor=70
    
```

The `x`, `y` parameters specify the middle of the polygon, the `major` and `minor` parameters specify the radial distance of the major and minor axes. The `pts` parameters specifies the number of vertices used, as shown in Figure 54.

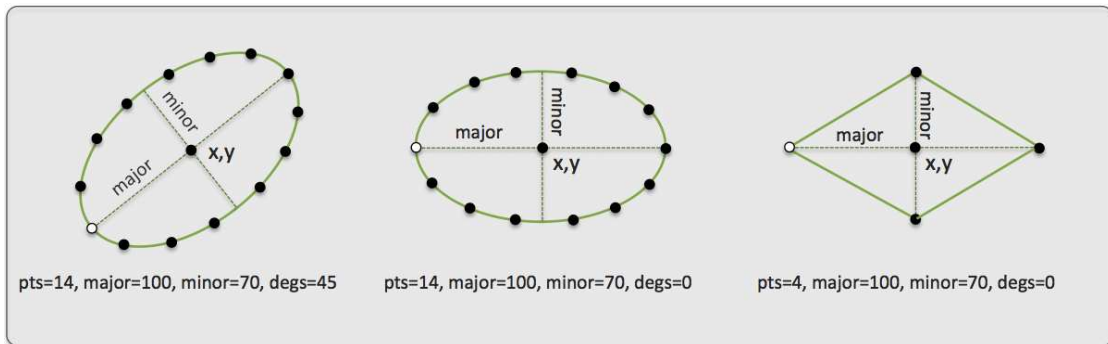


Figure 54: **Polygons built with the ellipse format:** Ellipse polygons are specified by (a) the location of their center, (b) the number of vertices, (c) the length of their major axis, (d) the length of their minor axis, and (e) the rotation of the ellipse. The lighter vertex in each polygon indicates the first vertex if traversing in sequence, proceeding clockwise.

The rotation of the ellipse can optionally be specified in radians. For example, `degs=45` is equivalent to `rads=0.785398`. If, for some reason, both are specified, the polygon will be built using the `rads` parameter. When using the ellipse format, a minimum `pts=4` must be specified.

12.3.4 Optional Polygon Parameters

Polygons also may have several optional fields associated with them. The `label` field is string that is often rendered with a polygon in MOOS GUI applications such as the `pMarineViewer`. The `label_color` field represents a color preference for the label rendering. The `type` and `source` fields are additional string fields for further distinguishing a polygon in applications that handle them. The `active` field is a Boolean that is used in the `pMarineViewer` application to indicate whether the the polygon should be rendered. The `time` field is a double that may optionally be set to indicate when the polygon was generated, or how long it should exist before “expiring”, or however an application may wish to interpret it. The `vertex_color`, `edge_color`, and `vertex_size` fields represent further rendering preferences. The following are two equivalent further string representations:

```

polygon = format=radial, x=60, y=-40, radius=60, pts=8, snap=1, label=home,
          label_color=red, source=henry, type=survey, time=30, active=true,
          vertex_color=white, vertex_size=5, edge_size=2
polygon = format,radial:60,-40:radius,60:pts,8:snap,1:label,home:
          label_color,red:source,henry:type,survey:time,30:active,true:
          vertex_color,white:vertex_size,5:edge_size,2

```

The former is a more user-friendly format for specifying a polygon, perhaps found in a configuration file for example. The latter is the string representation passed around internally when `XYPolygon` objects are automatically converted to strings and back again in the code. This format is more likely to be found in log files or seen when scoping on variables with one of the MOOS scoping tools.

12.4 SegLists and their String Representations

12.4.1 Methods for Specifying Seglists

A *seglist* is a sequence of line segments given by a list of points. Seglists are specified with the `points` parameter, and the simplest way to specify the points is with a line comprised of a sequence of colon-separated pairs of comma-separated x-y points in local coordinates such as:

```

points = 60,-40:60,-160:150,-160:180,-100:150,-40:label,foxtrot

```

If one of the pairs, such as the last one above, contains the keyword `label` on the left, then the value on the right, e.g., `foxtrot` as above, is the label associated with the seglist.

12.4.2 A SegList String Representation using the Lawnmower Format

SegLists may also be built using the `lawnmower` format. The following is an example:

```

points = format=lawnmower, label=foxtrot, x=0, y=40, height=60, width=180,
          lane_width=15, rows=north-south, degs=45

```


The rotation of the pattern can optionally be specified in radians. For example, `degs=45` is equivalent to `rads=0.785398`. If, for some reason, both are specified, the seglist will be built using the `rads` parameter.

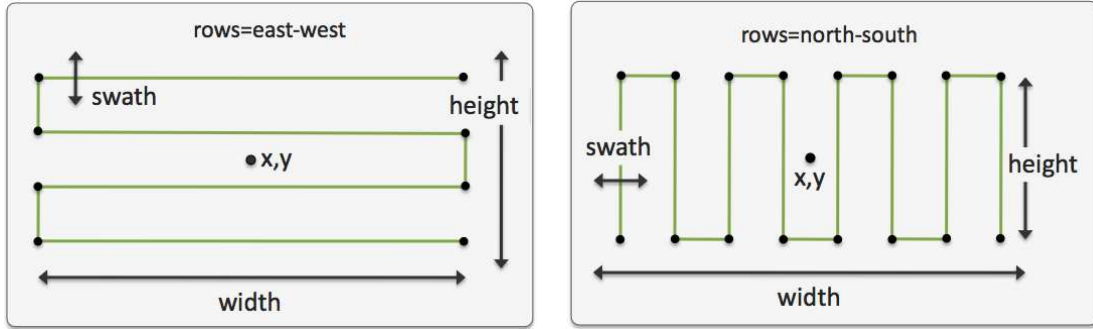


Figure 55: **SegLists built with the lawnmower format:** The pattern is specified by (a) the location of the center of the pattern, (b) the height and width of the pattern, (c) the lane width which determines the number of rows, (d) whether the pattern rows proceed north-south or east-west, and (e) an optional rotation of the pattern.

13 The pMarineViewer Utility: A GUI for Mission Control

13.1 Brief Overview

The pMarineViewer application is a MOOS application written with FLTK and OpenGL for rendering vehicles and associated information and history during operation or simulation. The typical layout shown in Figure 56 is that pMarineViewer is running in its own dedicated local MOOS community while simulated or real vehicles on the water transmit information in the form of a stream of *node reports* to the local community.

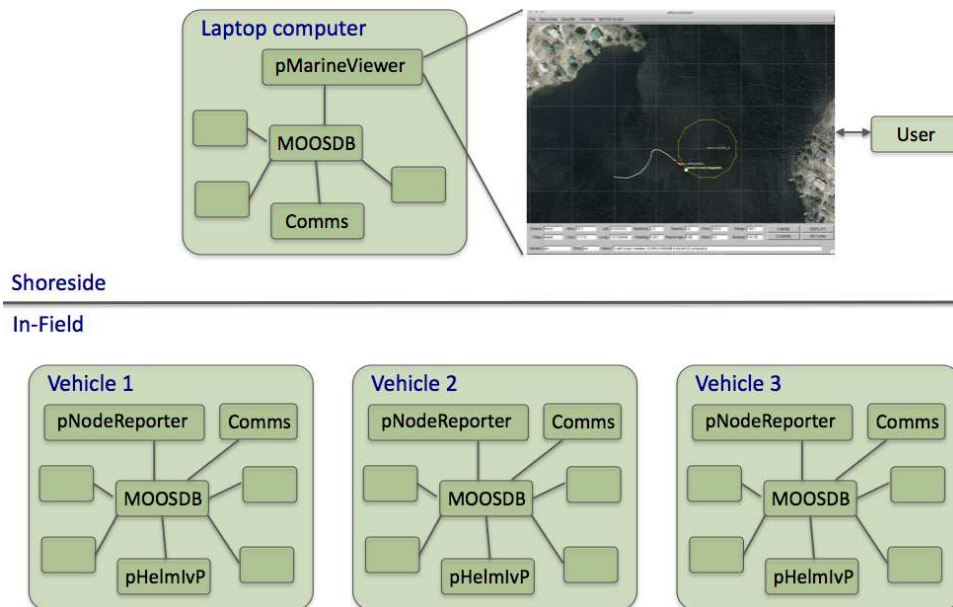


Figure 56: A common usage of the pMarineViewer is to have it running in a local MOOSDB community while receiving node reports on vehicle poise from other MOOS communities running on either real or simulated vehicles. The vehicles can also send messages with certain geometric information such as polygons and points that the view will accept and render.

The user is able to manipulate a geo display to see multiple vehicle tracks and monitor key information about individual vehicles. In the primary interface mode the user is a passive observer, only able to manipulate what it sees and not able to initiate communications to the vehicles. However, there are hooks available and described later in this section to allow the interface to accept field control commands.

A key variable subscribed to by pMarineViewer is the variable `NODE_REPORT`, which has the following structure given by an example:

```
NODE_REPORT = "NAME=nyak201,TYPE=kayak,MOOSDB_TIME=53.049,UTC_TIME=1195844687.236,X=37.49,
              Y=-47.36,SPD=2.40,HDG=11.17,DEPTH=0"
```

Reports from different vehicles are sorted by their vehicle name and stored in histories locally in the pMarineViewer application. The `NODE_REPORT` is generated by the vehicles based on either sensor information, e.g., GPS or compass, or based on a local vehicle simulator.

13.2 Description of the pMarineViewer GUI Interface

The viewable area of the GUI has two parts - a geo display area where vehicles and perhaps other objects are rendered, and a lower area with certain data fields associated with an *active* vehicle are updated. A typical screen shot is shown in Figure 57 with two vehicles rendered - one AUV and one kayak. Vehicle labels and history are rendered. Properties of the vehicle rendering such as the trail length, size, and color, and vehicle size and color, and pan and zoom can be adjusted dynamically in the GUI. They can also be set in the pMarineViewer MOOS configuration block. Both methods of tuning the rendering parameters are described later in this section.

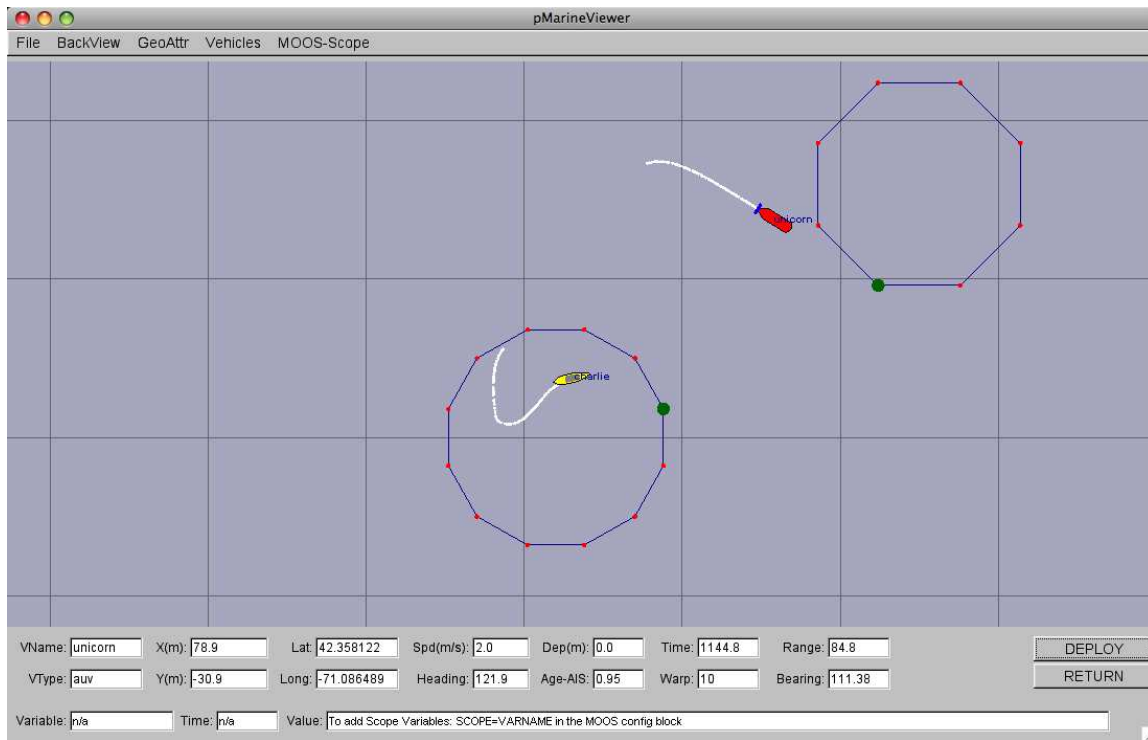


Figure 57: A screen shot of the pMarineViewer application running with two vehicles - one kayak platform, and one AUV platform. The Unicorn AUV platform is the *active* platform meaning the data fields on the bottom reflect the data for this platform.

The lower part of the display is dedicated to displaying detailed position information on a single *active* vehicle. Changing the designation of which vehicle is active can be accomplished by repeatedly hitting the 'v' key. The active vehicle is always rendered as red, while the non-active vehicles have a default color of yellow. Individual vehicle colors can be given different default values (even red, which could be confusing) by the user. The individual fields are described below:

- **VName:** The name of the active vehicle associated with the data in the other GUI data fields. The active vehicle is typically indicated also by changing to the color red on the geo display.
- **VType:** The platform type, e.g., AUV, Glider, Kayak, Ship or Unknown.
- **X(m):** The x (horizontal) position of the active vehicle given in meters in the local coordinate system.
- **Y(m):** The y (vertical) position of the active vehicle given in meters in the local coordinate system.

- **Lat:** The latitude (vertical) position of the active vehicle given in decimal latitude coordinates.
- **Lon:** The longitude (horizontal) position of the active vehicle given in decimal longitude coordinates.
- **Speed:** The speed of the active vehicle given in meters per second.
- **Heading:** The heading of the active vehicle given in degrees (0 – 359.99).
- **Depth:** The depth of the active vehicle given in meters.
- **Report-AGE:** The elapsed time in seconds since the last received node report for the active vehicle.
- **Time:** Time in seconds since the pMarineViewer process launched.
- **Warp:** The MOOS Time-Warp value. Simulations may run faster than real-time by this warp factor. MOOSTimeWarp is set as a global configuration parameter in the `.moos` file.
- **Range:** The range (in meters) of the active vehicle to a reference point. By default, this point is the datum, or the (0,0) point in local coordinates. The reference point may also be set to another particular vehicle. See Section 13.3.7 on the `ReferencePoint` pull-down menu.
- **Bearing:** The bearing (in degrees) of the active vehicle to a reference point. By default, this point is the datum, or the (0,0) point in local coordinates. The reference point may also be set to another particular vehicle. See Section 13.3.7 on the `ReferencePoint` pull-down menu.

In simulation, the age of the node report is likely to remain zero as shown in the figure, but when operating on the water, monitoring the node report age field can be the first indicator when a vehicle has failed or lost communications. Or it can act as an indicator of comms quality.

The lower three fields of the window are used for scoping on a single MOOS variable. See Section 13.3.4 for information on how to configure the pMarineViewer to scope on any number of MOOS variables and select a single variable via an optional pull-down menu. The scope fields are:

- **Variable:** The variable name of the MOOS variable currently being scoped, or "n/a" if no scope variables are configured.
- **Time:** The variable name of the MOOS variable currently being scoped, or "n/a" if no scope variables are configured.

13.3 Pull-Down Menu Options

Properties of the geo display rendering can be tuned to better suit a user or circumstance or for situations where screen shots are intended for use in other media such as papers or PowerPoint. There are two pull-down menus - the first deals with background properties, and the second deals with properties of the objects rendered on the foreground. Many of the adjustable properties can be adjusted by two other means besides the pull-down menus - by the hot keys defined for a particular pull-down menu item, or by configuring the parameter in the MOOS file configuration block.

13.3.1 The “BackView” Pull-Down Menu

Most pull-down menu items have hot keys defined (on the right in the menu). For certain actions like pan and zoom, in practice the typical user quickly adopts the hot-key interface. But the pull-down menu is one way to have a form of hot-key documentation always handy. The zooming commands affect the viewable area and apparent size of the objects. Zoom in with the 'i' or 'I' key, and zoom out with the 'o' or 'O' key. Return to the original zoom with ctrl+'z'.

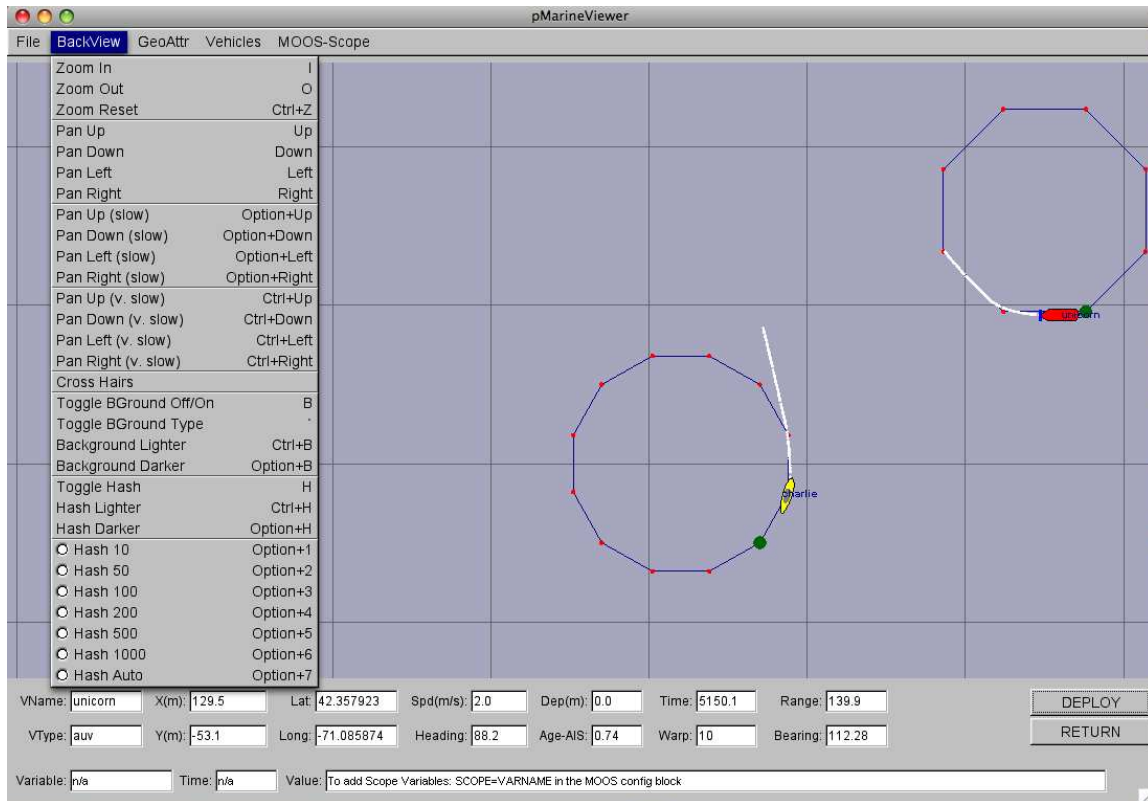


Figure 58: **The BackView menu:** This pull-down menu lists the options, with hot-keys, for affecting rendering aspects of the geo-display background.

Panning is done with the keyboard arrow keys. Three rates of panning are supported. To pan in 20 meter increments, just use the arrow keys. To pan “slowly” in one meter increments, use the Alt + arrow keys. And to pan “very slowly”, in increments of a tenth of a meter, use the Ctrl + arrow keys. The viewer supports two types of “convenience” panning. It will pan put the active vehicle in the center of the screen with the ‘C’ key, and will pan to put the average of all vehicle positions at the center of the screen with the ‘c’ key. These are part of the ‘Vehicles’ pull-down menu discussed in Section 13.3.3.

The background can be in one of two modes; either displaying a gray-scale background, or displaying a geo image read in as a texture into OpenGL from an image file. The default is the geo display mode if provided on start up, or the grey-scale mode if no image is provided. The mode can be toggled by typing the ‘b’ or ‘B’ key. The geo-display mode can have two sub-modes if two image files are provided on start-up. More on this in Section 13.7. This is useful if the user has access to a satellite image *and* a map image for the same operation area. The two can be toggled by hitting the back tick key. When in the grey-scale mode, the background can be made lighter by hitting the ctrl+‘b’ key, and darker by hitting the alt+‘b’ key.

Hash marks can be overlaid onto the background. By default this mode is off, but can be toggled with the ‘h’ or ‘H’ key. The hash marks are drawn in a grey-scale which can be made lighter by typing the ctrl+‘h’ key, and darker by typing the alt+‘h’ key. Certain hash parameters can also be set in the pMarineViewer configuration block of the MOOS file. The hash_view parameter can

be set to either `true` or `false`. The default is `false`. The `hash_delta` parameter can be set to any integer in the range `[10,1000]`. The default is `100`.

13.3.2 The “GeoAttributes” Pull-Down Menu

The GeoAttributes pull-down menu allows the user to edit the properties of geometric objects capable of being rendered by the `pMarineViewer`. In general the Polygon, SegList, Point, and XYGrid objects are received by the viewer at run time to reflect artifacts generated by the IvP Helm indicating aspects of progress during their mission. The polygons in Figure 59 for example represents the set of waypoints being used by the vehicles shown.

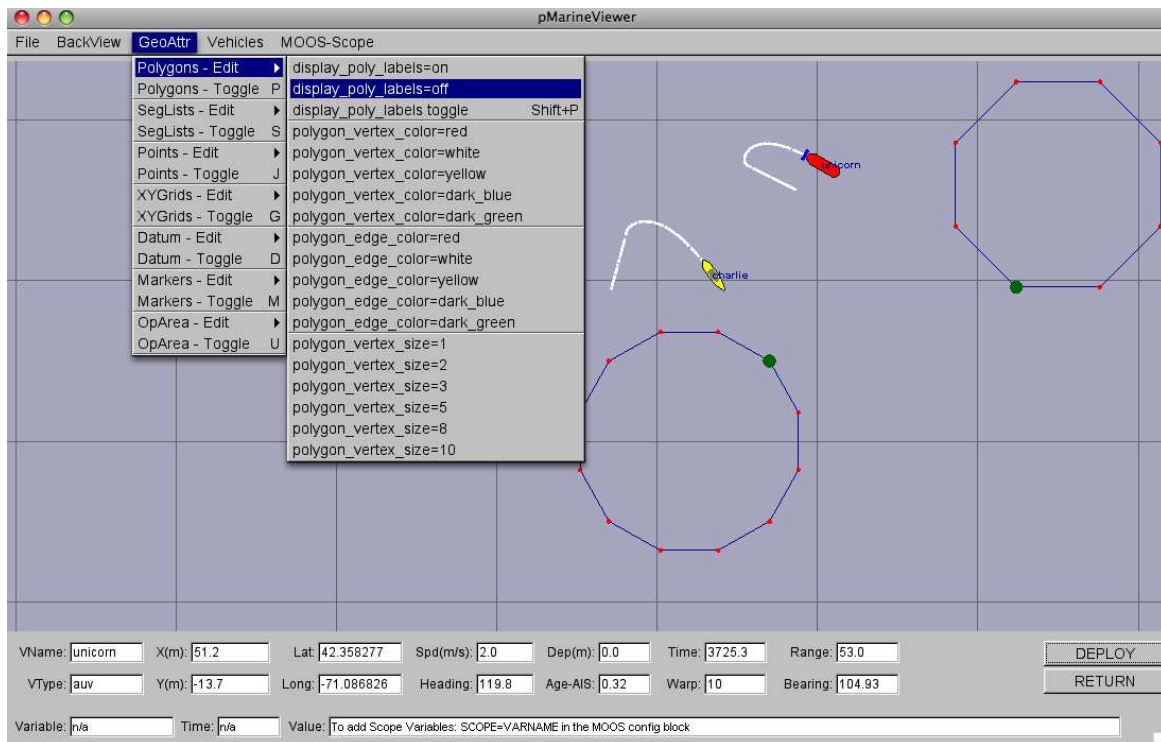


Figure 59: **The GeoAttributes menu:** This pull-down menu lists the options and hot keys for affecting the rendering of geometric objects.

The Datum, Marker and OpArea objects are typically read in once at start-up and reflect persistent info about the operation area. The datum is a single point that represents `(0,0)` in local coordinates. Marker objects typically represent physical objects in the environment such as a buoy, or a fixed sensor. The OpArea objects are typically a combination of points and lines that reflect a region of earth where a set of vehicles are being operated. Each category has a hot key that toggles the rendering of all objects of the same type, and a secondary drop-down menu as shown in the figure that allows the adjustment of certain rendering properties of objects. Many of the items in the menu have form `parameter = value`, and these settings can also be achieved by including this line in the `pMarineViewer` configuration block in the MOOS file.

13.3.3 The “Vehicles” Pull-Down Menu

The *Vehicles* pull-down menu deals with properties of the objects displayed in the geo display foreground. The *Vehicles-Toggle* menu item will toggle the rendering of all vehicles and all trails. The *Cycle Focus* menu item will set the index of the *active* vehicle, i.e., the vehicle who’s attributes are being displayed in the lower output boxes. The assignment of an index to a vehicle depends on the arrival of node reports. If an node report arrives for a previously unknown vehicle, it is assigned a new index.

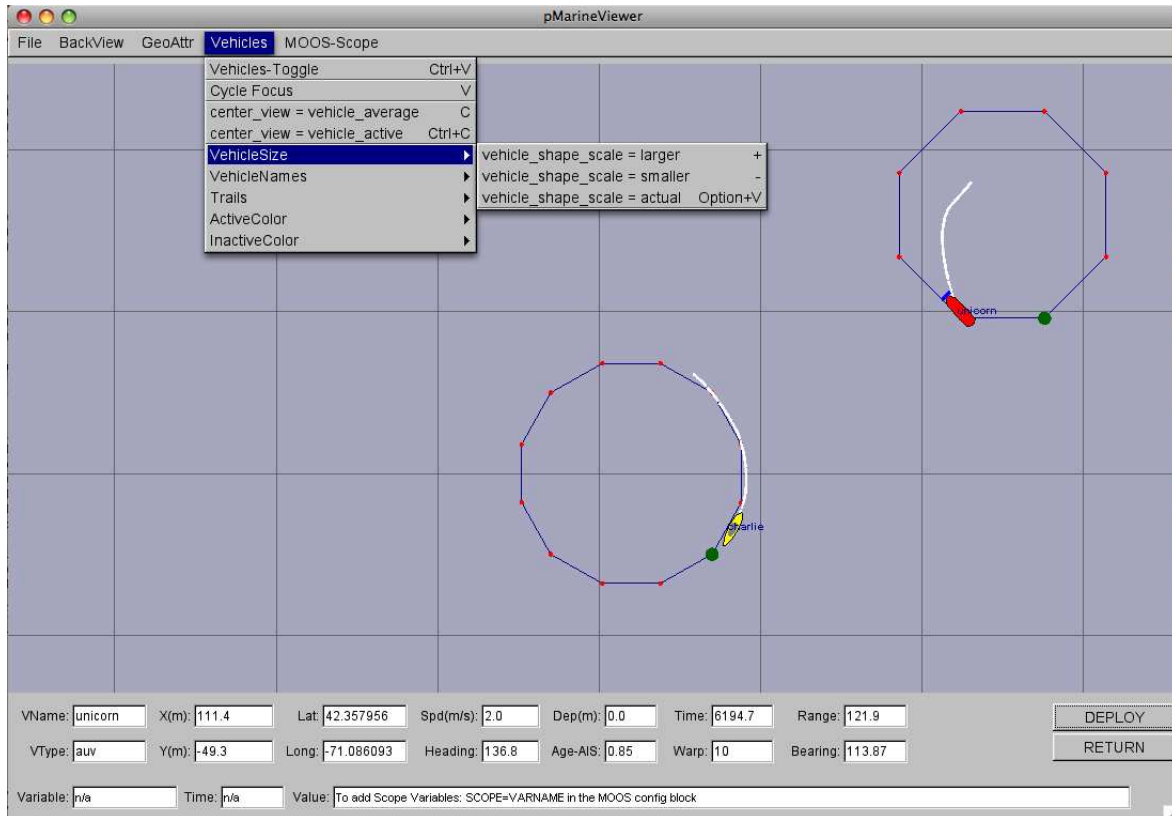


Figure 60: **The ForeView menu:** this pull-down menu of the *pMarineViewer* lists the options, with hot-keys, for affecting rendering aspects of the objects on the geo-display foreground, such as vehicles and vehicle track history.

The *center_view* menu items alters the center of the view screen to be panned to either the position of the active vehicle, or the position representing the average of all vehicle positions. Once the user has selected this, this mode remains *sticky*, that is the viewer will automatically pan as new vehicle information arrives such that the view center remains with the active vehicle or the vehicle average position. As soon as the user pans manually (with the arrow keys), the viewer breaks from trying to update the view position in relation to received vehicle position information. The rendering of the vehicles can be made larger with the '+' key, and smaller with the '-' key, as part of the *VehicleSize* pull-down menu as shown. The size change is applied to all vehicles equally as a scalar multiplier. Currently there is no capability to set the vehicle size individually, or to set the size automatically to scale.

Vehicle trail (track history) rendering can be toggled off and on with the 't' or 'T' key. The default is on. A set of predefined trail colors can be toggled through with the CTRL+'t' key. The individual trail points can be rendered with a line connecting each point, or by just showing the points. When the node report stream is flowing quickly, typically the user doesn't need or want to connect the points. When the viewer is accepting input from an AUV with perhaps a minute or longer delay in between reports, the connecting of points is helpful. This setting can be toggled with the 'y' or 'Y' key, with the default being off. The size of each individual trail point rendering can be made smaller with the '[' key, and larger with the ']' key.

The color of the active vehicle is by default red and can be altered to a handful of other colors in the ActiveColor sub-menu of the Vehicles pull-down menu. Likewise the inactive color, which is by default yellow, can be altered in the InactiveColor sub-menu. These colors can also be altered by setting the `active_vcolor` and `inactive_vcolor` parameters in the `pMarineViewer` configuration block of the MOOS file. They can be set to any color as described in the Colors Appendix.

13.3.4 The “MOOS-Scope” Pull-Down Menu

The “MOOS-Scope” pull-down menu allows the user to configure the `pMarineViewer` to scope on one or more variables in the MOOSDB. The viewer allows visual scoping on only a single variable at a time, but the user can select different variables via the pull-down menu, or toggle between the current and previous variable with the '/' key, or cycle between all registered variables with the CTRL+'/' key. The scope fields are on the bottom of the viewer as shown in Figures 57 - 60. The three fields show (a) the variable name, (b) the last time it was updated, and (c) the current value of the variable. Configuration of the menu is done in the MOOS configuration block with entries of the following form:

```
SCOPE = <variable>, <variable>, ...
```

The keyword `SCOPE` is not case sensitive, but the MOOS variables are. If no entries are provided in the MOOS configuration block, the pull-down menu contains a single item, the "Add Variable" item. By selecting this, the user will be prompted to add a new MOOS variable to the scope list. This variable will then immediately become the actively scoped variable, and is added to the pull-down menu.

13.3.5 The Optional ”Action” Pull-Down Menu

The “Action” pull-down menu allows the user to invoke pre-define pokes to the MOOSDB (the MOOSDB to which the `pMarineViewer` is connected). While hooks for a limited number of pokes are available by configuring on-screen buttons (Section 13.5.2), the number of buttons is limited to four. The “Action” pull-down menu allows for as many entries as will reasonably be shown on the screen. Each action, or poke, is given by a variable-value pair, and an optional grouping key. Configuration is done in the MOOS configuration block with entries of the following form:

```
ACTION = MENU_KEY=<key> # <variable>=<value> # <variable>=<value> # ...
```

If no such entries are provided, this pull-down menu will not appear. The fields to the right of the `ACTION=` are separated by the '#' character for convenience to allow several entries on one line. If one wants to use the '#' character in one of the variable values, putting double-quotes around the

value will suffice to treat the '#' character as part of the value and not the separator. If the pair has the key word `MENU_KEY` on the left, the value on the right is a key associated with all variable-value pairs on the line. When a menu selection is chosen that contains a key, then all variable-value pairs with that key are posted to the MOOSDB. If the `ACTION` key word has a trailing '+' character as below, the pull-down menu will render a line separator after the menu item. The following configuration will result in the pull-down menu depicted in Figure 61.

```
ACTION = MENU_KEY=deploy # DEPLOY = true # RETURN = false
ACTION+ = MENU_KEY=deploy # MOOS_MANUAL_OVERRIDE=false
ACTION = RETURN=true
```

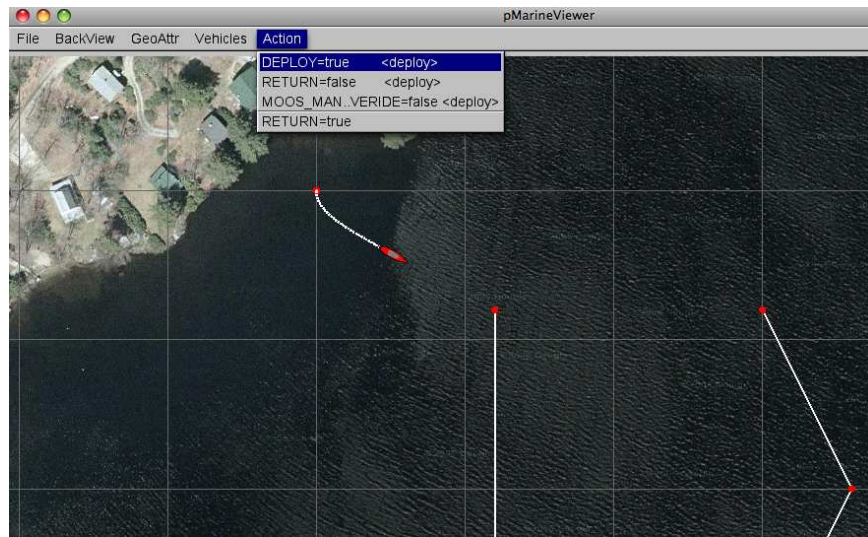


Figure 61: **The Action menu:** The variable value pairs on each menu item may be selected for poking or writing the MOOSDB. The three variable-value pairs above the menu divider will be poked in unison when any of the three are chosen, because they were configured with the same key, `<deploy>`, shown to the right on each item.

The variable-value pair being poked on an action selection will determine the variable type by the following rule of thumb. If the value is non-numerical, e.g., `true`, `one`, it is poked as a string. If it is numerical it is poked as a double value. If one really wants to poke a string of a numerical nature, the addition of quotes around the value will suffice to ensure it will be poked as a string. For example:

```
ACTION = Vehicle=Nomar # ID="7"
```

As with any other publication to the MOOSDB, if a variable has been previously posted with one type, subsequent posts of a different type will be ignored.

13.3.6 The Optional “Mouse-Context” Pull-Down Menu

When the user clicks the left or right mouse in the geo portion of the `pMarineViewer` window, the variables `MVIEWER_LCLICK` and `MVIEWER_RCLICK` are published respectively with the geo location of the mouse click, and the name of the active vehicle. This is described in more detail in Section 13.5.1. In short a publication of the following is typical:

```
MVIEWER_LCLICK = "x=82.0,y=-23.0,lat=43.825090305,lon=-70.32937733,vname=Unicorn"
```

The user may further optionally configure `pMarineViewer` to make additional pokes to the MOOSDB on each left or right mouse click. The user may custom configure the values to allow for the embedding of the operation area position detected under the mouse click. Configuration is done in the MOOS configuration block with entries of the following form:

```
left_context[<key>] = <var-data-pair>
right_context[<key>] = <var-data-pair>
```

The `left_context` and `right_context` keywords are case insensitive. If no such entries are provided, this pull-down menu will not appear. The `<key>` component is optional and allows for groups of variable-data pairs with the same key to be posted together with the same mouse click. If the `<key>` is empty, the defined poke will posted on all mouse clicks regardless of the grouping, as is the case with `MVIEWER_LCLICK` and `MVIEWER_RCLICK`.

Patterns may be embedded in the string to allow the string to contain information on where the user clicked in the operation area. These patterns are: `$(XPOS)` and `$(YPOS)` for the local x and y position respectively, and `$(LAT)`, and `$(LON)` for the latitude and longitude positions. The following configuration will result in the pull-down menu depicted in Figure 62.

```
left_context[surface_point] = SPOINT = x=$(XPOS), y=$(YPOS), vname=$(VNAME)
left_context[surface_point] = COME_TO_SURFACE = true
left_context[return_point] = RETURN_POINT = x=$(XPOS), y=$(YPOS), vname=$(VNAME)
left_context[return_point] = RETURN_HOME = true
right_context[loiter_point] = LOITER_POINT = lat=$(LAT), lon=$(LON)
right_context[loiter_point] = LOITER_MODE = true
```

Note in the figure that the first menu option is "no-action" which shuts off all MOOS pokes associated with any defined groups (keys). In this mode, the `MVIEWER_LCLICK` and `MVIEWER_RCLICK` pokes will still be made, along with any other poke configured without a `<key>`.

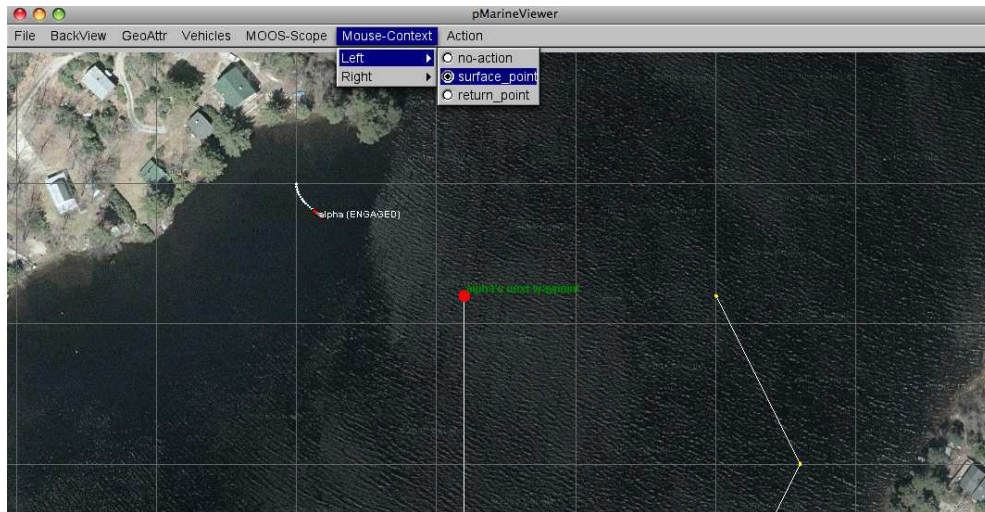


Figure 62: **The Mouse-Context menu:** Keywords selected from this menu will determine which groups of MOOS variables will be poked to the MOOSDB on left or mouse clicks. The variable values may have information embedded indicating the position of the mouse in the operation area at the time of the click.

13.3.7 The Optional “Reference-Point” Pull-Down Menu

The “Reference-Point” pull-down menu allows the user to select a reference point other than the datum, the (0,0) point in local coordinates. The reference point will affect the data displayed in the **Range** and **Bearing** fields in the viewer window. This feature was originally designed for field experiments when vehicles are being operated from a ship. An operator on the ship running the pMarineViewer would receive position reports from the unmanned vehicles as well as the present position of the ship. In these cases, the ship is the most useful point of reference. Prior versions of this code would allow for a single declaration of the ship name, but the current version allows for any number of ship names as a possible reference point. This allows the viewer to display the bearing and range between two deployed unmanned vehicles for example. Configuration is done in the MOOS configuration block with entries of the following form:

```
reference_vehicle = vehicle
```

If no such entries are provided, this pull-down menu will not appear. When the menu is present, it looks like that shown in Figure 63. When the reference point is a vehicle with a known heading, the user is able to alter the **Bearing** field from reporting either the relative bearing or absolute bearing. Hot keys are defined for each.

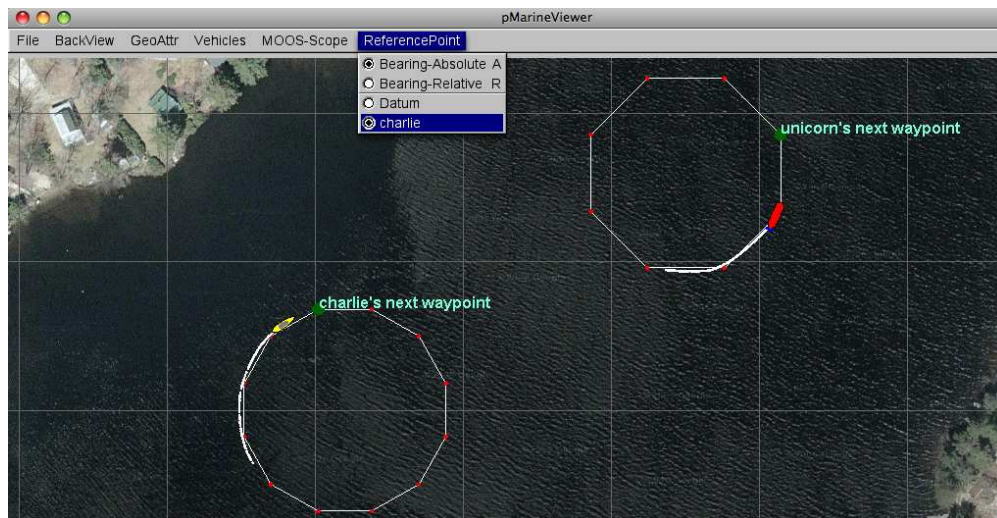


Figure 63: **The Reference-Point menu:** This pull-down menu of the pMarineViewer lists the options for selecting a reference point. The reference point determines the values for the **Range** and **Bearing** fields in the viewer for the active vehicle. When the reference point is a vehicle with known heading, the user also may select whether the **Bearing** is the relative bearing or absolute bearing.

13.4 Displayable Vehicle Shapes, Markers, Drop Points, and other Geometric Objects

The pMarineViewer window displays objects in three general categories, (1) the vehicles based on their position reports, (2) markers, which are generally static and things like triangles and squares

with labels, and (3) geometric objects such as polygons or lists of line segments that may indicate a vehicle's intended path or other such artifact of its autonomy situation.

13.4.1 Displayable Vehicle Shapes

The shape rendered for a particular vehicle depends on the *type* of vehicle indicated in the node report received in pMarineViewer. There are four types that are currently handled, an AUV shape, a glider shape, a kayak shape, and a ship shape, shown in Figure 64.

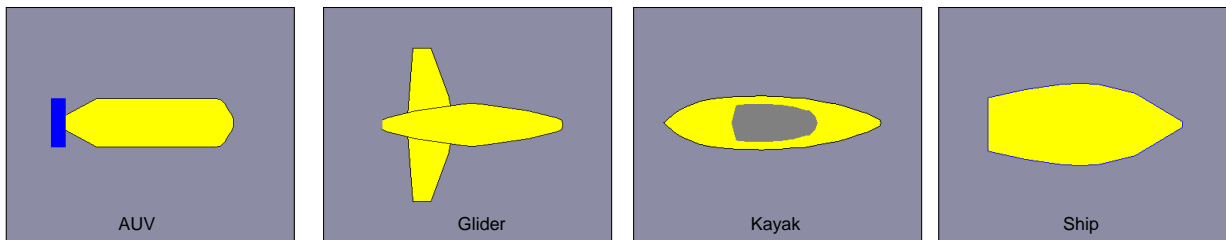


Figure 64: **Vehicles:** Types of vehicle shapes known to the pMarineViewer.

The default shape for an unknown vehicle type is currently set to be the shape “ship”. The default color for a vehicle is set to be yellow, but can be individually set within the pMarineViewer MOOS configuration block with entries like the following:

```
vehicolor = alpha, turquoise  
vehicolor = charlie, navy,  
vehicolor = philly, 0.5, 0.9, 1.0
```

The parameter `vehicolor` is case insensitive, as is the color name. The vehicle name however is case sensitive. All colors of the form described in the Colors Appendix are acceptable.

Mini Exercise #2: Poking a Vehicle into the Viewer.

Issues Explored: (1) Posting a MOOS message resulting in a vehicle rendered in pMarineViewer. (2) Erasing and moving the vehicle.

- Try running the Alpha mission again from the Helm documentation. Note that when the simulation is first launched, a kayak-shaped vehicle sits at position (0,0).
- Use the pMarineViewer MOOS-Scope utility to scope on the variable `NODE_REPORT_LOCAL`. Either select "Add Variable" from the MOOS-Scope pull-down menu, or type the short-cut key 'a'. Type the `NODE_REPORT_LOCAL` variable into the pop-up window, and hit Enter. The scope field at the bottom of pMarineViewer should read something like:

```
NODE_REPORT_LOCAL = "NAME=alpha,TYPE=KAYAK,MOOSDB.TIME=2327.07,UTC.TIME=10229133704.48,
X=0.00,Y=0.00,LAT=43.825300,LON=-70.330400,SPD=0.00,HDG=180.00,YAW=180.00000,DEPTH=0.00,
LENGTH=4.0,MODE=DISENGAGED,ALLSTOP=ManualOverride
```

This is the posting that resulted in the vehicle currently rendered in the pMarineViewer window. This was likely posted by the `pNodeReporter` application, but a node report can be poked directly as well to experiment.

- Using the `uPokeDB` tool, try poking the MOOSDB as follows:

```
$ uPokeDB alpha.moos NODE_REPORT="NAME=bravo,TYPE=glider,X=100,Y=-90,HDG=88,SPD=1.0,
UTC.TIME=NOW,DEPTH=92,LENGTH=8"
```

Note the appearance of the glider at position (100,-90).

13.4.2 Displayable Marker Shapes

A set of simple static markers can be placed on the geo display for rendering characteristics of an operation area such as buoys, fixed sensors, hazards, or other things meaningful to a user. The six types of markers are shown in Figure 65. They are configured in the pMarineViewer configuration block of the MOOS file with the following format:

```
// Example marker entries in a pMarineViewer config block of a .moos file
// Parameters are case insensitive. Parameter values (except type and color)
// are case sensitive.
marker = type=efield,x=100,y=20,label=alpha,COLOR=red,width=4.5
marker = type=square,lat=42.358,lon=-71.0874,color=blue,width=8
```

Each entry is a string of comma-separated pairs. The order is not significant. The only mandatory fields are for the marker type and position. The position can be given in local x-y coordinates or in earth coordinates. If both are given for some reason, the earth coordinates will take precedent. The width parameter is given in meters drawn to scale on the geo display. Shapes are roughly 10x10 meters by default. The GUI provides a hook to scale all markers globally with the 'ALT-M' and 'CTRL-M' hot keys and in the GeoAttributes pull-down menu.

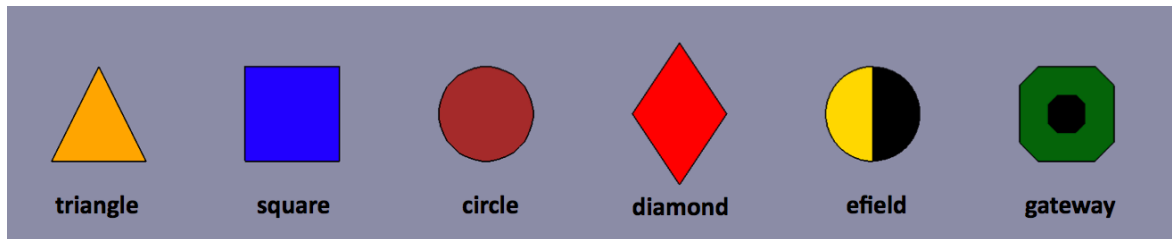


Figure 65: **Markers:** Types of markers known to the pMarineViewer.

The color parameter is optional and markers have the default colors shown in Figure 65. Any of the colors described in the Colors Appendix are fair game. The black part of the Gateway and Efield markers is immutable. The label field is optional and is by default the empty string. Note that if two markers of the same type have the same non-empty label, only the first marker will be acknowledged and rendered. Two markers of different types can have the same label.

In addition to declaring markers in the pMarineViewer configuration block, markers can be received dynamically by pMarineViewer through the VIEW_MARKER MOOS variable, and thus can originate from any other process connected to the MOOSDB. The syntax is exactly the same, thus the above two markers could be dynamically received as:

```
VIEW_MARKER = "type=efield,x=100,y=20,SCALE=4.3,label=alpha,COLOR=red,width=4.5"
VIEW_MARKER = "type=square,lat=42.358,lon=-71.0874,scale=2,color=blue,width=8"
```

The effect of a “moving” marker, or a marker that changes color, can be achieved by repeatedly publishing to the VIEW_MARKER variable with only the position or color changing while leaving the label and type the same.

13.4.3 Displayable Drop Points

A user may be interested in determining the coordinates of a point in the geo portion of the pMarineViewer window. The mouse may be moved over the window and when holding the SHIFT key, the point under the mouse will indicate the coordinates in the local grid. When holding the CTRL key, the point under the coordinates are shown in lat/lon coordinates. The coordinates are updated as the mouse moves and disappear thereafter or when the SHIFT or CTRL keys are release. Drop points may be left on the screen by hitting the left mouse button at any time. The point with coordinates will remain rendered until cleared or toggled off. Each click leaves a new point, as shown in Figure 66.

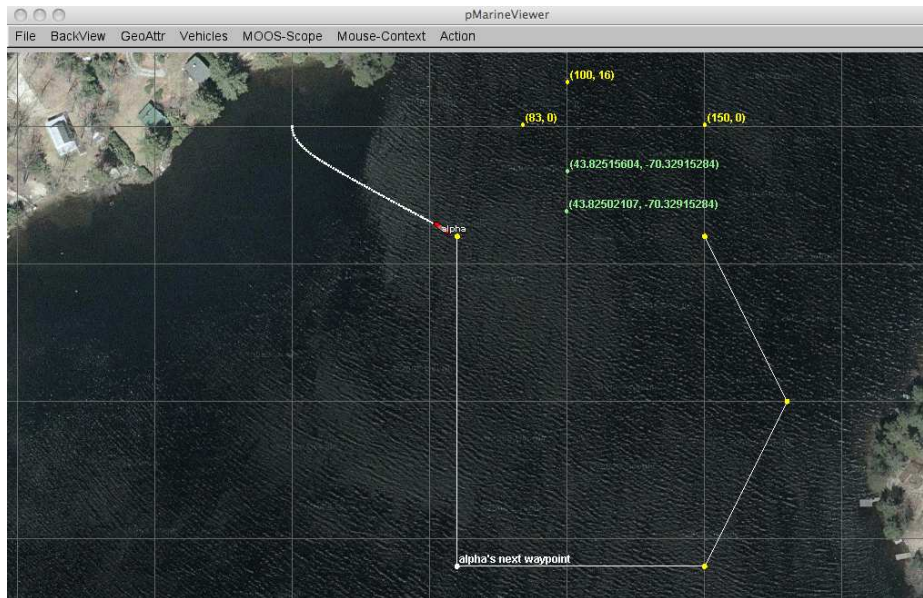


Figure 66: **Drop points:** A user may leave drop points with coordinates on the geo portion of the pMarineViewer window. The points may be rendered in local coordinates or in lat/lon coordinates. The points are added by clicking the left mouse button while holding the **SHIFT** key or **CTRL** key. The rendering of points may be toggled on/off, cleared in their entirety, or reduced by popping the last dropped point.

Parameters regarding drop points are accessible from the **GeoAttr** pull-down menu. The rendering of drop points may be toggled on/off by hitting the 'r' key. The set of drop points may be cleared in its entirety. Or the most recently dropped point may be removed by typing the **CTRL-r** key. The pull-down menu may also be used to change the rendering of coordinates from "as-dropped" where some points are in local coordinates and others in lat/lon coordinates, to "local-grid" where all coordinates are rendered in the local grid, or "lat-lon" where all coordinates are rendered in the lat/lon format.

13.4.4 Displayable Geometric Objects

Some additional objects can be rendered in the viewer such as convex polygons, points, and a set of line segments. In Figures 57 and 58, each vehicle has traversed to and is proceeding around a hexagon pattern. This is apparent from both the rendered hexagon, and confirmed by the trail points. Displaying certain markers in the display can be invaluable in practice to debugging and confirming the autonomy results of vehicles in operation. The intention is to allow for only a few key additional objects to be drawable to avoid letting the viewer become overly specialized and bloated.

In addition to the **NODE_REPORT** variable indicating vehicle pose, pMarineViewer registers for the following additional **MOOS** variables - **VIEW_POLYGON**, **VIEW_SEGLIST**, **VIEW_POINT**. Example values of these variables:

```
VIEW_POLYGON = "label,nyak201-LOITER:85,-9:100,-35:85,-61:55,-61:40,-35:55,-9"
VIEW_POINT   = 10.00,-80.00,5,nyak200
VIEW_SEGLIST = "label,nyak201-WAYPOINT:0,100:50,-35:25,-63"
```

Each variable describes a data structure implemented in the geometry library linked to by `pMarineViewer`. Instances of these objects are initialized directly by the strings shown above. A key member variable of each geometric object is the *label* since `pMarineViewer` maintains a (C++, STL) map for each object type, keyed on the label. Thus a newly received polygon replaces an existing polygon with the same label. This allows one source to post its own geometric cues without clashing with another source. By posting empty objects, i.e., a polygon or seglist with zero points, or a point with zero radius, the object is effectively erased from the geo display. The typical intended use is to let a behavior within the helm to post its own cues by setting the label to something unique to the behavior. The `VIEW_POLYGON` listed above for example was produced by a loiter behavior and describes a hexagon with the six points that follow.

13.5 Support for Command-and-Control Usage

For the most part `pMarineViewer` is intended to be only a receiver of information from the vehicles and the environment. Adding command and control capability, e.g., widgets to re-deploy or manipulate vehicle missions, can be readily done, but make the tool more specialized, bloated and less relevant to a general set of users. A certain degree of command and control can be accomplished by poking key variables and values into the local `MOOSDB`, and this section describes three methods supported by `pMarineViewer` for doing just that.

13.5.1 Poking the MOOSDB with Geo Positions

The graphic interface of `pMarineViewer` provides an opportunity to poke information to the `MOOSDB` based on visual feedback of the operation area shown in the geo display. To exploit this, two command and control hooks were implemented with a small footprint. When the user clicks on the geo display, the location in local coordinates is noted and written out to one of two variables - `MVIEWER_LCLICK` for left mouse clicks, and `MVIEWER_RCLICK` for right mouse clicks, with the following syntax:

```
MVIEWER_LCLICK = "x=958.0,y=113.0,vname=nyak200",
```

and

```
MVIEWER_RCLICK = "x=740.0,y=-643.0,vname=nyak200".
```

One can then write another specialized process, e.g., `pViewerRelay`, that subscribes to these two variables and takes whatever command and control actions desired for the user's needs. One such incarnation of `pViewerRelay` was written (but not distributed or addressed here) that interpreted the left mouse click to have the vehicle station-keep at the clicked location.

13.5.2 Configuring GUI Buttons for Command and Control

The `pMarineViewer` GUI can be optionally configured to allow for four push-buttons to be enabled and rendered in the lower-right corner. Each button can be associated with a button label, and a list of variable-value pairs that will be poked to the `MOOSDB` to which the `pMarineViewer` process is connected. The basic syntax is as follows:


```

BUTTON_ONE   = <label> # <variable>=VALUE # <variable>=<value> ...
BUTTON_TWO   = <label> # <variable>=VALUE # <variable>=<value> ...
BUTTON_THREE = <label> # <variable>=VALUE # <variable>=<value> ...
BUTTON_FOUR  = <label> # <variable>=VALUE # <variable>=<value> ...

```

The left-hand side contains one of the four button keywords, e.g., `BUTTON_ONE`. The right-hand side consists of a '#'-separated list. Each component in this list is either a '='-separated variable-value pair, or otherwise it is interpreted as the button's label. The ordering does not matter and the '#'-separated list can be continued over multiple lines as in lines 59-60 in Listing 32 on page 202.

The variable-value pair being poked on a button call will determine the variable type by the following rule of thumb. If the value is non-numerical, e.g., `true`, `one`, it is poked as a string. If it is numerical it is poked as a double value. If one really wants to poke a string of a numerical nature, the addition of quotes around the value will suffice to ensure it will be poked as a string. For example:

```

BUTTON_ONE   = Start # Vehicle=Nomar # ID="7"

```

In this case, clicking the button labeled "Start" will result in two pokes, the second of which will have a string value of "7", not a numerical value. As with any poke to the MOOSDB of a given variable-value pair, if the value is of a type inconsistent with the first write to the DB under that variable name, it will simply be ignored.

As described in Section 13.3.5, additional variable-value pairs for poking the MOOSDB can be configured in the "Action" pull-down menu. Unlike the use of buttons, which is limited to four, the number of actions in the pull-down menu is limited only by what can reasonably be rendered on the user's screen.

13.6 Configuration Parameters for pMarineViewer

Many of the display settings available in the pull-down menus described in Sections 13.3 can also be set in the `pMarineViewer` block of the MOOS configuration file. Mostly this redundancy is for convenience for a user to have the desired settings without further keystrokes after start-up. An example configuration block is shown in Listing 32.

Parameter	Description	Allowed Values	Default
<code>hash_view</code>	Turning off or on the hash marks.	<code>true, false</code>	<code>true</code>
<code>hash_delta</code>	Distance between hash marks	[10, 1000]	50
<code>hash_shade</code>	Shade of hash marks - 0 is black to 1 is white	[0, 1.0]	0.65
<code>back_shade</code>	Shade of hash marks - 0 is black to 1 is white	[0, 1.0]	0.55
<code>tiff_view</code>	Background image used if set to true	<code>true, false</code>	<code>true</code>
<code>tiff_type</code>	Uses the first (A) image if set to true	<code>true, false</code>	<code>true</code>
<code>tiff_file</code>	Filename of a tiff file background image	any tiff file	<code>Default.tif</code>
<code>tiff_file.b</code>	Filename of a tiff file background image	any tiff file	<code>DefaultB.tif</code>
<code>view_center</code>	The center of the viewing image (the zoom-to point)	(x, y)	(0, 0)

Table 24: **Background parameters:** Parameters affecting the rendering of the `pMarineViewer` background.

Parameter	Description	Allowed Values	Default
bearing_lines_viewable	Render bearing line objects	true, false	true
trails_color	Color of points rendered in a trail history	any color	white
trails_connect_viewable	Render lines between dots if true	true, false	false
trails_history_size	Number of points stored in a trail history	[0, 10,000]	1,000
trails_length	Number of points rendered in a trail history	[0, 10,000]	100
trails_point_size	Size of dots rendered in a trail history	[0, 100]	1
trails_viewable	Trail histories note rendered if false	true, false	true
vehicles_active_color	Color of the one active vehicle	any color	red
vehicles_inactive_color	Color of other inactive vehicles	any color	yellow
vehicles_name_active	Active vehicle set to the named vehicle	known name	1st
vehicles_name_center	Center vehicle set to the named vehicle	known name	n/a
vehicles_name_color	Color of the font for all vehicle labels	any color	white
vehicles_name_viewable	Vehicle labels not rendered if set to off	off, names, names+mode, names+shortmode, names+depth	names
vehicles_shape_scale	Change size rendering - 1.0 is actual size	[0.1, 100]	1
vehicles_viewable	Vehicles not rendered is set to false	true, false	false
vehicolor	Override inactive vehicle color individually	See p.x	n/a

Table 25: **Vehicle parameters:** Parameters affecting how vehicles are rendered in pMarineViewer.

Parameter	Description	Allowed Values	Default
marker	Add and newly defined marker	See p. 196	n/a
markers_viewable	If true all markers are rendered	true, false	true
markers_labels_viewable	If true marker labels are rendered	true, false	true
markers_scale_global	Marker widths are multiplied by this factor	[0.1, 100]	1
markers_label_color	Color of rendered marker labels	any color	white

Table 26: **Marker parameters:** Parameters affecting the rendering of the pMarineViewer markers.

Parameter	Description	Allowed Values	Default
circle_edge_color	Color rendered circle lines	any color	yellow
circle_edge_width	Line width of rendered circle lines	[0, 10]	2
grid_edge_color	Color of rendered grid lines	any color	white
grid_edge_width	Line width of rendered grid lines	[0, 10]	2
grid_viewable_all	If true grids will be rendered	true, false	true
grid_viewable_labels	If true grid labels will be rendered	true, false	true
point_viewable_all	If true points will be rendered	true, false	true
point_viewable_labels	If true point labels will be rendered	true, false	true
point_vertex_color	Color of rendered points	any color	yellow
point_vertex_size	Size of rendered points	[0, 10]	4
polygon_edge_color	Color of rendered polygon lines	any color	yellow
polygon_edge_width	Line width of rendered polygon edges	[0, 10]	1
polygon_label_color	Color rendered polygon labels	any color	khaki
polygon_viewable_all	If true all polygons are rendered	true, false	true
polygon_viewable_labels	If true polygon labels are rendered	true, false	true
polygon_vertex_color	Color of rendered polygon vertices	any color	red
polygon_vertex_size	Size of rendered polygon vertices	[0, 10]	3
seglis_edge_color	Color or rendered seglist lines	any color	white
seglis_edge_width	Line width of rendered seglist edges	[0,10	1
seglis_label_color	Color of rendered seglist labels	any color	orange
seglis_viewable_all	If true all seglists are rendered	true, false	true
seglis_viewable_labels	If true seglist labels are rendered	true, false	true
seglis_vertex_color	Color of rendered seglist vertices	any color	blue
seglis_vertex_size	Size of rendered seglist vertices	[0, 10]	3

Table 27: **Geometric parameters:** Parameters affecting the rendering of the pMarineViewer geometric objects.

Listing 32 - An example pMarineViewer configuration block.

```

1 LatOrigin = 47.7319
2 LongOrigin = -122.8500
3
4 //-----
5 // pMarineViewer configuration block
6
7 ProcessConfig = pMarineViewer
8 {
9     // Standard MOOS parameters affecting comms and execution
10    AppTick = 4
11    CommsTick = 4
12
13    // Set the background images
14    TIFF_FILE = long_beach_sat.tif
14    TIFF_FILE_B = long_beach_map.tif
15
16
17    // Parameters and their default values
18    hash_view = false
19    hash_delta = 50
20    hash_shade = 0.65
21    back_shade = 0.70

```

```
22  trail_view    = true
23  trail_size   = 0.1
24  tiff_view    = true
25  tiff_type    = true
26  zoom        = 1.0
27  verbose     = true
28  vehicles_name_viewable = false
29  bearing_lines_viewable = true
30
31  // Setting the vehicle colors - default is yellow
32  vehicolor    = henry,dark_blue
33  vehicolor    = ike,0.0,0.0,0.545
34  vehicolor    = jane,hex:00,00,8b
35
36  // All polygon parameters are optional - defaults are shown
37  // They can also be set dynamically in the GUI in the GeoAttrs pull-down menu
38  polygon_edge_color = yellow
39  polygon_vertex_color = red
40  polygon_label_color = khaki
41  polygon_edge_width = 1.0
42  polygon_vertex_size = 3.0
43  polygon_viewable_all = true;
44  polygon_viewable_labels = true;
45
46  // All seglist parameters are optional - defaults are shown
47  // They can also be set dynamically in the GUI in the GeoAttrs pull-down menu
48  seglist_edge_color = white
49  seglist_vertex_color = dark_blue
50  seglist_label_color = orange
51  seglist_edge_width = 1.0
52  seglist_vertex_size = 3.0
53  seglist_viewable_all = true;
54  seglist_viewable_labels = true;
55
56  // All point parameters are optional - defaults are shown
57  // They can also be set dynamically in the GUI in the GeoAttrs pull-down menu
58  point_vertex_size = 4.0;
59  point_vertex_color = yellow
60  point_viewable_all = true;
61  point_viewable_labels = true;
62
63  // Define two on-screen buttons with poke values
64  button_one = DEPLOY # DEPLOY=true
65  button_two = MOOS_MANUAL_OVERRIDE=false # RETURN=false
66  button_two = RETURN # RETURN=true
67  button_three = DEPTH-10 # OPERATION_DEPTH=10
68  button_four = DEPTH-30 # OPERATION_DEPTH=30
69
70  // Declare variable for scoping. Variable names case sensitive
71  scope = PROC_WATCH_SUMMARY
72  scope = BHV_WARNING
73  scope = BHV_ERROR
74
75  // Declare Variable-Value pairs for convenient poking of the MOOSDB
76  action = OPERATION_DEPTH=50
```

```

77  action = OPERATION_DEPTH=0 # STATUS="Coming To the Surface"
78  }

```

Color references as in lines 31-33 can be made by name or by hexadecimal or decimal notation. (All three colors in lines 31-33 are the same but just specified differently.) See the Colors Appendix for a list of available color names and their hexadecimal equivalent.

The `VERBOSE` parameter on line 27 controls the output to the console. The console output lists the types of mail received on each iteration of `pMarineViewer`. In the non-verbose mode, a single character is output for each received mail message, with a '*' for `NODE_REPORT`, a 'P' for a `VIEW_POLYGON`, a '.' for a `VIEW_POINT`, and a 'S' for a `VIEW_SEGLIST`. In the verbose mode, each received piece of mail is listed on a separate line and the source of the mail is also indicated. An example of both modes is shown in Listing 33.

Listing 33 - An example pMarineViewer console output.

```

1  // Example pMarineViewer console output NOT in verbose mode
2
3  13.56 > ****..
4  13.82 > ***.
5  14.08 > **..
6  14.35 > **..
7  14.61 > ****.P.P
8  14.88 > ***.
9  15.14 > ***.
10
11 // Example pMarineViewer console output in verbose mode
12
13 15.42 >
14  NODE-REPORT(nyak201)
15  NODE-REPORT(nyak200)
16  Point(nyak201_wpt)
17  Point(nyak200_wpt)
18
19 15.59 >
20  Point(nyak201)
21  Poly(nyak201-LOITER)
22  NODE-REPORT(nyak201)
23  NODE-REPORT(nyak200)
24  Point(nyak200)
25  Poly(nyak200-LOITER)

```

13.7 More about Geo Display Background Images

The geo display portion of the viewer can operate in one of two modes, a grey-scale background, or an image background. Section 13.3.1 addressed how to switch between modes in the GUI interface. To use an image in the geo display, the input to `pMarineViewer` comes in two files, an image file in TIFF format, and an information text file correlating the image to the local coordinate system. The file names should be identical except for the suffix. For example `dabob_bay.tif` and `dabob_bay.info`. Only the `.tif` file is specified in the `pMarineViewer` configuration block of the MOOS file, and the application then looks for the corresponding `.info` file. The info file contains six lines - an example is given in Listing 34.

The geo display portion of the viewer can operate in one of two modes, a grey-scale background, or an image background. Section 13.3.1 addressed how to switch between modes in the GUI interface. To use an image in the geo display, the input to `pMarineViewer` comes in two files. The first is an image file in TIFF format. This file is read by the `lib.tiff` library linked to `pMarineViewer` and, as of this writing, this library requires the image to be square, and the number of pixels in each dimension to be a power of two. The jpeg image patches served from Google Maps for example all this property.

The second file is an information text file correlating the image to the local coordinate system. The file names should be identical except for the suffix. For example `dabob_bay.tif` and `dabob_bay.info`. Only the `.tif` file is specified in the `pMarineViewer` configuration block of the MOOS file, and the application then looks for the corresponding `.info` file. The info file contains six lines - an example is given in Listing 34.

Listing 34 - An example .info file for the pMarineViewer

```
1 // Lines may be in any order, blank lines are ok
2 // Comments begin with double slashes
3
4 datum_lat = 47.731900
5 datum_lon = -122.85000
6 lat_north = 47.768868
7 lat_south = 47.709761
8 lon_west = -122.882080
9 lon_east = -122.794189
```

All four latitude/longitude parameters are mandatory. The two datum lines indicate where (0,0) in local coordinates is in earth coordinates. However, the datum used by `pMarineViewer` is determined by the `LatOrigin` and `LongOrigin` parameters set globally in the MOOS configuration file. The datum lines in the above information file are used by applications other than `pMarineViewer` that are not configured from a MOOS configuration file. The `lat_north` parameters correlates the upper edge of the image with its latitude position. Likewise for the other three parameters and boundaries. Two image files may be specified in the `pMarineViewer` configuration block. This allows a map-like image and a satellite-like image to be used interchangeably during use. (Recall the `ToggleBackGroundType` entry in the `BackView` pull-down menu discussed earlier.) An example of this is shown in Figure 67 with two images of Dabob Bay in Washington State. Both image files were created from resources at www.maps.google.com.

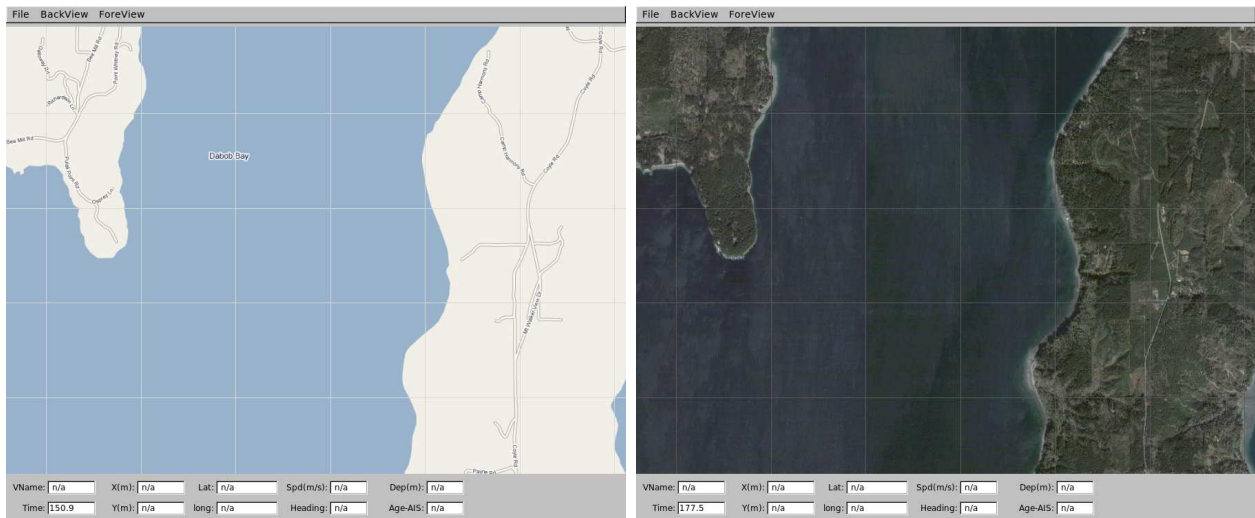


Figure 67: **Dual background geo images:** Two images loaded for use in the geo display mode of pMarineViewer. The user can toggle between both as desired during operation.

In the configuration block, the images can be specified by:

```
TIFF_FILE   = dabob_bay_map.tif
TIFF_FILE_B = dabob_bay_sat.tif
```

By default pMarineViewer will look for the files `Default.tif` and `DefaultB.tif` in the local directory unless alternatives are provided in the configuration block.

13.8 Publications and Subscriptions for pMarineViewer

13.8.1 Variables published by the pMarineViewer application

Variables published by pMarineViewer are summarized in Table 28 below. A more detail description of each variable follows the table.

#	Variable	Description
1	MVIEWER_LCLICK	The position in local coordinates of a user left mouse button click
2	MVIEWER_RCLICK	The position in local coordinates of a user right mouse button click
3	HELM_MAP_CLEAR	A message read by pHelmIvP to re-send information on viewer startup.

Table 28: **Variables published by the pMarineViewer application.**

Note that pMarineViewer may be configured to poke the MOOSDB via either the Action pull-down menu (Section 13.3.5), or via configurable GUI buttons (Section 13.5.2). It may also publish to the MOOSDB variables configured to mouse clicks (Section 13.3.6). So the list of variables that pMarineViewer publishes is somewhat user dependent, but the following few variables may be published in all configurations.

- **MVIEWER_LCLICK:** When the user clicks the left mouse button, the position in local coordinates, along with the name of the active vehicle is reported. This can be used as a command and control hook as described in Section 13.5. As an example:

```
MVIEWER_LCLICK = 'x=-56.0,y=-110.0,vname=alpha'
```

- **MVIEWER_RCLICK:** This variable is published when the user clicks with the right mouse button. The same information is published as with the left click.
- **HELM_MAP_CLEAR:** This variable is published once when the viewer connects to the MOOSDB. It is used in the pHelmIvP application to clear a local buffer used to prevent successive identical publications to its variables.

13.8.2 Variables subscribed for by pMarineViewer application

- **BEARING_LINE:** A string designation of a bearing from a given vehicle in a given direction. An example:

```
BEARING_LINE = "vname=alpha, bearing=174, range=90, vector_width=1, vector_color=green,
time_limit=15"
```

OR

```
BEARING_LINE = "vname=alpha, bearing=174, range=90, vector_width=1, vector_color=green,
time_limit=nolimit, bearing_absolute=true"
```

- **NODE_REPORT:** This is the primary variable consumed by pMarineViewer for collecting vehicle position information. An example:

```
NODE_REPORT = "NAME=nyak201,TYPE=kayak,MOOSDB_TIME=53.049,UTC_TIME=1195844687.236,X=37.49,
Y=-47.36, SPD=2.40,HDG=11.17,DEPTH=0"
```

- **NODE_REPORT_LOCAL:** This serves the same purpose as the above variable. In some simulation cases this variable is used.
- **TRAIL_RESET:** When the viewer receives this variable it will clear the history of trail points associated with each vehicle. This is used when the viewer is run with a simulator and the vehicle position is reset and the trails become discontinuous.
- **VIEW_POLYGON:** A string representation of a polygon.
- **VIEW_POINT:** A string representation of a point.
- **VIEW_SEGLIST:** A string representation of a segment list.
- **VIEW_CIRCLE:** A string representation of a circle.
- **VIEW_MARKER:** A string designation of a marker type, size and location.

14 The uTimerScript Utility: Scripting Events to the MOOSDB

The `uTimerScript` application allows the user to script a set of pre-configured pokes to a MOOSDB with each entry in the script happening after a specified amount of elapsed time. The execution of the script may be paused, or fast-forwarded a given amount of time, or forwarded to the next event on the script by writing to a MOOS variable from which `uTimerScript` accepts such cues. Event timestamps may be given as an exact point in time relative to the start of the script, or a range in times with the exact time determined randomly at run-time. The variable value of an event may also contain information generated randomly. The script may also be reset or repeated any given number of times. In short, the `uTimerScript` application may be used to effectively simulate the output of other MOOS applications when those applications are not available. We give a few examples, including a simulated GPS unit and a crude simulation of wind gusts.

14.1 Overview of the uTimerScript Interface and Configuration Options

The `uTimerScript` application may be configured with a configuration block within a `.moos` file, and from the command line. Its interface is defined by its publications and subscriptions for MOOS variables consumed and generated by other MOOS applications. An overview of the set of configuration options and interface is provided in this section.

14.1.1 Brief Summary of the uTimerScript Configuration Parameters

The following parameters are defined for `uTimerScript`. A more detailed description is provided in other parts of this section. Parameters having default values indicate so in parentheses below.

CONDITION:	A logic condition that must be met for the script to be un-paused.
DELAY_RESET:	Number of seconds added to each event time, <i>on each script pass</i> (0).
DELAY_START:	Number of seconds added to each event time, <i>on first pass only</i> (0).
EVENT:	A description of a single event in the timer script.
FORWARD_VAR:	A MOOS variable for taking cues to forward time (<code>UTS_FORWARD</code>).
PAUSED:	A Boolean indicating whether the script is paused upon launch (<code>false</code>).
PAUSE_VAR:	A MOOS variable for receiving pause state cues (<code>UTS_PAUSE</code>).
RAND_VAR:	A declaration of a random variable macro to be expanded in event values.
RESET_MAX:	The maximum amount of resets allowed (<code>"any"</code>).
RESET_TIME:	The time or condition when the script is reset (<code>"none"</code>).
RESET_VAR:	A MOOS variable for receiving reset cues (<code>UTS_RESET</code>).
SCRIPT_NAME:	Unique (hopefully) name given to this script (<code>"no-name"</code>).
SCRIPT_ATOMIC:	When <code>true</code> , a started script will complete if conditions suddenly fail (<code>false</code>).
SHUFFLE:	If <code>true</code> , timestamps are recalculated on each reset of the script (<code>true</code>).
STATUS_VAR:	A MOOS variable for posting status summary (<code>UTS_STATUS</code>).
TIME_WARP:	Rate at which time is accelerated, $[0, \infty]$, in executing the script (1).
UPON_AWAKE:	Reset or re-start the script upon conditions being met after failure (<code>"n/a"</code>).
VERBOSE:	If <code>true</code> , progress output is generated to the console (<code>true</code>).

14.1.2 MOOS Variables Posted by uTimerScript

The primary output of uTimerScript to the MOOSDB is the set of configured events, but one other variable is published on each iteration:

UTS_STATUS: A status string of script progress.

This variable will be published on each iteration if one of the following conditions is met: (a) two seconds has passed since the previous status message posted, or (b) an event has been posted, or (c) the paused state has changed, or (d) the script has been reset, or (e) the state of script logic conditions has changed. An example string:

```
UTS_STATUS = "name=RND_TEST, elapsed_time=2.00, posted=1, pending=4, paused=false,
             conditions_ok=true, time_warp=3, start_delay=0, shuffle=false, upon_awake=reset, resets=0/4"
```

14.1.3 MOOS Variables Subscribed for by uTimerScript

The uTimerScript application will subscribe for the following four MOOS variables to provide optional control over the flow of the script by the user or other MOOS processes:

- UTS_NEXT:** When received with the value "next", the script will fast-forward in time to the next event. Described in Section 14.3.3.
- UTS_RESET:** When received with the value of either "true" or "reset", the timer script will be reset. Described in Section 14.2.2.
- UTS_FORWARD:** When received with a numerical value greater than zero, the script will fast-forward by the indicated time. Described in Section 14.3.3.
- UTS_PAUSE:** When received with the value of "true", "false", "toggle", the script will change its pause state correspondingly. Described in Section 14.3.1.

In addition to the above MOOS variables, uTimerScript will subscribe for any variables involved in logic conditions, described in Section 14.3.2.

14.1.4 Command Line Usage of uTimerScript

The uTimerScript application is typically launched as a part of a batch of processes by pAntler, but may also be launched from the command line by the user. The basic command line usage for the uTimerScript application is the following:

Listing 35 - Command line usage for the uTimerScript tool.

```
0 Usage: uTimerScript file.moos [OPTIONS]
1
2 Options:
3   --alias=<ProcessName>
4       Launch and connect to the MOOSDB with the given process name
5       rather than uTimerScript.
6   --help, -h
7       Display this help message.
8   --shuffle=Boolean (true/false)
```

```

 9      If true, script is recalculated on each reset.
10      If event times configured with random range, the
11      ordering may change after a reset.
12      The default is true.
13  --verbose=Boolean (true/false)
14      Display script progress and diagnostics if true.
15      The default is true.
16  --version,-h
17      Display the release version of uTimerScript.

```

Note that the `--alias` option is the only way to launch more than one `uTimerScript` process connected to the same MOOSDB.

14.2 Basic Usage of the `uTimerScript` Utility

Configuring a script minimally involves the specification of one or more events, with an event comprising of a MOOS variable and value to be posted and the time at which it is to be posted. Scripts may also be reset on a set policy, or from a trigger by an external process.

14.2.1 Configuring the Event List

The event list or script is configured by declaring a set of event entries with the following format:

```
EVENT = var=<moos-variable>, val=<var-value>, time=<time-of-event>
```

The keywords `EVENT`, `var`, `val`, and `time` are not case sensitive, but the values `<moos-variable>` and `<var-value>` are case sensitive. The `<var-value>` type is posted either as a string or double based on the following heuristic: if the `<var-value>` has a numerical value it is posted as a double, and otherwise posted as a string. If one wants to post a string with a numerical value, putting quotes around the number suffices to have it posted as a string. Thus `val=99` posts a double, but `var="99"` posts a string. If a string is to be posted that contains a comma such as "apples, pears", one must put the quotes around the string to ensure the comma is interpreted as part of `<var-value>`. The value field may also contain one or more macros expanded at the time of posting, as described in Section 14.4.

Setting the Event Time or Range of Event Times

The value of `<time-of-event>` is given in seconds and must be a numerical value greater or equal to zero. The time represents the amount of elapsed time since the `uTimerScript` was first launched and un-paused. The list of events provided in the configuration block need not be in order - they will be ordered by the `uTimerScript` utility. The `<time-of-event>` may also be specified by an interval of time, e.g., `time=0:100`, such that the event may occur at some point in the range with uniform probability. The only restrictions are that the lower end of the interval is greater or equal to zero, and less than or equal to the higher end of the interval. By default the timestamps are calculated once from their specified interval, at the the outset of `uTimerScript`. The script may alternatively be configured to recalculate the timestamps from their interval each time the script is reset, using the `SHUFFLE=true` configuration. This parameter, and resetting in general, are described in the next Section (14.2.2).

14.2.2 Resetting the Script

The timer script may be reset to its initial state, resetting the stored elapsed-time to zero and marking all events in the script as pending. This may occur either by cueing from an event outside `uTimerScript`, or automatically from within `uTimerScript`. Outside-cued resets can be triggered by posting `UTS_RESET="reset"`, or `"true"`. The `RESET_VAR` parameter names a MOOS variable that may be used as an alternative to `UTS_RESET`. It has the format:

```
RESET_VAR = <moos-variable> // Default is UTS_RESET
```

The script may be also be configured to auto-reset after a certain amount of time, or immediately after all events are posted, using the `RESET_TIME` parameter. It has the format:

```
RESET_TIME = <time-or-condition> // Default is "none"
```

The `<time-or-condition>` may be set to `"all-posted"` which will reset after the last event is posted. If set to a numerical value greater than zero, it will reset after that amount of elapsed time, regardless of whether or not there are pending un-posted events. If set to `"none"`, the default, then no automatic resetting is performed. Regardless of the `RESET_TIME` setting, prompted resets via the `UTS_RESET` variable may take place when cued.

The script may be configured to accept a hard limit on the number of times it may be reset. This is configured using the `RESET_MAX` parameter and has the following format:

```
RESET_MAX = <amount> // Default is "unlimited" or "any"
```

The `<amount>` specified may be any number greater or equal to zero, where the latter, in effect, indicates that no resets are permitted. If unlimited resets are desired (the default), the case insensitive argument `"unlimited"` or `"any"` may be used.

The script may be configured to recalculate all event timestamps specified with a range of values whenever the script is reset. This is done with the following parameter:

```
SHUFFLE = true // Default is "false"
```

The script may be configured to reset or restart each time it transitions from a situation where its conditions are not met to a situation where its conditions are met, or in other words, when the script is "awoken". The use of logic conditions is described in more detail in Section 14.3.1. This is done with the following parameter:

```
UPON_AWAKE = restart // Default is "n/a", no action
```

Note that this does not apply when the script transitions from being paused to un-paused as described in Section 14.3.1. See the example in Section 14.7.1 for a case where the `UPON_AWAKE` feature is handy.

14.3 Script Flow Control

The script flow may be affected in a number of ways in addition to the simple passage of time. It may be (a) paused by explicitly pausing it, (b) implicitly paused by conditioning the flow on one or more logic conditions, (c) fast-forwarded directly to the next scheduled event, or fast-forwarded some number of seconds. Each method is described in this section.

14.3.1 Pausing the Timer Script

The script can be paused at any time and set to be paused initially at start time. The `PAUSED` parameter affects whether the timer script is actively unfolding at the outset of launching `uTimerScript`. It has the following format:

```
PAUSED = <Boolean>
```

The keyword `PAUSED` and the string representing the Boolean are not case sensitive. The Boolean simply must be either `"true"` or `"false"`. By setting `PAUSED=true`, the elapsed time calculated by `uTimerScript` is paused and no variable-value pairs will be posted. When un-paused the elapsed time begins to accumulate and the script begins or resumes unfolding. The default value is `PAUSED=false`.

The script may also be paused through the MOOS variable `UTS_PAUSE` which may be posted by some other MOOS application. The values recognized are `"true"`, `"false"`, or `"toggle"`, all case insensitive. The name of this variable may be substituted for a different one with the `PAUSE_VAR` parameter in the `uTimerScript` configuration block. It has the format:

```
PAUSE_VAR = <moos-variable> // Default is UTS_PAUSE
```

If multiple scripts are being used (with multiple instances of `uTimerScript` connected to the MOOSDB), setting the `PAUSE_VAR` to a unique variable may be needed to avoid unintentionally pausing or un-pausing multiple scripts with single write to `UTS_PAUSE`.

14.3.2 Conditional Pausing of the Timer Script and Atomic Scripts

The script may also be configured to condition the “paused-state” to depend on one or more logic conditions. If conditions are specified in the configuration block, the script must be both un-paused as described above in Section 14.3.1, and all specified logic conditions must be met in order for the script to begin or resume proceeding. The logic conditions are configured as follows:

```
CONDITION = <logic-expression>
```

The `<logic-expression>` syntax is described in Appendix A, and may involve the simple comparison of MOOS variables to specified literal values, or the comparison of MOOS variables to one another. See the script configuration in Section 14.7.1 for one example usage of logic expressions.

An *atomic* script is one that does not check conditions once it has posted its first event, and prior to posting its last event. Once a script has started, it is treated as unpausable with respect to the the logic conditions. It can however be paused and unpaused via the pause variable, e.g., `UTS_PAUSE`, as described in Section 14.3.1. If the logic conditions suddenly fail in an atomic script midway, the check is simply postponed until after the script completes and is perhaps reset. If the conditions in the meanwhile revert to being satisfied, then no interruption should be observable.

14.3.3 Fast-Forwarding the Timer Script

The timer script, when un-paused, moves forward in time with events executed as their event times arrive. However, the script may be moved forward by writing to the MOOS variable `UTS_FORWARD`. If the value received is zero (or negative), the script will be forwarded directly to the

point in time at which the next scheduled event occurs. If the value received is positive, the elapsed time is forwarded by the given amount. Alternatives to the MOOS variable `UTS_FORWARD` may be configured with the parameter:

```
FORWARD_VAR = <moos-variable>      // Default is UTS_FORWARD
```

If multiple scripts are being used (with multiple instances of `uTimerScript` connected to the MOOSDB), setting the `FORWARD_VAR` to a unique variable may be needed to avoid unintentionally fast forwarding multiple scripts with single write to `UTS_FORWARD`.

14.4 Macro Usage in Event Postings

Macros may be used to add a dynamic component to the value field of an event posting. This substantially expands the expressive power and possible uses of the `uTimerScript` utility. Recall that the components of an event are defined by:

```
EVENT = var=<moos-variable>, val=<var-value>, time=<time-of-event>
```

The `<var-value>` component may contain a macro of the form `#[MACRO]`, where the macro is either one of a few built-in macros available, or a user-defined macro with the ability to represent random variables. Macros may also be combined in simple arithmetic expressions to provide further expressive power. In each case, the macro is expanded at the time of the event posting, typically with different values on each successive posting.

14.4.1 Built-In Macros Available

There are five built-in macros available: `#[DBTIME]`, `#[UTCTIME]`, `#[COUNT]`, `#[TCOUNT]`, and `#[IDX]`. The first macro expands to the estimated time since the MOOSDB started, similar to the value in the MOOS variable `DB_UPTIME` published by the MOOSDB. An example usage:

```
EVENT = var=DEPLOY_RECEIVED, val=#[DBTIME], time=10:20
```

The `#[UTCTIME]` macro expands to the UTC time at the time of the posting. The `#[COUNT]` macro expands to the integer total of all posts thus far in the current execution of the script, and is reset to zero when the script resets. The `#[TCOUNT]` macro expands to the integer total of all posts thus far since the application began, i.e., it is a running total that is not reset when the script is reset.

The `#[DBTIME]`, `#[UTCTIME]`, `#[COUNT]`, and `#[TCOUNT]` macros all expand to numerical values, which if embedded in a string, will simply become part of the string. If the value of the MOOS variable posting is solely this macro, the variable type of the posting is instead a double, not a string. For example `val=#[DBTIME]` will post a type double, whereas `val="time:#[DBTIME]"` will post a type string.

The `#[IDX]` macro is similar to the `#[COUNT]` macro in that it expands to the integer value representing an event's count or index into the sequence of events. However, it will always post as a string and will be padded with zeros to the left, e.g., "000", "001", ... and so on.

14.4.2 User Configured Macros with Random Variables

Further macros are available for use in the `<var-value>` component of an event, defined and configured by the user, and based on the idea of a random variable. In short, the macro may expand to a numerical value chosen within a user specified range, and recalculated according to a user-specified policy. The general format is:

```
RAND_VAR = varname=<variable>, min=<low_value>, max=<high_value>, key=<key_name>
```

The `<variable>` component defines the macro name. The `<low_value>` and `<high_value>` components define the range from which the random value will be chosen uniformly. The `<key_name>` determines when the random value is reset. The following three key names are significant: "at_start", "at_reset", and "at_post". Random variables with the key name "at_start" are assigned a random value only at the start of the uTimerScript application. Those with the "at_reset" key name also have their values re-assigned whenever the script is reset. Those with the "at_post" key name also have their values re-assigned after any event is posted.

14.4.3 Support for Simple Arithmetic Expressions with Macros

Macros that expand to numerical values may be combined in simple arithmetic expressions with other macros or scalar values. The general form is:

```
{<value> <operator> <value>}
```

The `<value>` components may be either a scalar or a macro, and the `<operator>` component may be one of '+', '-', '*', '/'. Nesting is also supported. Below are some examples:

```
{${FOOBAR} * 0.5}
{-2-${FOOBAR}}
{${APPLES} + ${PEARS}}
{35 / {${FOOBAR}-2}}
{${DBTIME} - {35 / {${UTCTIME}+2}}}
```

If a macro should happen to expand to a string rather than a double (numerical) value, the string evaluates to zero for the sake of the remaining evaluations.

14.5 Random Time Warps and Initial Delays

A time warp and initial start delay may be optionally configured into the script to change the event schedule without having to edit all the time entries for each event. They may also be configured to take on a new random value at the outset of each script execution to allow for simulation of events in nature or devices having a random component.

14.5.1 Random Time Warping

The time warp is a numerical value in the range $(0, \infty]$, with a default value of 1.0. Lower values indicate that time is moving more slowly. As the script unfolds, a counter indicating "elapsed_time" increases in value as long as the script is not paused. The "elapsed_time" is multiplied by the time warp value. The time warp may be specified as a single value or a range of values as below:

```
TIME_WARP = <value>
TIME_WARP = <low-value>:<high-value>
```

When a range of values is specified, the time warp value is calculated at the outset, and re-calculated whenever the script is reset. See the example in Section 14.7.2 for a use of random time warping to simulate random wind gusts.

14.5.2 Random Initial Start Delays

The start delay is given in seconds in the range $[0, \infty]$, with a default value of 0. The effect of having a non-zero delay of n seconds is to have `elapsed_time=n` at the outset of the script and all resets of the script. Thus a delay of n seconds combined with a time warp of 0.5 would result in observed delay of $2 * n$ seconds. The start delay may be specified as a single value or a range of values as below:

```
START_DELAY = <value>
START_DELAY = <low-value>:<high-value>
```

When a range of values is specified, the start delay value is calculated at the outset, and re-calculated whenever the script is reset. See the example in Section 14.7.1 for a use of random start delays to simulate the delay in acquiring satellite fixes in a GPS unit on an UUV coming to the surface.

14.6 More on uTimerScript Output to the MOOSDB and Console

The activity of uTimerScript may be monitored in two ways: (a) by a status message posted the MOOSDB, and by standard output to the uTimerScript console window.

14.6.1 Status Messages Posted to the MOOSDB by uTimerScript

The uTimerScript periodically publishes a string indicating the status of the script. The following is an example:

```
UTS_STATUS = "name=RND_TEST, elapsed_time=2.00, posted=1, pending=5, paused=false,
conditions_ok=true, time_warp=3, start_delay=0, shuffle=false, upon_awake=restart, resets=2/5"
```

In this case, the script has posted one of six events (`posted=1`, `pending=5`). It is actively unfolding, since `paused=false` (Section 14.3.1) and `conditions_ok=true` (Section 14.3.2). It has been reset twice out of a maximum of five allowed resets (`resets=2/5`, Section 14.2.2). Time warping is being

deployed (`time_warp=3`, Section 14.5.1), there is no start delay in use (`start_delay=0`, Section 14.5.2). The shuffle feature is turned off (`shuffle=false`, Section 14.2.2). The script is not configured to reset upon re-entering the un-paused state (`awake_reset=false`, Section 14.2.2).

When multiple scripts are running in the same MOOS community, one may want to take measures to discern between the status messages generated across scripts. One way to do this is to use a unique MOOS variable other than `UTS_STATUS` for each script. The variable used for publishing the status may be configured using the `STATUS_VAR` parameter. It has the following format:

```
STATUS_VAR = <moos-variable> // Default is UTS_STATUS
```

Alternatively, a unique name may be given to each to each script. All status messages from all scripts would still be contained in postings to `UTS_STATUS`, but the different script output could be discerned by the name field of the status string. The script name is set with the following format.

```
SCRIPT_NAME = <string> // Default is "unnamed"
```

14.6.2 Console Output Generated by uTimerScript

The script configuration and progress of script execution may also be monitored from an open console window where `uTimerScript` is launched, if the verbose setting is turned on (by default). Example output is shown below in Listing 36.

Listing 36 - Example uTimerScript console output.

```
0 Random Variable configurations:
1   [0]: varname=ANGLE, keyname=at_reset, min=10, max=350
2   [1]: varname=MAGN, keyname=at_reset, min=0.5, max=1.5
3
4
5 The Raw Script: =====
6 Total Elements: 10
7 [0] MARINESIM_FORCE_ANGLE=${[ANGLE]}, TIME:-1, RANGE=[0,0], POSTED=false
8 [1] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*0.2}, TIME:-1, RANGE=[2,2], POSTED=false
9 [2] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*0.2}, TIME:-1, RANGE=[4,4], POSTED=false
10 [3] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*0.2}, TIME:-1, RANGE=[6,6], POSTED=false
11 [4] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*0.2}, TIME:-1, RANGE=[8,8], POSTED=false
12 [5] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*0.2}, TIME:-1, RANGE=[10,10], POSTED=false
13 [6] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*-0.2}, TIME:-1, RANGE=[12,12], POSTED=false
14 [7] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*-0.2}, TIME:-1, RANGE=[14,14], POSTED=false
15 [8] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*-0.2}, TIME:-1, RANGE=[16,16], POSTED=false
16 [9] MARINESIM_FORCE_MAGNITUDE_D=${[MAGN]*-0.2}, TIME:-1, RANGE=[18,18], POSTED=false
17 =====
18
19 uTimerScript_wind is Running:
20     AppTick    @ 5.0 Hz
21     CommsTick  @ 5 Hz
22 Script (Re)Initialized. Time Warp=5 StartDelay=0
23 [a/239.512] [0]: MARINESIM_FORCE_ANGLE = 78.068
24 [u/239.915] [2.01267]: MARINESIM_FORCE_MAGNITUDE_D = 0.19936
25 [o/240.318] [4.02825]: MARINESIM_FORCE_MAGNITUDE_D = 0.19936
26 [i/240.722] [6.04633]: MARINESIM_FORCE_MAGNITUDE_D = 0.19936
```

```
27 [c/241.124] [8.06040]: MARINESIM_FORCE_MAGNITUDE_D = 0.19936
28 [w/241.528] [10.0767]: MARINESIM_FORCE_MAGNITUDE_D = 0.19936
29 [q/241.931] [12.0913]: MARINESIM_FORCE_MAGNITUDE_D = -0.19936
30 [j/242.313] [14.0038]: MARINESIM_FORCE_MAGNITUDE_D = -0.19936
31 [d/242.716] [16.0205]: MARINESIM_FORCE_MAGNITUDE_D = -0.19936
32 [x/243.119] [18.0340]: MARINESIM_FORCE_MAGNITUDE_D = -0.19936
```

In the first block (lines 1-2), the configuration of random variables for use as macros is displayed. In the second block (lines 5-17), the raw script, prior to macro expansion or time-stamp allocation is displayed. In the third block (lines 22-32), events are printed as they occur. Each event shows two timestamps. The first, on the left, shows the approximate time relative to the MOOSDB start time (which is typical in MOOS log files). The second set of timestamps shown in the second column is the "elapsed_time" since the start of the script (which may be affected by time warp, start delay, and pausing).

14.7 Examples

The examples in this section demonstrate the constructs thus far described for the `uTimerScript` application. In each case, the use of the script obviated the need for developing and maintaining a separate dedicated MOOS application.

14.7.1 A Script Used as Proxy for an On-Board GPS Unit

Typical operation of an underwater vehicle includes the periodic surfacing to obtain a GPS fix to correct navigation error accumulated while under water. A GPS unit that has been out of satellite communication for some period normally takes some time to re-acquire enough satellites to resume providing position information. From the perspective of the helm and configuring an autonomy mission, it is typical to remain at the surface only long enough to obtain the GPS fix, and then resume other aspects of the mission at-depth.

Consider a situation as shown in Figure 68, where the autonomy system is running in the payload on a payload computer, receiving not only updated navigation positions (in the form of `NAV_DEPTH`, `NAV_X`, and `NAV_Y`), but also a "heartbeat" signal each time a new GPS position has been received (`GPS_RECEIVED`). This heartbeat signal may be enough to indicate to the helm and mission configuration that the objective of the surface excursion has been achieved.

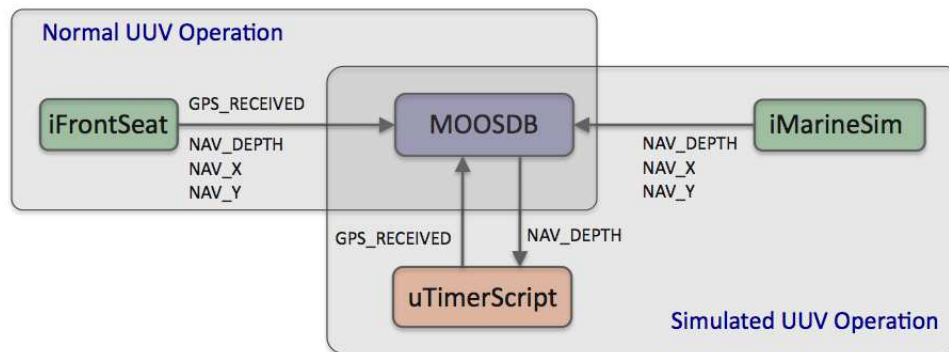


Figure 68: **Simulating a GPS Acknowledgment:** In a physical operation of the vehicle, the navigation solution and a `GPS_UPDATE_RECEIVED` heartbeat are received from the main vehicle (front-seat) computer via a MOOS module acting as an interface to the front-seat computer. In simulation, the navigation solution is provided by the simulator without any `GPS_UPDATE_RECEIVED` heartbeat. This element of simulation may be provided with `uTimerScript` configured to post the heartbeat, conditioned on the `NAV_DEPTH` information and a user-specified start delay to simulate GPS acquisition delay.

In simulation, however, the simulator only produces a steady stream of navigation updates with no regard to a simulated GPS unit. At this point there are three choices: (a) modify the simulator to fake GPS heartbeats and satellite delay, (b) write a separate simple MOOS application to do the same simulation. The drawback of the former is that one may not want to branch a new version of the simulator, or even introduce this new complexity to the simulator. The drawback of the latter is that, if one wants to propagate this functionality to other users, this requires distribution and version control of a new MOOS application.

A third and perhaps preferable option (c) is to write a short script for `uTimerScript` simulating the desired GPS characteristics. This achieves the objectives without modifying or introducing new source code. The below script in Listing 37 gets the job done.

Listing 37 - A `uTimerScript` configuration for simulating aspects of a GPS unit.

```

1 //-----
2 // uTimerScript configuration block
3
4 ProcessConfig = uTimerScript
5 {
6   AppTick    = 4
7   CommsTick  = 4
8
9   PAUSED     = false
10  RESET_MAX  = unlimited
11  RESET_TIME = end
12  CONDITION  = NAV_DEPTH < 0.2
13  UPON_AWAKE = restart
14  DELAY_START = 20:120
15  SCRIPT_NAME = GPS_SCRIPT
16
17  EVENT = var=GPS_UPDATE_RECEIVED, val="RCVD_${COUNT}", time=0:1
18 }
```

This script posts a `GPS.UPDATE_RECEIVED` heartbeat message roughly once every second, based on the event time `"time=0:1"` on line 17. The value of this message will be unique on each posting due to the `#[COUNT]` macro in the value component. See Section 14.4.1 for more on macros. The script is configured to restart each time it awakes (line 13), defined by meeting the condition of `(NAV_DEPTH < 0.2)` which is a proxy for the vehicle being at the surface. The `DELAY_START` simulates the time needed for the GPS unit to reacquire satellite signals and is configured to be somewhere in the range of 20 to 120 seconds (line 14). Once the script gets past the start delay, the script is a single event (line 17) that repeats indefinitely due to the `RESET_MAX=unlimited` and `RESET_TIME=end` settings in lines 10 and 11. This script is used in the IvP Helm example simulation mission labeled `"s4_delta"` illustrating the `PeriodicSurface` helm behavior.

14.7.2 A Script as a Proxy for Simulating Random Wind Gusts

Simulating wind gusts, or in general, somewhat random external periodic forces on a vehicle, are useful for testing the robustness of certain autonomy algorithms. Often they don't need to be grounded in very realistic models of the environment to be useful, and here we show how a script can be used simulate such forces in conjunction with the `iMarineSim` application.

The `iMarineSim` application is a simple simulator that produces a stream of navigation information, `NAV_X`, `NAV_Y`, `NAV_SPEED`, `NAV_DEPTH`, and `NAV_HEADING` (Figure 69), based on the vehicle's last known position and trajectory, and currently observed values for actuator variables. The simulator also stores local state variables reflecting the current external force in the x-y plane, by default zero. An external force may be specified in terms of a force vector, in absolute terms with the variable `IMS_FORCE_VECTOR`, or in relative terms with the variables `IMS_FORCE_VECTOR.ADD`.

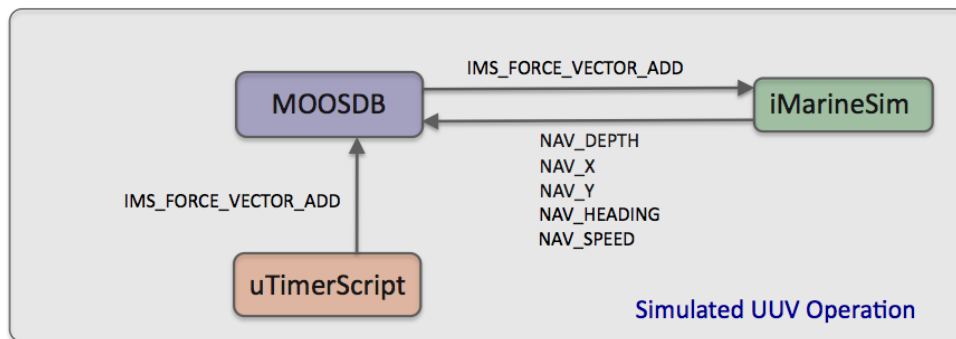


Figure 69: **Simulated Wind Gusts:** The `uTimerScript` application may be configured to post periodic sequences of external force values, used by the `iMarineSim` application to simulate wind gust effects on its simulated vehicle.

The script in Listing 38 makes use of the `iMarineSim` interface by posting periodic force vectors. It simulates a wind gust with a sequence of five posts to increase a force vector (lines 18-22), and complementary sequence of five posts to decrease the force vector (lines 24-28) for a net force of zero at the end of each script execution.

Listing 38 - A `uTimerScript` configuration for simulating simple wind gusts.

```
0 //-----
```

```

1 // uTimerScript configuration block
2
3 ProcessConfig = uTimerScript
4 {
5     AppTick    = 2
6     CommsTick  = 2
7
8     PAUSED      = false
9     RESET_MAX   = unlimited
10    RESET_TIME  = end
11    DELAY_RESET = 10:60
12    TIME_WARP   = 0.25:2.0
13    SCRIPT_NAME = WIND
14    SCRIPT_ATOMIC = true
15
16    RANDVAR = varname=ANG, min=0, max=359, key=at_reset
17    RANDVAR = varname=MAG, min=0.5, max=1.5, key=at_reset
18
19    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=0
20    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=2
21    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=4
22    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=6
23    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=8
24
25    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=10
26    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=12
27    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=14
28    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=16
29    EVENT = var=IMS_FORCE_VECTOR_ADD, val="${ANG},{${MAG}*0.2}", time=18
30 }

```

The force *angle* is chosen randomly in the range of [0, 359] by use of the random variable macro `${ANG}` defined on line 16. The peak *magnitude* of the force vector is chosen randomly in the range of [0.5, 1.5] with the random variable macro `${MAG}` defined on line 17. Note that these two macros have their random values reset each time the script begins, by using the `key=at_reset` option, to ensure a stream of wind gusts of varying angles and magnitudes.

The duration of each gust sequence also varies between each script execution. The default duration is about 20 seconds, given the timestamps of 0 to 18 seconds in lines 19-29. The `TIME_WARP` option on line 12 affects the duration with a random value chosen from the interval of [0.25, 2.0]. A time warp of 0.25 results in a gust sequence lasting about 80 seconds, and 2.0 results in a gust of about 10 seconds. The time between gust sequences is chosen randomly in the interval [10, 60] by use of the `DELAY_RESTART` parameter on line 11. Used in conjunction with the `TIME_WARP` parameter, the interval for possible observed delays between gusts is [5, 240]. The `RESET_TIME=end` parameter on line 10 is used to ensure that the script posts all force vectors to avoid any accumulated forces over time. The `RESET_MAX` parameter is set to "unlimited" to ensure the script runs indefinitely.

15 The pBasicContactMgr Utility: Managing Platform Contacts

The pBasicContactMgr application deals with information about other known vehicles in its vicinity. It is not a sensor application, but rather handles incoming “contact reports” which may represent information received by the vehicle over a communications link, or may be the result of on-board sensor processing. By default the pBasicContactMgr posts to the MOOSDB summary reports about known contacts, but it also may be configured to post alerts, i.e., MOOS variables, with select content about one or more of the contacts.

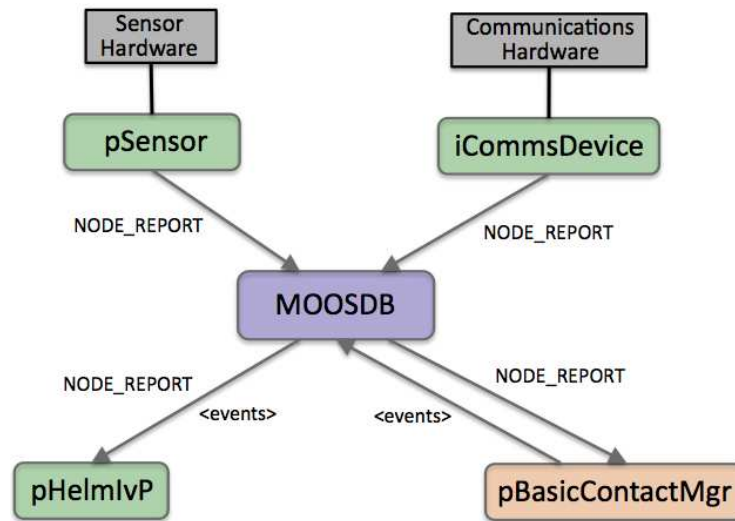


Figure 70: **The pBasicContactMgr Application:** The pBasicContactMgr utility receives NODE_REPORT information from other MOOS applications and manages a list of unique contact records. It may post additional user-configurable alerts to the MOOSDB based on the contact information and user-configurable conditions. The source of contact information may be external (via communications) or internal (via on-board sensor processing). The pSensor and iCommsDevice modules shown here are fictional applications meant to convey these two sources of information abstractly.

The pBasicContactMgr application is partly designed with simultaneous usage of the IvP Helm in mind. The alerts posted by pBasicContactMgr may be configured to trigger the dynamic spawning of behaviors in the helm, such as collision-avoidance behaviors. The pBasicContactMgr application does not perform sensor fusion, and does not reason about or post information regarding the confidence it has in the reported contact position relative to ground truth. These may be features added in the future, or perhaps may be features of an alternative contact manager application developed by a third party source.

15.1 Overview of the pBasicContactMgr Interface and Configuration Options

The pBasicContactMgr application may be configured with a configuration block within a .moos file, and from the command line. Its interface is defined by its publications and subscriptions for MOOS variables consumed and generated by other MOOS applications. An overview of the set of configuration options and interface is provided in this section.

15.1.1 Brief Summary of the pBasicContactMgr Configuration Parameters

The following parameters are defined for pBasicContactMgr. A more detailed description is provided in other parts of this section. Parameters having default values are indicated so in parentheses below.

- ALERT: A description of a single alert.
- ALERT_RANGE: The range to a contact, in meters, within which an alert is posted (1,000).
- ALERT_CPA_RANGE: The range to a contact, in meters, within which an alert is posted if CPA over ALERT_CPA_TIME falls within the ALERT_RANGE distance (1,000).
- ALERT_CPA_TIME: The time, in seconds, for which ALERT_CPA_RANGE is calculated (0).
- CONTACT_MAX_AGE: Seconds between reports before a contact is dropped from the list (3600).
- DISPLAY_RADII: If true, the two alert ranges are posted as viewable circles (false).
- VERBOSE: If true, progress output is generated to the console (true).

15.1.2 MOOS Variables Posted by pBasicContactMgr

The primary output of pBasicContactMgr to the MOOSDB is the set of user-configured alerts. Other variables are published on each iteration where a change is detected on its value:

- CONTACTS_LIST: A comma-separated list of contacts.
- CONTACTS_RECAP: A comma-separated list of contact summaries.
- CONTACTS_ALERTED: A list of contacts for which alerts have been posted.
- CONTACTS_UNALERTED: A list of contacts for which alerts are pending, based on the range criteria.
- CONTACTS_RETIRED: A list of contacts removed due to the information staleness.
- CONTACT_MGR_WARNING: A warning message indicating possible mishandling of or missing data.

Some examples:

```
CONTACTS_LIST = "delta,gus,charlie,henry"
CONTACTS_ALERTED = "delta,charlie"
CONTACTS_UNALERTED = "gus,henry"
CONTACTS_RETIRED = "bravo,foxtrot,kilroy"
CONTACTS_RECAP = "name=delta,age=11.3,range=193.1 # name=gus,age=0.7,range=48.2 # \
                 name=charlie,age=1.9,range=73.1 # name=henry,age=4.0,range=18.2"
```

15.1.3 MOOS Variables Subscribed for by pBasicContactMgr

The pBasicContactMgr application will subscribe for the following MOOS variables:

- CONTACT_RESOLVED: A name of a contact that has been declared resolved.
- NODE_REPORT: A report about a known contact.
 - NAV_X: Present position of ownship in local x coordinates.
 - NAV_Y: Present position of ownship in local y coordinates.
 - NAV_HEADING: Present ownship heading in degrees.

NAV.SPEED: Present ownship speed in meters per second.

NAV.DEPTH: Present ownship depth in meters.

15.1.4 Command Line Usage of pBasicContactMgr

The pBasicContactMgr application is typically launched as a part of a batch of processes by pAntler, but may also be launched from the command line by the user. The basic command line usage for the pBasicContactMgr application is the following:

Listing 39 - Command line usage for the pBasicContactMgr application.

```

0 Usage: pBasicContactMgr file.moos [OPTIONS]
1
2 Options:
3   --alias=<ProcessName>
4       Launch pBasicContactMgr with the given process name
5       rather than pBasicContactMgr.
6   --help, -h
7       Display this help message.
8   --verbose=<Boolean>
9       Display status updates and diagnostics if true.
10      The default is true.
11   --version,-h
12      Display the release version of pBasicContactMgr.
```

15.2 Basic Usage of the pBasicContactMgr Utility

The operation of pBasicContactMgr consists of posting user-configured alerts, and the posting of several MOOS variables, the CONTACTS_* variables, indicating the status of the contact manager.

15.2.1 Contact Alert Messages

Alert messages are used to alert other MOOS applications when a contact has been detected within a certain range of ownship. Messages are configured in the pBasicContactMgr block of the .moos file:

```
ALERT = var=<moos-variable>, val=<alert-content>
```

The <alert-content> may be any string with any, none, or all of the following macros available for expansion:

The following is an example configuration:

```
ALERT = var=CONTACT_INFO, val="name=avd_${VNAME} # contact=${VNAME}"
```

The right-hand side of the ALERT specification is a #-separated list of parameter=value pairs. Note that in the above example, the value component in the val=<alert-content> pair itself is a string with comma-separated parameter=value pairs. Putting the whole <alert-content> component in double-quotes ensures that the comma separator is interpreted locally within that string.

- \$[VNAME]: The name of the contact.
- \$[X]: The position of the contact in local x coordinates.
- \$[Y]: The position of the contact in local y coordinates.
- \$[LAT]: The latitude position of the contact in earth coordinates.
- \$[LON]: The longitude position of the contact in earth coordinates.
- \$[HDG]: The reported heading of the contact.
- \$[SPD]: The reported speed of the contact.
- \$[DEP]: The reported depth of the contact.
- \$[VTYPE]: The reported vessel type of the contact.
- \$[UTIME]: The UTC time of the last report for the contact.

15.2.2 Contact Alert Triggers

Alerts are triggered for all contacts based on range between ownship and the reported contact position. It is assumed that each incoming contact report minimally contains the contact's name and present position. An alert will be triggered if the current range to the contact falls within the distance given by `ALERT_RANGE`, as in Contact-A in Figure 71.

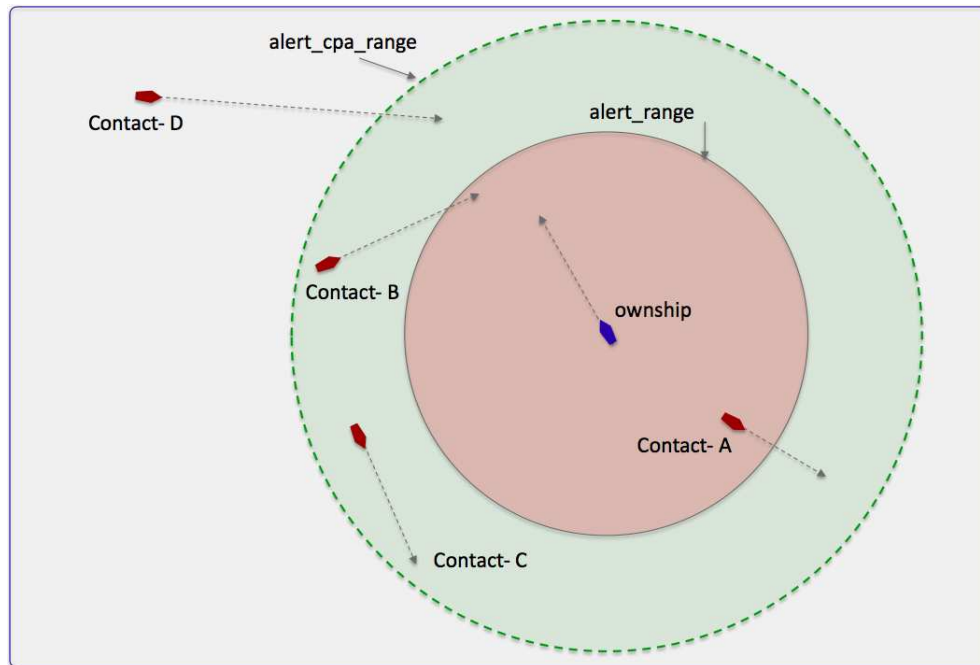


Figure 71: **Alert Triggers in pBasicContactMgr:** An alert may be triggered by pBasicContactMgr if the contact is within the `alert_range`, as with Contact-A. It may also be triggered if the contact is within the `alert_cpa_range`, and contact's CPA distance is within the `alert_range`, as with Contact-B. Contact-C shown here would not trigger an alert since its CPA distance is its current range and is not within the `alert_range`. Contact-D also would not trigger an alert despite the fact that its CPA with ownship is apparently small, since its current absolute range is outside the `alert_cpa_range` range.

The contact manager may also be configured with a second trigger criteria consisting of another range and time interval:

```
ALERT_CPA_RANGE = <distance>
ALERT_CPA_TIME = <duration>
```

The ALERT_CPA_RANGE is typically larger than the ALERT_RANGE. (Its influence is effectively disabled when or if it is set to be equal to or less than the ALERT_RANGE.) When a contact is outside the ALERT_RANGE, but within the ALERT_CPA_RANGE, as with Contact-B in Figure 71, the closest point of approach (CPA) between the contact and ownship is calculated given their presently-known position and trajectories. If the CPA distance falls below the ALERT_RANGE value, an alert is triggered. The ALERT_CPA_TIME interval is applied to the CPA calculation to mean that the calculated CPA distance is the CPA distance within the next ALERT_CPA_TIME seconds.

15.2.3 Contact Alert Record Keeping

The contact manager keeps a record of all known contacts for which it has received a report. This list is posted in the MOOS variable CONTACTS_LIST, in a comma-separated string such as:

```
CONTACTS_LIST = "delta,gus,charlie,henry"
```

Once an alert is generated for a contact it is put on the “alerted” list and this subset of all contacts is posted in the MOOS variable CONTACTS_ALERTED, in a comma-separated string:

```
CONTACTS_ALERTED = "delta,charlie"
```

Likewise, those contacts for which no alert has been generated are in the “unalerted” list and this is reflected in the MOOS variable CONTACTS_UNALERTED:

```
CONTACTS_UNALERTED = "gus,henry"
```

Contact records are not maintained indefinitely and eventually are “retired” from the records after some period of time during which no new reports are received for that contact. That period of time is given by the CONTACT_MAX_AGE configuration parameter. The list of retired contacts is posted in the MOOS variable CONTACTS_RETIRED:

```
CONTACTS_RETIRED = "bravo,foxtrot,kilroy"
```

A contact recap of all non-retired contacts is also posted in the MOOS variable CONTACTS_RECAP:

```
CONTACTS_RECAP = "name=delta,age=11.3,range=193.1 # name=gus,age=0.7,range=48.2 # \
name=charlie,age=1.9,range=73.1 # name=henry,age=4.0,range=18.2"
```

Each of these five MOOS variables is published only when its contents differ from its previous posting.

15.2.4 Contact Resolution

An alert is generated by the contact manager for a given contact *once*, when the alert trigger criteria is first met. In the iteration when the criteria is met, the contact is moved from the “un-alerted” list to the “alerted” list, the alert is posted to the MOOSDB, and no further alerts are posted despite any future calculations of the trigger criteria. One exception to this is when the `pBasicContactMgr` receives notice that a contact has been “resolved”, through the MOOS variable `CONTACT_RESOLVED`. When a contact is resolved, it is moved from the alerted list back on to the un-alerted list.

15.3 Usage of the `pBasicContactMgr` with the IvP Helm

The IvP helm may be used in conjunction with the contact manager to coordinate the dynamic spawning of certain helm behaviors where the instance of the behavior is dedicated to a helm objective associated with a particular contact. For example, a collision avoidance behavior, or a behavior for maintaining a relative position to a contact for achieving sensing objectives, would be examples of such behaviors. One may want to arrange for a new behavior to be spawned as the contact becomes known. The helm needs a cue in the form of a MOOS variable posting to trigger a new behavior spawning, and this is easily arranged with the alerts in the `pBasicContactMgr`.

On the flip-side of a new behavior spawning, a behavior may eventually declare itself completed and remove itself from the helm. The conditions leading to completion are defined within the behavior implementation and configuration. No cues external to the helm are required to make that happen. However, once an alert has been generated by the contact manager for a particular contact, it is not generated again, unless it receives a message that the contact has been “resolved”. Therefore, if the helm wishes to receive future alerts related to a contact for which it has received an alert in the past, it must declare the contact “resolved” to the contact manager as discussed in Section 15.2.4. This would be important, for example, in the following scenario: (a) a collision avoidance behavior is spawned for a new contact that has come within range, (b) the behavior completes and is removed from the helm, presumably because the contact has slipped safely out of range, (c) the contact or ownership turns such that a collision avoidance behavior is once again needed for the same contact.

An example mission is available for showing the use of the contact manager and its coordination with the helm to spawn behaviors for collision avoidance. This mission is `m2.bertha` and is described in the IvP Helm documentation. In this mission two vehicles are configured to repeatedly go in and out of collision avoidance range, and the contact manager repeatedly posts alerts that result in the spawning of a collision avoidance behavior in the helm. Each time the vehicle goes out of range, the behavior completes and dies off from the helm and is declared to the contact manager to be resolved.

15.4 Console Output Generated by `pBasicContactMgr`

The status of the contact manager may be monitored from an open console window where `pBasicContactMgr` is launched, if the verbose setting is turned on (by default). Example output is shown below in Listing 40.

Listing 40 - Example `pBasicContactMgr` console output.

```
0 ----- Iteration: 407
1 Time: 202.563
2 List: vehicle1
3 Alerted: vehicle1
4 UnAlerted:
5 Retired:
6 Recap: vname=vehicle1,range=34.36,age=1.26
7
8 Recent Alerts:
9 [0.00]: CONTACT_INFO=name=avd_vehicle1#contact=vehicle1
10 [81.27]: Resolved: vehicle1
11 [133.09]: CONTACT_INFO=name=avd_vehicle1#contact=vehicle1
```

In lines 2-6, the record-keeping status of the contact manager is output. These five lines are equivalent to the content of the CONTACTS_* variables described in Section 15.2.3. The iteration number on line 0 is the iteration counter associated with the Iterate() loop of pBasicContactMgr. The time stamp on line 1 represents the duration of time since the pBasicContactMgr was launched. The Recent Alerts output in lines 8-11 reflect the ten most recent alert related events - either an actual alert being posted or a contact resolution.

Part IV

Appendices

A Use of Logic Expressions

Logic conditions are employed in both the `pHelmIvP` and `uTimerScript` applications, to condition certain activities based on the prescribed logic state of elements of the MOOSDB. The use of logic conditions in the `helm` is done in behavior file (`.bhv` file). For the `uTimerScript` application, logic conditions are used in the configuration block of the mission file (`.moos` file). The MOOS application using logic conditions maintains a local buffer representing a snapshot of the MOOSDB for variables involved in the logic expressions. The key relationships and steps are shown in Figure 72:

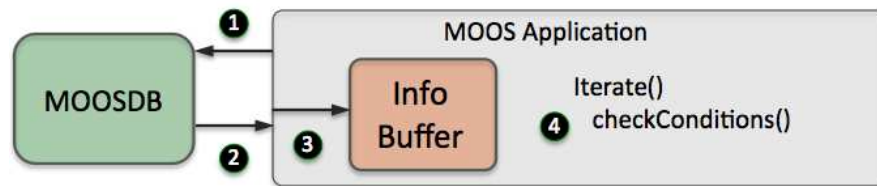


Figure 72: **Logic conditions in a MOOS application:** Step 1: the applications registers to the MOOSDB for any MOOS variables involved in the logic expressions. Step 2: The MOOS application reads incoming mail from the MOOSDB. Step 3: Any new mail results in an update to the information buffer. Step 4: Within the applications `Iterate()` method, the logic expressions are evaluated based on the contents of the information buffer.

The logic conditions are configured as follows:

```
CONDITION = <logic-expression>
```

The keyword `CONDITION` and is case insensitive. When multiple conditions are specified, it is implied that the overall criteria for “meeting conditions” is the conjunction of all such conditions. In what remains below, the allowable syntax for `<logic-expression>` is described.

Simple Relational Expressions

Each logic expression is comprised of either Boolean operators (`and`, `or`, `not`) or relation operators (`≤`, `<`, `≥`, `>`, `=`, `! =`). All expressions have at least one relational expression, where the left-hand side of the expression is treated as a variable, and the right-hand side is a literal (either a string or numerical value). The literals are treated as a string value if quoted, or if the value is non-numerical. Some examples:

```
DEPLOY = true // Example 1
QUALITY >= 75 // Example 2
```

Variable names are case sensitive since MOOS variables in general are case sensitive. In matching string values of MOOS variables in Boolean conditions, the matching is *case insensitive*. If for example, in Example 1 above, the MOOS variable `DEPLOY` had the value `"TRUE"`, this would satisfy the condition. But if the MOOS variable `deploy` had the value `"true"`, this would not satisfy Example 1.

Simple Logical Expressions with Two MOOS Variables

A relational expression generally involves a variable and a literal, and the form is simplified by insisting the variable is on the left and the literal on the right. A relational expression can also involve the comparison of two variables by surrounding the right-hand side with `$()`. For example:

```
REQUESTED_STATE != $(RUN_STATE)           // Example 3
```

The variable types need to match or the expression will evaluate to `false` regardless of the relation. The expression in Example 3 will evaluate to `false` if, for example, `REQUESTED_STATE="run"` and `RUN_STATE=7`, simply because they are of different type, and regardless of the relation being the inequality relation.

Complex Logic Expressions

Individual relational expressions can be combined with Boolean connectors into more complex expressions. Each component of a Boolean expression must be surrounded by a pair of parentheses. Some examples:

```
(DEPLOY = true) or (QUALITY >= 75)         // Example 4
```

```
(MSG != error) and !((K <= 10) or (w != 0)) // Example 5
```

A relational expression such as `(w != 0)` above is false if the variable `w` is undefined. In MOOS, this occurs if variable has yet to be published with a value by any MOOS client connected to the MOOSDB. A relational expression is also `false` if the variable in the expression is the wrong type, compared to the literal. For example `(w != 0)` in Example 5 would evaluate to `false` even if the variable `w` had the string value "alpha" which is clearly not equal to zero.

B Behavior Summaries

Parameter Summary for BHV_Waypoint

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
capture_radius	double	7	-	0	97
cycleflag	MOOSVAR=value	CYCLED=true	yes	-	99
lead	double	10	-	-1	98
lead_damper	double	2	-	-1	98
lead_on_start	Boolean string	TRUE	no	false	98
slip_radius	double	18	-	0	97
order	string	reverse	no	normal	97
point	string	20,5	yes	-	97
points, polygon	string	0,0:45,0:45,80:0,0	yes	-	97
post_suffix	string	IKE	yes	""	96
repeat	int	3	no	0	97
speed	double	1.2	-	0	96
visual_hints	string	edge_size=1	no	-	96

Table 29: Parameters for the BHV_Waypoint behavior.a

Variables posted by the BHV_Waypoint Behavior

The following variables may be posted by the BHV_Waypoint behavior in addition to any configured flags (with the runflag, idleflag, activeflag, inactiveflag, and cycleflag parameters).

- VIEW_POINT, VIEW_SEGLIST, WPT_INDEX, CYCLE_INDEX, WPT_STAT

The variable names used may be changed with the POST_MAPPING parameter. See page 79.

Example Behavior File Configuration for BHV_Waypoint

Listing B.1 - An example BHV_Waypoint configuration.

```

0 Behavior = BHV_Waypoint
1 {
2   name      = waypt_survey
3   priority  = 100

```



```
4  updates    = WPT_SURVEY_UPDATES
5  condition  = (DEPLOY == true) or (SURVEY == on)
6  endflag    = SURVEY = COMPLETE
7
8      points = label,survey_points:-57,-60:-70,-109:-77,-144:-51
9
10     speed = 3.0 // meters per second
11  capture_radius = 8.0 // meters
12     nm_radius = 16.5 // meters
13     repeat = 0 // number of iterations
14     lead = 10 // meters
15 }
```

Parameter Summary for BHV_OpRegion

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
polygon	string	0,0:45,0:45,80:0,80:0,0	-	-	103
max_depth	double	200	-	0	104
min_altitude	double	25	-	0	104
max_time	double	3600	-	0	103
trigger_entry_time	double	1.5	-	0	103
trigger_exit_time	double	2.4	-	0	103
visual_hints	string	edge_size=1	no	-	102

Table 30: Parameters for the BHV_OpRegion behavior.

Example Behavior File Configuration for BHV_OpRegion

Listing B.2 - An example BHV_OpRegion configuration.

```

0 Behavior = BHV_OpRegion
1 {
2   name           = bhv_opregion
3   polygon        = label,opregion : -57,-60 : -70,-109 : -77,-144
4
5   max_depth      = 50      // meters
6   min_altitude  = 10      // meters
7   max_time       = 3600    // seconds
8   trigger_entry_time = 0.5 // seconds
9   trigger_exit_time = 1.0  // seconds
10 }

```

Parameter Summary for BHV_Loiter

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
acquire_dist	double	15	-	10	108
capture_radius	double	10	-	0	107
center_activate	Boolean	true	no	false	106
center_assign	string	present_position	no	-	106
clockwise	Boolean string	FALSE	no	true	107
polygon	string	0,0:45,0:45,80:0,80:0,0	yes	-	107
post_suffix	string	REGION-1	yes	""	108
speed	double	1.5	-	0	107
slip_radius	double [0,100]	25	-	0	107
spiral_factor	double	45	-	99	106
visual_hints	string	edge_size=1	no	-	106
x_center_assign	double	20	no	-	106
y_center_assign	double	25	no	-	106

Table 31: Parameters for the BHV_Loiter behavior.

Example Behavior File Configuration for BHV_Loiter

Listing B.3 - An example BHV_Loiter configuration.

```

0 Behavior = BHV_Loiter
1 {
2   name      = loiter_alpha
3   pwt       = 100
4   duration  = 3600 // One hour
5   updates   = LOITER_ALPHA_UPDATES
6
7   polygon   = radial:100,-100,80,12
8   speed     = 3.0
9
10  capture_radius = 8.0
11  slip_radius   = 16.0
12  clockwise    = true
13  acquire_dist = 25
14  center_assign = present_position
14 }

```

Parameter Summary for BHV_PeriodicSpeed

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
basewidth	double	0.5	-	0	110
initially_busy	Boolean string	true	no	false	110
peakwidth	double	0.2	-	0	110
period_busy	double	60	-	0	110
period_lazy	double	600	-	0	110
period_speed	double	0.8	-	0	110
reset_upon_running	Boolean string	false	no	true	110
summit_delta	double [0,100]	0.5	-	25	110

Table 32: Parameters for the BHV_PeriodicSpeed behavior.

Example Behavior File Configuration for BHV_PeriodicSpeed

Listing B.3 - An example BHV_PeriodicSpeed configuration.

```

0 Behavior = BHV_PeriodicSpeed
1 {
2   name      = periodic_speed
3   priority  = 500
4
5   period_length = 30 // Seconds
6   period_gap   = 120 // Seconds
7   reset_on_idle = true // The default
7   initially_busy = false // The default
7   period_speed = 0.5 // Meters/sec
8   peakwidth   = 0.3 // Meters/sec
9   basewidth   = 0.5 // Meters/sec
9   summit_delta = 25 // The default
12 }

```

Parameter Summary for BHV_PeriodicSurface

Parameter	Argument Type	Example	Case-Sense	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
acomms_mark_variable	MOOSVAR	RANGE_RECEIVED	yes	-	113
ascent_grade	string	quasi	no	linear	113
ascent_speed	double	1.0	-	*	113
mark_variable	MOOSVAR	GPS_RECEIVED	yes	GPS_UPDATE_RECEIVED	113
max_time_at_surface	MOOSVAR	60	yes	300	113
period	double	60	-	300	113
zero_speed_depth	double	2.5	-	0	113

Table 33: Parameters for the BHV_PeriodicSurface behavior.

Example Behavior File Configuration for BHV_PeriodicSurface

Listing B.4 - An example BHV_PeriodicSurface configuration.

```

0 Behavior = BHV_PeriodicSurface
1 {
2   name           = bhv_periodic_surface
3   priority       = 500
4   active_flag    = SURFACING, IN_PROGRESS
5   inactive_flag  = SURFACING, NO
6
7               period = 3600      // seconds
8   ascent_speed   = 1.0          // meters per second
9   zero_speed_depth = 2.5        // meters
10  max_time_at_surface = 120      // seconds
11  ascent_grade    = linear
12  acomms_mark_variable = RANGE_RECEIVED
13  mark_variable   = GPS_UPDATE_RECEIVED
14  status_variable = PERIODIC_PENDING_SURFACE
15 }
```

Parameter Summary for BHV_ConstantDepth

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
depth	double	35	-	0	114
peakwidth	double	5	-	0	114
basewidth	double	15	-	2	114

Table 34: Parameters for the BHV_ConstantDepth behavior.

Example Behavior File Configuration for BHV_ConstantDepth

Listing B.5 - An example BHV_ConstantDepth configuration.

```

0 Behavior = BHV_ConstantDepth
1 {
2   // General Behavior Parameters
3   name      = constant_depth_survey
4   priority  = 100
5   condition = AUTONOMY_MODE = SURVEY
6   duration  = no-time-limit
7   updates   = NEW_SURVEY_DEPTH
8   nostarve = NAV_DEPTH, 3.0
9
10  // BHV_ConstantDepth Behavior Parameters
11  depth = 50      // meters
12  peakwidth = 5
13  basewidth = 10
14 }

```

Parameter Summary for BHV_ConstantHeading

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
heading	double	35	-	0	115
peakwidth	double	5	-	10	115
basewidth	double	175	-	170	115

Table 35: Parameters for the BHV_ConstantHeading behavior.

Example Behavior File Configuration for BHV_ConstantHeading

Listing B.6 - An example BHV_ConstantHeading configuration.

```

0 Behavior = BHV_ConstantHeading
1 {
2   name      = bhv_constant_heading
3   priority  = 100
4   duration  = 60
5   condition = AUTONOMY_MODE = PID_TEST
6   updates   = NEW_TEST_HEADING
7   nostarve  = NAV_HEADING, 3.0
8
9   heading   = 45 // degrees
10  peakwidth = 0
11  basewidth = 5
12 }
```

Parameter Summary for BHV_ConstantSpeed

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
speed	double	1.2	-	0.0	116
peakwidth	double	0.1	-	0.0	116
basewidth	double	0.6	-	2.0	116

Table 36: Parameters for the BHV_ConstantSpeed behavior.

Example Behavior File Configuration for BHV_ConstantSpeed

Listing B.7 - An example BHV_ConstantSpeed configuration.

```

0 Behavior = BHV_ConstantSpeed
1 {
2   name      = const_speed_bravo
3   priority  = 100
4   duration  = 60
5   active_flag = BRAVO_SPEED_TEST = in-progress
6   nostarve  = NAV_SPEED, 2.0
7
8   speed     = 1.8 // meters per second
9   peakwidth = 0.3
10  basewidth = 1.0
11 }

```


Parameter Summary for BHV_GoToDepth

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
depth, depths	string	50,10:40,60	yes	-	117
repeat	int	5	-	0	117
capture_delta	double	2	-	2.5	117
capture_flag	MOOSVAR	DEPTH_HIT	yes	-	117

Table 37: Parameters for the BHV_GoToDepth behavior.

Example Behavior File Configuration for BHV_GoToDepth

Listing B.8 - An example BHV_GoToDepth configuration.

```

0 Behavior = BHV_GoToDepth
1 {
2   name      = goto_depth_set_alpha
3   priority  = 100
4   condition = DEPLOY == true
9   endflag   = GOTO_DEPTH_ALPHA = DONE
5
6     depths  = 15,30: 30,30: 45,60: 15,30
7   capture_delta = 1 // meters
8   capture_flag = DEPTH_LEVELS_ACHIEVED
9     repeat  = 4
10 }

```

Parameter Summary for BHV_MemoryTurnLimit

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
memory_time	double	60	-	-1	119
turn_range	double	45	-	-1	119

Table 38: Parameters for the BHV_MemoryTurnLimit behavior.

Example Behavior File Configuration for BHV_MemoryTurnLimit

Listing B.9 - An example BHV_MemoryTurnLimit configuration.

```

0 Behavior = BHV_MemoryTurnLimit
1 {
2   name      = memturnlimit
3   priority  = 1000
4
5   memory_time = 60 // seconds
6   turn_range = 35 // degrees
7 }
```

Parameter Summary for BHV_StationKeep

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
station_pt, point	string	50,75	yes	0,0	122
center_activate	Boolean string	TRUE	no	false	122
inner_radius	double	10	-	4	122
outer_radius	double	25	-	15	122
outer_speed	double	1.8	-	1.2	122
transit_speed	double	1.9	-	2.5	122
passive_station_radius	double	200	-	0	123
passive_station_variable	MOOSVAR	PSK_MODE.CHARLIE	-	PSKEEP_MODE	123

Table 39: Parameters for the BHV_StationKeep behavior.

Example Behavior File Configuration for BHV_StationKeep

Listing B.10 - An example BHV_StationKeep configuration.

```

0 Behavior = BHV_StationKeep
1 {
2   name      = bhv_station_keep
3   priority  = 100
4   condition = (ON_STATION=true) and (RETURN=false)
5   updates   = STATION_UPDATES
6
7             station_pt = 200,-150
8   center_activate = true
9   inner_radius   = 10
10  outer_radius   = 40
11  outer_speed    = 0.8
12  transit_speed  = 1.8
13  passive_station_radius = 400 // meters
14  passive_station_variable = PSKEEP_MODE // the default
15 }

```

Parameter Summary for BHV_Timer

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
No additional parameters for this behavior					

Table 40: Parameters for the BHV_Timer behavior.

Example Behavior File Configuration for BHV_Timer

Listing B.11 - An example BHV_Timer configuration.

```

0 Behavior = BHV_Timer
1 {
2   name      = bhv_timer_a
3   duration  = 60           // seconds
4   condition = loiter = alpha
5   end_flag  = loiter = beta
6 }
```

Parameter Summary for BHV_AvoidCollision

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
contact	string	Alliance	yes	-	128
on_no_contact_ok	boolean	true	no	true	129
extrapolate	boolean	true	no	false	128
decay	double,double	10, 30	-	0,0	128
bearing_lines	string		no	-	132
pwt_grade	string	quadratic	no	linear	132
completed_dist	double	200	-	500	132
pwt_inner_dist	double	50	-	50	132
pwt_outer_dist	double	200	-	200	132
max_util_cpa_dist	double	100	-	75	132
min_util_cpa_dist	double	10	-	10	132

Table 41: Parameters for the BHV_AvoidCollision behavior.

Example Behavior File Configuration for BHV_AvoidCollision

Listing B.12 - An example BHV_AvoidCollision configuration.

```

0 Behavior = BHV_AvoidCollision
1 {
2   name      = avoid_collision_alpha
3   pwt      = 100
4   condition = AVOIDANCE_MODE != INACTIVE
5
6           contact = alpha
7   on_no_contact_ok = true
8   extrapolate = true
9   decay = 30,60
10
11   pwt_outer_dist = 150
12   pwt_inner_dist = 75
13   min_util_cpa_dist = 15
14   max_util_cpa_dist = 80
15   pwt_grade = linear
16   bearing_line_config = white:0, green:0.65, yellow:0.8, red:1.016
14 }
```

Parameter Summary for BHV_CutRange

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
contact	string	Alliance	yes	-	128
on_no_contact_ok	boolean	true	no	true	129
extrapolate	boolean	true	no	false	128
decay	double,double	10, 30	-	0,0	128
dist_priority_interval	double,double	40,100	-	0,0	136
time_on_leg	double	60	-	15	136
give_up_range	double	500	-	0	136
patience	double	50	-	0	136

Table 42: Parameters for the BHV_CutRange behavior.

Example Behavior File Configuration for BHV_CutRange

Listing B.13 - An example BHV_CutRange configuration.

```

0 Behavior = BHV_CutRange
1 {
2   name      = bhv_cutrange
3   pwt      = 100
4   contact   = zulu
5
6   dist_priority_interval = 25,100
7     time_on_leg = 60
8     give_up_range = 400
9     patience = 75
10 }

```

Parameter Summary for BHV_Shadow

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
contact	string	Alliance	yes	-	128
on_no_contact_ok	boolean	true	no	true	129
extrapolate	boolean	true	no	false	128
decay	double,double	10, 30	-	0,0	128
max_range	double	100	-	0	136
heading_peakwidth	double	10	-	20	136
heading_basewidth	double	170	-	160	136
speed_peakwidth	double	0.3	-	0.1	136
speed_basewidth	double	0.5	-	2.0	136

Table 43: Parameters for the BHV_Shadow behavior.

Example Behavior File Configuration for BHV_Shadow

Listing B.14 - An example BHV_Shadow configuration.

```

0 Behavior = BHV_Shadow
1 {
2   name      = bhv_shadow
3   pwt       = 100
4   contact   = delta
5
6     max_range = 200
7   heading_peakwidth = 10
8   heading_basewidth = 170
9   speed_peakwidth = 10
10  speed_basewidth = 170
11 }
```

Parameter Summary for BHV_Trail

Parameter	Argument Type	Example	Case-Sensitive	Default	Page
name	string	loiter-west-zone	yes	-	78
duration	double	600	-	-1	81
duration_status	MOOSVAR	loiter_remaining	yes	-	81
priority, pwt	double	100	-	100	78
runflag	MOOSVAR=value	LOITERING = maybe	yes	-	70
endflag	MOOSVAR=value	LOITERING = done	yes	-	70
activeflag	MOOSVAR=value	LOITERING = yes	yes	-	70
inactiveflag	MOOSVAR=value	LOITERING = off	yes	-	70
idleflag	MOOSVAR=value	LOITERING = no	yes	-	70
nostarve	MOOSVAR,double	INFO,60	yes	-	82
perpetual	Boolean string	false	no	false	82
post_mapping	MOOSVAR,MOOSVAR	FOO,BAR	yes	-	79
updates	MOOSVAR	LOITER_INFO	yes	-	80
condition	Logic Expression	QUALITY <= 7	yes	-	69
contact	string	Alliance	yes	-	128
on_no_contact_ok	boolean	true	no	true	129
extrapolate	boolean	true	no	false	128
decay	double,double	10, 30	-	0,0	128
trail_range	double	20	-	50	136
trail_angle	double	270	-	180	136
trail_angle_type	string	absolute	no	relative	136
radius	double	8	-	5	136
nm_radius	double	20	-	20	136
max_range	double	50	-	0	136

Table 44: Parameters for the BHV_Trail behavior.

Example Behavior File Configuration for BHV_Trail

Listing B.15 - An example BHV_Trail configuration.

```

0 Behavior = BHV_Trail
1 {
2   name           = bhv_trail
3   priority       = 100
4
5   contact        = delta
6   extrapolate    = true
7   on_no_contact_ok = true
8   decay          = 20,60    // seconds
9
10  trail_range    = 50        // meters
11  trail_angle    = 185      // degrees
12  trail_angle_type = relative
13    radius       = 10        // meters
14    nm_radius    = 30        // meters
15    max_range    = 300      // meters
16 }

```


C Colors

Below are the colors used by IvP utilities that use colors. Colors are case insensitive. A color may be specified by the string as shown, or with the '_' character as a separator. Or the color may be specified with its hexadecimal or floating point form. For example the following are equivalent: "darkblue", "DarkBlue", "dark_blue", "hex:00,00,8b", and "0,0,0.545".

antiquewhite, (fa,eb,d7)	deeppink (ff,14,93)
aqua (00,ff,ff)	deepskyblue (00,bf,ff)
aquamarine (7f,ff,d4)	dimgray (69,69,69)
azure (f0,ff,ff)	dodgerblue (1e,90,ff)
beige (f5,f5,dc)	firebrick (b2,22,22)
bisque (ff,e4,c4)	floralwhite (ff,fa,f0)
black (00,00,00)	forestgreen (22,8b,22)
blanchedalmond(ff,eb,cd)	fuchsia (ff,00,ff)
blue (00,00,ff)	gainsboro (dc,dc,dc)
blueviolet (8a,2b,e2)	ghostwhite (f8,f8,ff)
brown (a5,2a,2a)	gold (ff,d7,00)
burlywood (de,b8,87)	goldenrod (da,a5,20)
cadetblue (5f,9e,a0)	gray (80,80,80)
chartreuse (7f,ff,00)	green (00,80,00)
chocolate (d2,69,1e)	greenyellow (ad,ff,2f)
coral (ff,7f,50)	honeydew (f0,ff,f0)
cornsilk (ff,f8,dc)	hotpink (ff,69,b4)
cornflowerblue(64,95,ed)	indianred (cd,5c,5c)
crimson (de,14,3c)	indigo (4b,00,82)
cyan (00,ff,ff)	ivory (ff,ff,f0)
darkblue (00,00,8b)	khaki (f0,e6,8c)
darkcyan (00,8b,8b)	lavender (e6,e6,fa)
darkgoldenrod (b8,86,0b)	lavenderblush (ff,f0,f5)
darkgray (a9,a9,a9)	lawngreen (7c,fc,00)
darkgreen (00,64,00)	lemonchiffon (ff,fa,cd)
darkkhaki (bd,b7,6b)	lightblue (ad,d8,e6)
darkmagenta (8b,00,8b)	lightcoral (f0,80,80)
darkolivegreen(55,6b,2f)	lightcyan (e0,ff,ff)
darkorange (ff,8c,00)	lightgoldenrod(fa,fa,d2)
darkorchid (99,32,cc)	lightgray (d3,d3,d3)
darkred (8b,00,00)	lightgreen (90,ee,90)
darksalmon (e9,96,7a)	lightpink (ff,b6,c1)
darkseagreen (8f,bc,8f)	lightsalmon (ff,a0,7a)
darkslateblue (48,3d,8b)	lightseagreen (20,b2,aa)
darkslategray (2f,4f,4f)	lightskyblue (87,ce,fa)
darkturquoise (00,ce,d1)	lightslategray(77,88,99)
darkviolet (94,00,d3)	lightsteelblue(b0,c4,de)

lightyellow (ff,ff,e0)
lime (00,ff,00)
limegreen (32,cd,32)
linen (fa,f0,e6)
magenta (ff,00,ff)
maroon (80,00,00)
mediumblue (00,00,cd)
mediumorchid (ba,55,d3)
mediumseagreen(3c,b3,71)
mediumslateblue(7b,68,ee)
mediumspringgreen(00,fa,9a)
mediumturquoise(48,d1,cc)
mediumvioletred(c7,15,85)
midnightblue (19,19,70)
mintcream (f5,ff,fa)
mistyrose (ff,e4,e1)
moccasin (ff,e4,b5)
navajowhite (ff,de,ad)
navy (00,00,80)
oldlace (fd,f5,e6)
olive (80,80,00)
olivedrab (6b,8e,23)
orange (ff,a5,00)
orangered (ff,45,00)
orchid (da,70,d6)
palegreen (98,fb,98)
paleturquoise (af,ee,ee)
palevioletred (db,70,93)
papayawhip (ff,ef,d5)
peachpuff (ff,da,b9)
pelegoldenrod (ee,e8,aa)
peru (cd,85,3f)
pink (ff,c0,cb)
plum (dd,a0,dd)
powderblue (b0,e0,e6)
purple (80,00,80)
red (ff,00,00)
rosybrown (bc,8f,8f)
royalblue (41,69,e1)
saddlebrowm (8b,45,13)
salmon (fa,80,72)
sandybrown (f4,a4,60)
seagreen (2e,8b,57)
seashell (ff,f5,ee)
sienna (a0,52,2d)
silver (c0,c0,c0)
skyblue (87,ce,eb)
slateblue (6a,5a,cd)
slategray (70,80,90)
snow (ff,fa,fa)
springgreen (00,ff,7f)
steelblue (46,82,b4)
tan (d2,b4,8c)
teal (00,80,80)
thistle (d8,bf,d8)
tomatao (ff,63,47)
turquoise (40,e0,d0)
violet (ee,82,ee)
wheat (f5,de,b3)
white (ff,ff,ff)
whitesmoke (f5,f5,f5)
yellow (ff,ff,00)
yellowgreen (9a,cd,32)

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Index

- DISENGAGED, [45](#), [144](#)
 - ENGAGED, [45](#)
 - IVPHELM_ALLSTOP, [47](#)
- Action Selection, [59](#)
- All-Stop, [47](#)
- Antler, [40](#)
- AvoidCollision Behavior, [132](#)
- Backseat Driver, [18](#)
- Behavior Files, [62](#)
 - Loading, [49](#)
 - Syntax checking, [52](#)
 - Variable Initialization, [62](#)
- Behavior Subscriptions, [44](#)
- Behavior-Posts, [56](#), [175](#)
- Command and Control
 - pMarineViewer, [199](#)
- Command Line Usage
 - pBasicContactMgr, [223](#)
 - uTimerScript, [209](#)
- Conditions, [229](#)
- Configuration Parameters
 - pBasicContactMgr, [222](#), [223](#)
 - pMarineViewer, [200](#)
 - uHelmScope, [178](#)
 - uTimerScript, [208](#), [209](#)
- ConstantDepth Behavior, [114](#), [154](#)
- ConstantHeading Behavior, [115](#)
- ConstantSpeed Behavior, [116](#)
- Contact Management, [169](#), [221](#)
- CutRange Behavior, [135](#)
- Duplication Filter, [55](#), [61](#)
- Dynamic Behavior Spawning, [89](#), [161](#), [168](#)
- Engagement State, [45](#)
 - START_ENGAGED, [47](#), [50](#)
 - On Helm Start-Up, [47](#)
 - Relation to All-Stop, [49](#)
 - Transitions, [45](#)
- Example Missions
 - Mission M1: The Multi-Loiter Mission, [166](#)
 - Mission M2: The Berta Mission, [167](#)
 - Mission S3: The Charlie Mission, [144](#)
 - Mission S4: The Delta Mission, [152](#)
 - Mission S5: The Echo Mission, [160](#)
- Geometry Utilities, [180](#)
 - Ellipses, [144](#)
 - Points, [180](#)
 - SegLists, [155](#), [183](#)
- GoToDepth Behavior, [117](#)
- GPS, [217](#)
- Hierarchical Mode Declarations, [63](#), [69](#), [144](#)
 - Example Mission, [65](#)
 - Realizable Modes, [67](#)
 - Run Time Monitoring, [67](#)
 - Syntax, [66](#)
- iMarineSim, [41](#), [219](#)
 - IMS_FORCE_VECTOR_ADD, [219](#)
 - IMS_FORCE_VECTOR, [219](#)
- IvP Behavior Functions
 - Helm-Invoked Functions, [83](#)
 - Helm-Invoked Immutable Functions, [85](#)
 - Helm-Invoked Overloadable Functions, [85](#)
 - Implementor-Invoked Functions, [86](#)
 - The addInfoVars() Function, [86](#), [88](#)
 - The checkUpdates() Function, [85](#)
 - The getBuffer*() Functions, [86](#), [88](#)
 - The getBufferCurrTime() Function, [86](#)
 - The isComplete() Function, [85](#)
 - The isRunnable() Function, [85](#)
 - The onIdleState() Function, [77](#), [85](#), [89](#)
 - The onRunState() Function, [77](#), [85](#), [89](#)
 - The post*Message() Functions, [86](#), [87](#)
 - The postFlags() Function, [85](#)
 - The setComplete() Function, [86](#)
 - The setParam() Function, [77](#), [83](#), [85](#)
- IvP Behavior Parameters, [78](#)
 - activeflag, [70](#), [79](#)

- condition, 38, 59, 79
- duration_idle_decay, 79
- duration_reset, 78
- duration_status, 78
- duration, 69, 78, 81
- endflag, 38, 59, 70, 80
- idleflag, 70, 79
- inactiveflag, 70
- name, 38, 78
- nostarve, 80, 82
- perpetual, 80, 82
- post_mapping, 79
- priority, 38, 78
- runflag, 70, 79
- templating, 80
- updates, 80, 97, 163, 174
- IvP Behaviors, 61, 68
 - Conditions, *see* Run Conditions
 - Duration, 69
 - Dynamic Configuration, 80, 97, 174
 - Flags, 70
 - Independence, 58
 - Messages, 70
 - Priority Weights, 75
 - Run Conditions, 68, 69
 - Run States, 69, 71
 - Sequences, 59
 - State, 59
 - Subscriptions, 44
 - The Information Buffer, 87
- IvP Behaviors Implemented
 - BHV_AvoidCollision, 132, 167
 - BHV_BearingLine, 160
 - BHV_ConstantDepth, 114, 154
 - BHV_ConstantHeading, 115
 - BHV_ConstantSpeed, 116
 - BHV_CutRange, 135
 - BHV_GoToDepth, 117, 119
 - BHV_Loiter, 106, 144, 146, 167
 - BHV_OpRegion, 102
 - BHV_PeriodicSpeed, 110
 - BHV_PeriodicSurface, 112, 154
 - BHV_Shadow, 137
 - BHV_StationKeep, 121, 144, 148
 - BHV_Timer, 126
 - BHV_Trail, 138
 - BHV_Waypoint, 95, 144, 152, 155, 160
- IvP Build Toolbox, 72
- IvP Domain, 46, 49, 59
- IvP Function, 58, 59, 61, 72
- IvP Helm
 - Iterate() Loop, 60
 - All-Stop, 47, 49
 - Behavior Files, 62
 - Behaviors, 58
 - Console Output, 50, 51
 - Decision Space, 61
 - Design Philosophy, 19
 - Duplication Filter, 55, 61
 - Engagement State, 45, 49
 - Hierarchical Mode Declarations, 63
 - Initial Engagement State, 47
 - Manual Override, 49
 - Publications, 53
 - Solver, 72
 - Subscriptions, 55
- IvP Helm Parameters, 48
- IvP Solver, 75
- Life Events, 91
- Logic Expressions, 229
- Loiter Behavior, 106, 146
- MemoryTurnLimit Behavior, 119
- Mission Behavior Files, *see* Behavior Files
- MOOS, 22
 - Acronymn, 11
 - Architecture, 19, 22
 - Background, 11
 - Code Re-use, 16
 - Community, 22, 26, 27, 29, 31, 49
 - Design Philosophy, 15
 - Documentation, 14
 - Messages, 22
 - Operating Systems, 13
 - Publish and Subscribe, 22
 - Source Code, 12
 - Sponsors, 11
- MOOS Messages, 22
 - Skew, 49
- MOOSDB

- Community, 26
- ServerHost, 26
- ServerPort, 26
- Mouse
 - Mouse Poke Configuration, 163, 193
 - Mouse Pokes in pMarineViewer, 156, 163, 192
- OpRegion Behavior, 102
- pAntler, 40
- pBasicContactMgr, 221
 - Command Line Usage, 223
 - Configuration Parameters, 222, 223, 225
 - ALERT_CPA_RANGE, 225
 - ALERT_CPA_TIME, 225
 - ALERT, 223
 - CONTACT_MAX_AGE, 225
 - Publications, 222
 - Subscriptions, 222
- PeriodicSpeed Behavior, 110
- PeriodicSurface Behavior, 112, 154
- pMarinePID, 41
- pMarineViewer, 42, 185
 - Actions, 191
 - Command and Control, 199
 - Configuration Parameters, 200
 - vehicles_name_viewable, 146
 - Drop Points, 197
 - Geometric Objects, 198
 - GUI Buttons, 199
 - Markers, 196
 - Poking the MOOSDB, 191, 199
 - Pull-Down Menu (Action), 191
 - Pull-Down Menu (BackView), 187
 - Pull-Down Menu (GeoAttributes), 189
 - Pull-Down Menu (MouseContext), 156, 163, 192
 - Pull-Down Menu (ReferencePoint), 194
 - Pull-Down Menu (Scope), 191
 - Pull-Down Menu (Vehicles), 190
 - Vehicle Shapes, 195
- pNodeReporter, 42
- Points, 180
- Priority Weights, *see* IvP Behaviors, Priority Weights
- Publications
 - pBasicContactMgr, 222
 - uTimerScript, 209
- Publications and Subscriptions
 - pHelmIvP, 52
 - uHelmScope, 179
- SegLists, 155, 183
- ServerHost, *see* MOOSDB, ServerHost
- ServerPort, *see* MOOSDB, ServerPort
- Shadow Behavior, 137
- Skew, *see* MOOS Messages, Skew
- Source Code
 - Building, 12
 - Example Missions, 36
 - Obtaining, 12
 - Running, 29, 36
- Start Delay
 - uTimerScript, 215
- StationKeep Behavior, 121, 148
- Subscriptions
 - pBasicContactMgr, 222
 - uTimerScript, 209
- Time Warp
 - uTimerScript, 215
- Timer Behavior, 126
- Trail Behavior, 138
- uHelmScope, 67, 71, 92, 173
 - Configuration Parameters, 178
 - Console output, 173
 - Life Event History, 92
 - Mission Modes, 67
 - Publications and Subscriptions, 179
 - Scoping the MOOSDB, 175
 - Stepping through time, 176
 - User Input, 176
- uTimerScript, 208
 - Arithmetic Expressions, 214
 - Atomic Scripts, 212
 - Command Line Usage, 209
 - Conditional Pausing, 212
 - Configuration Parameters, 208–216
 - CONDITION, 212, 218
 - DELAY_RESET, 220

- DELAY_RESTART, [218](#)
- EVENT, [210](#), [218](#), [220](#)
- FORWARD_VAR, [213](#)
- PAUSED, [212](#)
- PAUSE_VAR, [212](#)
- RAND_VAR, [214](#), [220](#)
- RESET_MAX, [211](#), [218](#), [220](#)
- RESET_TIME, [211](#), [218](#), [220](#)
- RESET_VAR, [211](#)
- SCRIPT_ATOMIC, [212](#)
- SCRIPT_NAME, [216](#), [218](#), [220](#)
- SHUFFLE, [211](#)
- START_DELAY, [215](#)
- STATUS_VAR, [216](#)
- TIME_WARP, [215](#), [220](#)
- UPON_AWAKE, [211](#), [218](#)
- Configuring the Event List, [210](#)
- Example Usage, [91](#), [167](#)
- Fast Forwarding in Time, [212](#)
- Jumping To the Next Event, [212](#)
- Logic Conditions, [212](#)
- Macros, [213](#), [218](#), [220](#)
- Macros Built-In, [213](#)
- Pausing the Script, [212](#)
- Pausing the Script with Conditions, [212](#)
- Publications, [209](#)
- Resetting, [211](#), [218](#), [220](#)
- Script Flow Control, [211](#), [212](#)
- Simulated GPS Unit, [217](#)
- Simulated Random Wind Gusts, [219](#)
- Start Delay, [215](#), [218](#), [220](#)
- Subscriptions, [209](#)
- Time Warp, [215](#)
- uXMS, [175](#)
- Virgin Variables, [175](#)
- Waypoint Behavior, [95](#), [155](#)
- Wind, [219](#)
- Wind - Simulated Wind Gusts, [144](#)

Index of MOOS Variables

BEARING_POINT, 163
 CLOSING_SPD_AVD, 132
 CONTACTS_ALERTED, 222, 225
 CONTACTS_LIST, 222, 225
 CONTACTS_RECAP, 222, 225
 CONTACTS_RETIRED, 222, 225
 CONTACTS_UNALERTED, 222, 225
 CONTACT_INFO, 167, 169
 CONTACT_MGR_WARNING, 222
 CONTACT_RESOLVED, 132, 222
 CYCLE_INDEX, 96, 99
 DEPLOY, 42
 DESIRED_HEADING, 41
 DESIRED_RUDDER, 41
 DESIRED_SPEED, 41
 DESIRED_THRUST, 41
 GPS_UPDATE_RECEIVED, 113, 218
 HELM_MAP_CLEAR, 55, 57
 IMS_DECELERATION, 149
 IMS_FORCE_VECTOR_ADD, 219
 IMS_FORCE_VECTOR, 219
 IVPHELM_ALLSTOP, 47
 IVPHELM_DOMAIN, 177, 179
 IVPHELM_ENGAGED, 177, 179
 IVPHELM_ENGAGEMENT, 46
 IVPHELM_LIFE_EVENT, 91, 177
 IVPHELM_MODESET, 177, 179
 IVPHELM_POSTINGS, 177, 179
 IVPHELM_STATEVARS, 177, 179
 IVPHELM_SUMMARY, 145, 177, 179
 LOITER_ACQUIRE, 107
 LOITER_DIST_TO_POLY, 107
 LOITER_ETA_TO_POLY, 107
 LOITER_INDEX, 107
 LOITER_REPORT, 107, 146
 MOOS_MANUAL_OVERRIDE, 45, 46, 50, 55, 145
 MOOS_MANUAL_OVERRIDE, 45, 46, 50, 55, 145
 MVIEWER_LCLICK, 156, 192, 199
 MVIEWER_RCLICK, 156, 192, 199
 NAV_DEPTH, 219, 223
 NAV_HEADING, 41, 42, 219, 222
 NAV_SPEED, 41, 42, 219, 223
 NAV_X, 41, 42, 219, 222
 NAV_Y, 41, 42, 219, 222
 NODE_REPORT_LOCAL, 42
 NODE_REPORT, 42, 222
 OPREG_ABSOLUTE_PERIM_DIST, 102
 OPREG_ABSOLUTE_PERIM_ETA, 102
 OPREG_TIME_REMAINING, 102
 OPREG_TRAJECTORY_PERIM_DIST, 102
 OPREG_TRAJECTORY_PERIM_ETA, 102
 PENDING_SURFACE, 113
 PSKEEP_MODE, 123
 PS_BUSY_COUNT, 111
 PS_PENDING_BUSY, 111
 PS_PENDING_LAZY, 111
 RANGE_AVD, 132
 RETURN, 42
 SURVEY_UPDATES, 155
 TIMER_IDLE, 126
 TIMER_RUNNING, 126
 TIME_AT_SURFACE, 113
 UTS_FORWARD, 208, 209, 213
 UTS_NEXT, 209
 UTS_PAUSE, 208, 209, 212
 UTS_RESET, 208, 209, 211
 UTS_STATUS, 208, 209, 215, 216
 VIEW_MARKER, 42
 VIEW_POINT, 42, 96, 99, 107
 VIEW_POLYGON, 42, 102, 107
 VIEW_SEGLIST, 42, 57, 96, 99, 132, 135, 139
 WPT_INDEX, 96, 99
 WPT_STAT, 96, 99

