Action Selection and Vertical Plane Dynamic Control for Survey-Class Autonomous Underwater Vehicles

by

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S.B., Massachusetts Institute of Technology (1991)

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Abstract

As autonomous underwater vehicles (AUVs) expand their role in oceanographic research, the complexity of their expected missions and behavior sets also increases. This trend requires an approach to structuring AUV control which can provide reliable, rational, and time-sensitive trade-offs between relatively abstract criteria such as power conservation, robustness to environmental variations, and exploitation of serendipitous opportunities. Concepts from action selection and systems and control theories are integrated in an asynchronous action hierarchy to meet these challenges. A general transit dynamic controller is developed both to illustrate the use of the asynchronous action hierarchy concepts and to highlight the advantages to integrating the projects of action selection and dynamic control. The performance of the general transit controller and the asynchronous action hierarchy is evaluated and future areas of research are identified.

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I have learned
To look on nature, not as in the hour
Of thoughtless youth; but hearing oftentimes
The still, sad music of humanity,
Nor harsh not grating, though of ample power
To chasten and subdue. And I have felt
A presence that disturbs me with the joy
Of elevated thoughts; a sense sublime
Of something far more deeply interfused,
Whose dwelling is the light of setting suns,
And the round ocean and the living air,
And the blue sky, and in the mind of man.

—Wordsworth
from ‘Lines composed a few miles above Tintern Abbey’

To my Mother and Father
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List of Symbols

\( A \) \quad \text{system state matrix}

\( \mathcal{A} \) \quad \text{fin aspect ratio}

\( A \) \quad \text{thruster cross-sectional area}

\( a \) \quad \text{hull radius}

\( \bar{a} \) \quad \text{aspect ratio constant}

\( \frac{\partial C_L}{\partial \alpha} \) \quad \text{fin marginal lift coefficient}

\( D \) \quad \text{vehicle diameter}

\( F_i \) \quad \text{generalized force}

\( g \) \quad \text{gravitational acceleration}

\( I_{xx} \) \quad \text{moment of inertia along } x \text{ axis}

\( I_{yy} \) \quad \text{moment of inertia along } y \text{ axis}

\( I_{zz} \) \quad \text{moment of inertia along } z \text{ axis}

\( i \) \quad \text{thruster current}

\( i \) \quad \text{index}

\( j \) \quad \text{index}

\( K \) \quad \text{general roll moment}

\( K_{in} \) \quad \text{thruster entering fluid specific kinetic energy}
LIST OF SYMBOLS

$K_{out}$: thruster exiting fluid specific kinetic energy

$K_T$: thruster electrorotational gyrator conversion constant

$k$: index

$L$: vehicle length

$l$: index

$M$: body mass tensor

$M$: general pitch moment

$M_{\text{added mass}}$: pitch moment due to added mass

$M_{\text{body mass}}$: pitch moment due to body mass

$M_{\text{fin lift}}$: pitch moment due to fin lift

$M_{\text{hull lift}}$: pitch moment due to hull lift

$M_{\text{hydrostatic}}$: pitch moment due to hydrostatic forces

$M_i$: generalized moment

$M_{\text{nom}}$: nominal force upon which pitch process noise is based

$M_q$: pitch velocity pitch hydrodynamic coefficient

$M_{\dot{q}}$: pitch acceleration pitch hydrodynamic coefficient

$M_{\ddot{u}}$: surge acceleration pitch hydrodynamic coefficient

$M_w$: heave velocity pitch hydrodynamic coefficient

$M_{\dot{w}}$: heave acceleration pitch hydrodynamic coefficient

$M_{\text{section}}$: pitch moment on a cross-section

$M_{\text{slender body}}$: slender body approximation of pitch moment

$M_\delta$: fin angle pitch hydrodynamic coefficient
LIST OF SYMBOLS

\( M_\theta \) pitch angle pitch hydrodynamic coefficient

\( m \) vehicle mass

\( m_a \) added mass tensor

\( m_{a_{\text{circle}}} \) added mass coefficient for a circular cross-section

\( m_{a_{\text{circle with fins}}} \) added mass coefficient for a circular cross-section with cruciform fins

\( m_{ij} \) generalized mass coefficient

\( N \) general yaw moment

\( p \) roll angular velocity

\( Q \) thruster volumetric flowrate

\( q \) pitch angular velocity

\( \dot{q} \) perturbed pitch velocity

\( R_E \) thruster electrical resistance

\( r \) yaw angular velocity

\( S \) fin projected surface area

\( s \) fin span

\( s \) maximum radius of a circular cross-section with cruciform fins

\( T \) thruster thrust

\( T \) thruster fluid total kinetic energy

\( t \) time

\( t_s \) settling time

\( t_0 \) time at which a transition begins
LIST OF SYMBOLS

$U_i$ generalized velocity  
$u$ surge velocity  
$\bar{u}$ expected surge velocity  
$u_{no
dive}$ the critical velocity at which the steady state depth rate is zero  
$u_{out}$ thruster exit velocity  
$u_{ss}$ steady-state surge velocity  
$V$ total velocity in the vertical plane  
$V$ thruster input voltage  
$v$ sway velocity  
$w$ heave velocity  
$\bar{w}$ expected heave velocity  
$\hat{w}$ perturbed heave velocity  
$w_{section}$ heave velocity at a cross-section  
$w_{ss}$ steady-state heave velocity  
$X$ general axial force  
$X_{added
d mass}$ surge force due to added mass  
$X_{body
d mass}$ surge force due to body mass  
$X_{drag}$ surge force due to drag  
$X_{nom}$ nominal force upon which surge process noise is based  
$X_{\dot{q}}$ pitch acceleration surge hydrodynamic coefficient  
$X_u$ surge velocity surge hydrodynamic coefficient  
$X_{\ddot{u}}$ surge acceleration surge hydrodynamic coefficient
LIST OF SYMBOLS

\( x \) axial direction in vehicle-fixed coordinates
\( x_{\text{fin lift}} \) axial position of the fin lift force
\( x_{\text{hull}} \) axial position of a cross-section, restricted to the domain over which the hull is defined
\( x_{\text{hull lift}} \) axial position of the hull lift force
\( x_{\text{section}} \) axial position of a cross-section
\( Y \) general lateral force
\( y \) lateral direction in vehicle-fixed coordinates
\( Z \) general vertical force
\( Z_{\text{added mass}} \) heave force due to added mass
\( Z_{\text{body mass}} \) heave force due to body mass
\( Z_{\text{fin lift}} \) heave force due to fin lift
\( Z_{\text{hull lift}} \) heave force due to hull lift
\( Z_{\text{nom}} \) nominal force upon which heave process noise is based
\( Z_{\text{section}} \) heave force on a cross-section
\( Z_{\text{slender body}} \) slender body approximation of heave force
\( Z_{q} \) pitch velocity heave hydrodynamic coefficient
\( Z_{q} \) pitch acceleration heave hydrodynamic coefficient
\( Z_{w} \) heave velocity heave hydrodynamic coefficient
\( Z_{\dot{w}} \) heave acceleration heave hydrodynamic coefficient
\( Z_{\phi} \) fin angle heave hydrodynamic coefficient
\( z \) vertical direction in vehicle-fixed coordinates
LIST OF SYMBOLS

\( z_G \) distance between the centers of buoyancy and gravity in the \( z \) direction
\( \alpha \) sideslip angle in the vertical plane
\( \beta \) surge added mass coefficient parameter
\( \nabla \) effective thruster volume
\( \delta \) elevator angle
\( \delta_{\text{command}} \) commanded elevator angle
\( \delta_f \) target elevator angle
\( \delta_o \) constant or initial elevator angle
\( \varepsilon \) Kronecker delta
\( \zeta \) vertical direction in earth-fixed coordinates
\( \zeta_{\text{over}} \) depth overshoot
\( \zeta_{\text{rd}} \) recovery draft
\( \zeta_{\text{under}} \) depth undershoot
\( \eta \) lateral direction in earth-fixed coordinates
\( \eta p \) effective propeller pitch
\( \theta \) pitch angle
\( \theta_{\text{over}} \) pitch overshoot
\( \bar{\theta} \) perturbed pitch angle
\( \theta_{ss} \) steady-state pitch angle
\( \mu \) dive angle coefficient
\( \nu \) process noise variable
\( \xi \) horizontal direction in earth-fixed coordinates
LIST OF SYMBOLS

\( \rho \) water density
\( \sigma \) sideslip ratio
\( \sigma_{\text{noise}} \) process noise standard deviation
\( \tau \) propeller torque
\( \tau_{\text{decay}} \) transition decay time constant
\( \tau_{\text{SF}} \) propeller static friction
\( \Omega_i \) generalized angular velocity
\( \omega \) propeller angular velocity
Chapter 1

Introduction

Autonomous underwater vehicles (AUVs) hold great promise for enhancing oceanographic research. Their perceived role is increasing from a solution to the exploration of otherwise inaccessible regions, such as beneath the polar ice caps, to one of cooperative engagement with other forms of ocean monitoring, such as remotely operated vehicles (ROVs) and manned submersibles. As the role of AUVs in oceanographic research increases, they are required to exhibit ever more complex sets of behaviors and goals. A higher level of competence is demanded both in terms of autonomous decision-making and judgements about the vehicle’s situation and environment and in terms of reliability of individual subsystems and the vehicle as a whole. This trend requires an approach to structuring AUV control which can provide reliable, rational, and time-sensitive trade-offs between relatively abstract criteria such as power conservation, robustness to environmental variations, and exploitation of serendipitous opportunities. The objective of this thesis is to adapt the current structure of vehicle intelligence in order to provide such a unifying mechanism for vehicle action selection and control in the presence of widely varying goals, behaviors, and environments.

We begin with a consideration of the action selection problem in Chapter 2. Because of the wide range of behavior modules used in a complex autonomous agent such as an AUV, a single dynamic controller, such as the product of system and control theoretic considerations, will fail to address the varying control needs of different behaviors. Conversely, higher level studies of action selection have tended to focus at a level of abstration much more complex than vehicle dynamics, complicating the implementation of
these ideas on a mobile robotic platform with non-trivial dynamics. Consideration of the contributions of both fields leads to the development of an asynchronous action hierarchy to manage vehicle action selection, activity implementation, and dynamic control for the AUV. The next three chapters cover the development of a dynamic controller for general transit and illustrate the interleaving of concerns relating to action selection and dynamic control. The particular project of general transit dynamic control serves to highlight both the impact of dynamic control on action selection and the power of action selection theory in helping to formulate control strategies. A model of the vertical plane dynamics for a survey-class AUV is derived in Chapter 3. The importance of various forces in determining control attributes such as natural frequency and steady-state response is noted. The development of the general transit vertical plane dynamic controller is begun in Chapter 4. This controller is designed to demonstrate the construction of a vehicle dynamic controller using activity modules; traditional control theoretic principles give way to a more ethologically-inspired approach of action selection under conditions of general transit. The operating regimes for this controller are discussed along with its integration with other dynamic controllers in the asynchronous action hierarchy. The performance of the general transit controller is evaluated in Chapter 5. The performance of the controller in simulation is presented, and the sensitivity of the general transit controller to various types of modeling errors is also examined. In Chapter 6, conclusions about the action hierarchy approach to action selection and dynamic control are drawn. Future research possibilities, such as specific implementation issues for the hierarchy and the general transit controller, are discussed.
Chapter 2

The Problem of Action Selection

Perhaps the most central question for an autonomous agent such as an AUV is what to do next. The artificial intelligence literature refers to this as the action selection problem and has produced a number of approaches to its solution. Action selection approaches in behavior-based artificial intelligence accentuate the need for adaptivity and use of emerging opportunities to meet multiple, possibly conflicting goals. Literature on dynamic control, on the other hand, only implicitly asks the question. Control theory is concerned precisely with the question of what motor actions should be carried out. A control theoretic approach often involves determining the in some sense optimal general solution for mapping the current and desired vehicle states into an actuator command. When a system becomes more complex, the specific needs that the controller tries to meet may change drastically, in which case the action selection approach is necessary. But dynamic control is an ever present requirement, so the issue of vehicle dynamics cannot be ignored. In this chapter, the role of action selection for an AUV is examined and the impact of action selection on control strategies is addressed. This leads to the development of an action selection model for use in a survey-class AUV. Its relationship to other action selection approaches is described and its impact on vehicle control is identified.
2.1 The Action Selection Problem

2.1.1 Current Structure of Odyssey Intelligence

Before considering the action selection problem further, it is useful to take a look at the current intelligence architecture, shown in Figure 2.1. Intelligence architecture refers to the structure of the decision-making modules which make up the vehicle’s programming. The level of resolution of an intelligence architecture is more abstract than a specific software implementation, but captures to flow of information, control, and decision-making capabilities. The goals of the vehicle are embodied in a set of behavior modules. These modules synchronously produce suggested actions for the AUV based on the current vehicle state and their particular projects. The behavior modules and their associated suggested actions have a priority which is determined as part of the mission setup. A fixed arbitration scheme is used to select the appropriate (highest priority) action for the AUV to pursue. A dynamic controller transforms this desired action into actuator commands.

The current approach to structuring AUV intelligence have yielded good overall performance. Experience has indicated, however, that an improved approach to action selection will further streamline the process of combining the wide variety of behaviors necessary for reliable operation in an unknown and rich dynamic environment. While any particular control strategy might be suitable under certain circumstances, control theory does not extend to the dynamic breadth required of the vehicle under all circumstances. Additionally, the fixed arbitration scheme hampers vehicle adaptivity in the presence of changing goals. For these reasons, casting the control problem as a part of action selection makes sense.

2.1.2 Generalized AUV Intelligence Architecture

The combined problems of action selection and dynamic control are tackled by providing an organized structure between the behavior modules and the motor and sensory subsystems, as shown in Figure 2.2. This structure contains the mechanism for combining the suggested actions of the various behaviors (at various levels of abstraction) and processing them using the appropriate dynamic control strategy to produce commands at the level of the motor and sensory subsystems. Furthermore, we explicitly acknowledge the
CHAPTER 2. ACTION SELECTION

Figure 2.1: The current intelligence architecture of the AUV Odyssey. A state table configures the set of operative behavior modules. The arbitrator selects the highest priority requested action for implementation through the dynamic controller.
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Figure 2.2: Action selection and dynamic control in a more generalized AUV intelligence architecture. An integrated structure handles action selection and dynamic control for the agent. The context of the actions is encoded in meta-goals.

fact that action selection and dynamic control take place in the larger context of a vehicle mission. This context is represented by meta-goals, adaptive vehicle attributes which reflect a disposition or tendency in the way actions are implemented. These meta-goals facilitate the determination of the proper control trade-offs, such as between power conservation and trajectory accuracy, by the action selection and dynamic control mechanism. By providing a structured way of communicating intentions among behaviors, activities, and controllers, the meta-goal paradigm aids in maintaining modularity in the intelligence architecture.
2.1.3 Impact on Vehicle Control

The restructuring of the intelligence architecture to address the action selection problem amounts to a change in attitude about dynamic control from the control theoretic approach. We recognize that dynamic control solutions are not general. In fact, the real-time selection of and switching between controllers opens the possibility of developing niche controllers for particular situations. A dynamic controller is not monolithic; its control extends to the instantiation of a particular action in the context of the meta-goals. These changes place certain requirements upon controllers for them to be effectively used in this intelligence architecture. The controller must be able to handle asynchronous operation, being switched on and off, possibly often. Also, the controller should be able to incorporate the information from the meta-goals. The control parameters should be adaptive to the context of the action being performed. It should be noted that individual dynamic controllers can be developed using control theory, and in fact, existing controllers may be used. The only alterations necessary are:

1. the addition of hooks for using the meta-goals to determine control parameters where appropriate, and

2. the provision to the action selection mechanism of some knowledge about the controller's performance to ensure suitable arbitration.

2.2 Approaches to Action Selection

Action selection has become one of the major research questions in behavior-based artificial intelligence. There are several good surveys of research on the problem. Georgeff [13] and Chapman [8] are good overviews of the traditional approach to planning and how it bears on action selection. Although their domain-independent stance has proven less useful for mobile robots, these papers provide a good grounding of behavior-based action selection research in more traditional artificial intelligence planning. Tyrrell [29] and Maes [23] survey the major projects which have resulted from behavior-based action selection research. They also provide a useful set of criticisms of existing implementations of solutions to the action selection problem. We will now look at several seminal ideas that have emerged in the literature and consider how they bear upon the current project.
2.2.1 Behavior-based decomposition

In the traditional approach to AI (as opposed to behavior-based artificial intelligence) the project of general intelligence is decomposed by function rather than task. In such a system, action selection is performed by a general planner which is distinct from a general dynamic controller. Part of the drawback of such an approach has been addressed already as the difficulty in producing a general dynamic controller. The required dynamic range of such a controller for a complex agent is simply too broad for most control strategies to have any chance of producing an acceptable solution. There is, however, an even greater problem. When an agent’s activities are functionally decomposed, there is a computational bottleneck in perception and planning. Instead of each behavior paying attention to the sensory data which pertain to it, the agent processes all of its sensory data at once. The solution to this bottleneck came with a behavior-based decomposition of the agent’s software, as shown in Figure 2.3. This approach to decomposing the agent software is based on various tasks or behaviors. Behaviors that take little time and computational resources are run in parallel with slower, and necessarily more long-range, modules. In this way, the agent can maintain continuous control and respond to its environment in real time.

2.2.2 Emergent complexity

Braitenberg [5] argues that much of the behavior that is thought of as very complex or intelligent can be produced by simple feedback from the environment. Brooks [6] couples this idea with inspiration from insect systems and uses a behavior-based approach to emphasize the importance of low-level concerns in making an agent work. More complex behaviors are demonstrated as emerging from simple, low-level, reflex-like systems. Simple interactions between an agent and the environment can engender what is objectively interpreted as intelligent behavior. This idea has two important consequences. First, behavioral complexity needn’t be a result of a complex agent architecture. It could, rather, be the result of the interplay between a simple control law and a complex environment. Behaviors which appear to require a great deal of complexity or computation may have solutions which exploit simple geometrical or feedback interactions with the environment. Wehner [31] illustrates this with a variety of examples in animal behavior. Second,
CHAPTER 2. ACTION SELECTION

Figure 2.3: The behavior-based approach to action selection. While traditional artificial intelligence divides the activity of the agent according to function, behavior-based artificial intelligence decomposes agent intelligence by task, preventing bottlenecks in sensory processing. (after Brooks [6])
CHAPTER 2. ACTION SELECTION

and relatedly, a given behavioral response will acquire additional complexity when coupled with a rich dynamic environment. This complicates any global analysis of the resulting vehicle behavior.

2.2.3 Situated instruction use and deictic representation

Agre and Chapman [1] provide two very useful concepts for action selection and control: situated instruction use and deictic representation theory. The idea behind situated instruction use is that an agent knows quite a bit about what it is doing. Any instructions sent to the agent in real time can capitalize on the agent's knowledge of the situation. This idea plays itself out in human interactions all the time. For example, when two people are riding in a car and the passenger says 'Turn left,' the driver knows to wait until the next street before turning. By assuming a common base of knowledge between two behaviors or agents, the amount of communication required to deliver a given instruction can be greatly reduced.

Many traditional planners use a semantic representation of objects. A specific object is identified by its type and the instance of that type that it represents. A mobile robot might move from room 3 to room 4, for example. This follows the traditional AI tendency to separate symbolic understanding as a function. An approach more in line with behavior-based AI relies less heavily on typing objects. Deictic representation theory, also called indexical-functional representation, considers objects as they relate to the agent. Although the agent may use types to describe the objects, the relationship between the agent and the object is seen as more important. For example, the robot moves from the-room-I-am-in to the-room-I-want-to-be-in. Agre and Chapman [1] argue that a deictic representation of the agent's environment is more useful for action selection as response time becomes more critical. By focusing on the relationship between the object and the agent, deictic representation simplifies the decisions that the agent must make and concommitantly focuses the agent on those things most relevant to it.
2.2.4 Ethologically-inspired action hierarchies

The action hierarchy model of action selection has been inspired by a developed body of ethological research. Studies of animal behavior have led to (primarily) this type of description for animal behavioral systems. The work of Tinbergen [28], Lorenz [21], and Gould [16] has provided a rich starting point for the design of artificial action selection mechanisms. There are a variety of ethological models of action selection, but the essential features are as follows. Animal behavior is organized into behavioral systems, such as food-gathering, mating, and migration. Each system is a hierarchy of possible actions, composed at the finest grain of organized motor programs and fixed action patterns. These units are combined into instincts and behaviors. Activation for given behaviors comes about through the interplay of releasing mechanisms and endogenous factors. Releasing mechanisms are external stimuli which allow behavior to proceed in a certain direction. Endogenous factors include hormones, proprioceptive sensations, and motivational impulses from other parts of the action hierarchy. Maes [22] incorporates these ideas basically as they are presented by Tinbergen. Blumberg [4] extends this implementation with insight into the action selection project provided by Tyrrell [29].

2.2.5 Recommendations

The intelligence architectures of Brooks [6], [7] and Maes [22] are strictly winner-take-all. The agent decides which behavior will be given control and no attempt is made to incorporate the needs of other behaviors. The problem with such a approach, as pointed out by Tyrrell [29], is that the optimal action may be abandoned by considering only what the winning action requires. Blumberg's [4] implementation of an action hierarchy helps solve this problem. The final action is provided with recommendations from those actions which lost at each level in the hierarchy. This is a compromise between the combinatorial explosion occasioned by a full action-space search and the missed opportunities of a strictly winner-take-all contest. However, Blumberg doesn’t have much to say about implementing recommendations, and in fact his examples extend only to the level of behavioral systems, trading off searching for food versus bathing, for example. This assumes a great deal of shared knowledge among the actions both across each level of the hier-
CHAPTER 2. ACTION SELECTION

archy and between levels, as a low-level action may try to incorporate the recommendation of a higher-level action.

2.3 Asynchronous Action Hierarchies

The question posed at the beginning of this chapter was what form of action selection and dynamic control mechanism should be incorporated to mediate between vehicle behavioral modules and the actuation and perception subsystems. The following asynchronous action hierarchy incorporates the principles of action selection discussed while avoiding the problems which commonly exist in agent action selection architectures. Before we consider the detailed structure of the action hierarchy, it will be informative to revisit the general AUV agent architecture picture in light of the discussion of action selection. Figure 2.4 illustrates the agent architecture and indicates the flow of information of various types. The state configuration table sets the goals of the AUV for a particular mission phase by activating an appropriate set of behavior modules and their priorities. These behavior modules, in turn, provide suggested vehicle activities according to the vehicle's situation and the goals they represent. This is in line with the architecture currently in use. The action hierarchy arbitrates among suggested activities, incorporating information about the internal state of the vehicle, to produce a set of motor and sensory commands. These commands are then sent to the various actuation and perception subsystems, which are realized through distributed, embedded microprocessors. Endogenous variables comprising the internal state of the vehicle are influenced by the state configuration table and the behavior modules and are incorporated into the action selection process by the action hierarchy. External releasing mechanisms identified by the actuation and perception subsystems influence the decisions of the action hierarchy, the behavior modules, and the state configuration table. The structure of the action hierarchy provides modularity to the agent architecture, an increasingly important factor as the number of competencies, or behavioral capabilities, is increased.
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Figure 2.4: Information flow in the general agent architecture. An asynchronous action hierarchy is used to provide the functions of action selection and dynamic control. The contextual meta-goals are realized in a set of endogenous variables. Event-driven feedback is explicitly identified using ethologically-inspired releasing mechanisms.
2.3.1 Structure of the Action Hierarchy

The principal advantage to structuring the agent’s architecture is realized in ease of implementation. Extending the existing vehicle capabilities should be a fairly straightforward process. Additionally, modularity in competency design will help to contain complexity as the number of behaviors being activated increases, as the overall behavior of the vehicle becomes more complex. A useful design principle toward this end is to allow behavior modules and action controllers to be developed at the level of abstraction at which they are implemented. The proper inputs and outputs of a behavior module are best thought of in terms of that behavior module’s particular project. For example, when someone is walking along an icy sidewalk, she must carefully plan each step, her entire trajectory, or risk falling. The output of her walk-along-the-icy-sidewalk behavior module would take the from of specifying the placement of each step. On the other hand, if she happened to touch a hot stove, no time at all would be spent considering what trajectory to follow. The output is a jerk of the arm.

The situation is similar for any complex agent. A wide variety of behavior types results in a wide variety of suggested activity modes. In the vertical-plane maneuvering of an AUV, some behaviors, such as surveying and bottom-following, may be interested in specifying a depth or altitude for the vehicle. Others, such as water-column-sampling or obstacle-avoidance, may find depth rate or pitch a more natural mode for specifying desired vehicle motion. Still others, such as a side-scan sonar mapping behavior, might want to set limits on the vehicle pitch. The asynchronous action hierarchy accepts a range of suggested activity modes by providing multiple entry points into the action selection process. Activities are organized around particular types of vehicle motion, dynamic competencies which provide a modularity to the action selection portion of the agent architecture similar to that provided by behavioral competencies at higher levels. A dynamic competency can be a particular plan for vehicle motion, like the motor programs and fixed action patterns of ethological theory, or a feedback control mechanism, such as a sliding mode depth controller or a PID pitch controller. The action hierarchy is developed as basic dynamic competencies are combined to form more complex or extended maneuvering capabilities.

Each behavior sends its suggested activity to the appropriate activity module, or dynamic competency module, along with the behavior priority.
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when a particular activity is desired. Communication of suggested activities occurs asynchronously, allowing behaviors which operate at different rates to inform the action selection process in parallel and without extraneous processing. Asynchronous activity specification also allows each behavior to specify only those aspects of the desired vehicle motion which are relevant to it. This allows implementation of the ideas of situated instruction use and deictic representation theory. If the priority of the requested activity is greater than the current activity, the requested activity subsumes vehicle control, retaining any portion of the previous activity that is unspecified by the subsuming activity. The new activity spreads down the hierarchy, ultimately issuing commands to the actuation and perception subsystems. Decisions made as the activity filters down the hierarchy are made on the basis of endogenous variables. If the requested activity lacks the necessary priority to subsume vehicle control, it still propagates through the action hierarchy. The impact of such a request comes as a recommendation to the controlling activity. Recommended actions that are unspecified by the controlling activity and do not interfere with its functioning are implemented, for example. This prevents the loss of information which is usually suffered in strictly winner-take-all arbitration schemes. An example will help to illustrate the operation of the action hierarchy.

2.3.2 Example Operation of the Asynchronous Activity Hierarchy

Figure 2.5 illustrates a possible asynchronous activity hierarchy along with some of the behaviors which might be run on top of it. For this example, we focus on the vertical plane control of the vehicle and the associated action selection process in a given situation. There will, in general, be more behaviors running at any given time, but these are omitted for clarity. Consider the interaction between two behaviors: vent seeking and side-scan sonar mapping. The goal of the vent seeking behavior is to locate a hydrothermal vent. This is a complex behavior and has several phases. The first of these is to sample a large water volume in an attempt to identify the plume of emissions from such a vent. For this phase, the vent seeking behavior performs a yo-yo maneuver; the vehicle dives up and down through the water column in an attempt to swim through any plumes which may be present. This yo-yo
competency is realized within the action hierarchy as shown in Figure 2.5, and in turn depends (in this instance), upon the achieve depth command modality and a dynamic controller. Note that for this behavior, the specifics of the vehicle trajectory are unimportant as the goal (for the initial phase of the behavior) is simply to cover as much of water column as possible.

A second, competing behavior which is supposed to be active in this example is a side-scan sonar mapping behavior. At various points throughout the vehicle mission, this behavior starts the side-scan sonar to record samples of the seabed for later analysis. In order to provide a stable vehicle platform for the side-scan sonar, the behavior must ensure that the vehicle pitch be maintained to within ten degrees of horizontal while the sonar is operating. This is more restrictive than the default range of plus or minus thirty degrees and serves to improve the quality of the sonar reading. Since the sonar behavior isn’t really interested in the path the vehicle is taking and merely intends to stipulate a pitch envelope for vehicle maneuvering, this behavior could output to any of the basic command modes. The action requested by the side-scan sonar mapping behavior is meant as a recommendation or situated instruction for modifying whatever action the vehicle is in the process of executing. This behavior outputs to the depth rate command modality, since that is most closely associated with pitch.

The mission begins near the surface. The vehicle is traveling at speed in open water when the vent seeking behavior is activated. At this point, the side-scan sonar imaging behavior is dormant. To begin the process of finding a hydrothermal vent, the vent seeking behavior begins a yo-yo maneuver. A message is sent to the yo-yo activity module giving a range of depths and the priority of the behavior. This priority is high enough to make this action dominant in the current situation. At this point, the vent seeking behavior leaves the execution of the yo-yo to the activity module. It monitors the appropriate vehicle data until the appropriate releasing mechanism, in this case the detection of a plume, is encountered. The yo-yo activity module notes the current vehicle state and determines that the first action should be to dive to the lower depth specified by the vent seeking behavior. Note that this could also be an altitude. Once the proper depth is determined, the yo-yo module sends a command to the achieve depth activity module. This command consists of the depth to be achieved and the priority of the action (which is inherited from the original request for the maneuver coming from the vent seeking behavior).
Figure 2.5: An example of the asynchronous action hierarchy. Basic command modalities can choose between a number of dynamic controllers. More complex maneuvers and activities result by combining basic actions into richer competencies. Behaviors asynchronously request actions at the level of abstraction appropriate to their specific projects. See text for details.
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The achieve depth module selects the general transit controller for processing this command. This decision is based on three factors. First, the controller which is currently being used is considered. Since the vehicle was just cruising along in open water, this was most likely the general transit controller. Second, use of a particular controller might be stipulated with the command. In this case, it is not, since the details of vehicle dynamic control are unimportant to the vent seeking behavior during this phase of the search. Third, the internal state of the vehicle is considered. The vehicle internal state consists of the values encoded in the endogenous variables. These values help influence how goals are realized. The state table plays the most crucial role in setting endogenous variables, but they can be affected by behaviors as well (recall Figure 2.4). Although there is no requisite set of endogenous variables, assume for the purposes of this example that two affect this decision. There is an endogenous variable that indicates the desired trade-off for the vehicle as a whole between power conservation and control accuracy. In the current instance, this would weigh more heavily on the side of restricting power consumption, thus favoring the general transit controller over, for example, the sliding mode depth controller because the general transit controller uses less fin activity overall. Another endogenous variable which might play a role would be the overall importance of maintaining a strict trajectory. This variable reflects the vehicle's confidence in its control abilities relative to the environment. In open water, the vehicle needn't worry about precise control, but when the number of obstacles increases, more care, and precision, is necessary. As a result of these factors, the achieve depth module passes the depth command to the general transit controller. This dynamic controller determines an appropriate regimen of fin commands based on the current pitch envelope, vehicle speed, and desired depth. These elevator commands are sent, and the vehicle begins diving with a pitch angle of thirty degrees.

While the vehicle is diving, the side-scan sonar mapping behavior notices that it is time to sample the seabed characteristics again. The vehicle, however, is at an unacceptable pitch rate for sonar sampling. The behavior issues a command to restrict the pitch to within ten degrees of horizontal to the achieve depth rate activity module. Although the sonar behavior has no intention of taking over the vertical plane actions of the vehicle, its request is given high priority (by the state table which instantiated it) so that the command will be treated as a high priority recommendation. Since this is only a
recommendation to change the pitch envelope, the side-scan sonar imaging behavior indicates that the current dynamic controller should retain vehicle control if possible. Accordingly, the achieve depth rate module passes the command on to the general transit controller. The general transit controller (which is at this point simply monitoring vehicle state to ensure that the vehicle is maintaining the dive) calculates a regimen of elevator commands to transition down to the new dive angle, ten degrees. Note that the vent seeking behavior is not informed of this change, although it may note the changing vehicle state. Also, the vent seeking behavior is not required to recalculate its desired action, since this is unnecessary until the releasing mechanism upon which it is waiting is triggered.

2.3.3 Requirements for Vehicle Control

As this example shows, there is a price to pay for allowing the flexibility of multiple dynamic controllers. That price is an increased structural organization in the intelligence architecture of the vehicle. From the standpoint of a dynamic controller, this increased structure is realized by the necessity of providing the action hierarchy with the information necessary to choose between controllers. As the general transit controller is developed, this importance of knowing about the performance of the controller and being able to properly specify it to the action hierarchy will become clear.
Chapter 3
Vehicle Modeling

The purpose of modeling the vehicle is to get a feel for its dynamic response. Ideas about the possible vehicle motions can then be combined with desired characteristics of vehicle behavior to begin forming a notion of appropriate action selection. Knowledge about the operating environment further restricts the focus to a set of applicable operating regimes. In this chapter, the vehicle dynamics are derived to examine the results of various control actions. The dynamic model is constructed by considering the forces which act on a survey-class AUV. These forces are combined to produce hydrodynamic derivatives, allowing us to consider the functional dependencies of the vehicle dynamics on the state variables. By deriving the vehicle dynamics from force considerations, physical insight into what causes various results is retained. It is this development of intuition about vehicle motion that provides the basis for exploring control and action selection strategies.

There are other approaches to modeling underwater vehicle dynamics, often taking a more empirical attitude to estimating vehicle motion. All of the methods, however, result in an expansion of vehicle dynamics in terms of vehicle state variables around some operating condition. A typical example is the set of standard equations of submarine motion developed by the David Taylor Naval Ship Research Center (DTNSRC) [15] [10] [11]. These equations capture a broad range of vehicle dynamics and have evolved to accurately capture many hydrodynamic nonlinearities as a result of experience with Navy submarines and a great deal of model testing. The problem with using the DTNSRC model lies in coming up with estimates of the hydrodynamic derivatives. In order to balance the accuracy of a model and the difficulty
of estimating the parameters, only the important (in some sense) aspects of the physics should be modeled. Hydrodynamic coefficients for use with the DTNSRC standard submarine equations are often determined through towing tank model tests [12] [19] [20] or a high-end hydrodynamic modeling program such as HYDAT [24]. This approach is less appropriate in this case for three major reasons. First, the additional complexity in the model is not justified (for a general transit controller) by the added accuracy. Second, the additional accuracy also fails to justify the nonrecoverable engineering costs associated with extensive model testing. Finally, such an approach abandons the insight afforded by our simpler but more direct approach to modeling through force considerations.

3.1 Physical Description of the Vehicle Platform

A survey-class AUV is designed for use in missions which require the vehicle to cover a lot of ground. The ability to hover is given up in favor of a sleeker profile which incurs less drag. The vehicle cannot maneuver in place; all turns are executed during forward motion, making the dominant excursion of the vehicle horizontal. The specific vehicles considered in this thesis are the Odyssey vehicles, which have been developed by the MIT Sea Grant Underwater Vehicles Laboratory. These vehicles were designed to provide an investigative oceanographic monitoring tool capable of operating in previously-unmapped environments. Possible missions for the Odyssey vehicles include data-gathering or photographic surveying of a region, finding a chemical plume and locating its source, and working in a group to monitor large-scale ocean phenomena. The Odyssey vehicles provide test beds for AUV research as well as operational vehicles for the demonstration of AUV technologies in oceanographic research.

The general configuration of the AUV Odyssey is shown in Figure 3.1. Two or three glass spheres provide an unpressurized housing for electronics, batteries, and dry payload. A flooded fiberglass faired hull contains the spheres, various sensors and motors, and wet payload. The Odyssey has a length \( L = 2.1844 \text{ m} \) and a maximum hull diameter \( D = 0.5461 \text{ m} \). The shape of the faired hull is taken from a systematic series of model tests by
Figure 3.1: General configuration of an Odyssey vehicle. The hydrodynamic shape reduces drag, but a forward velocity is needed for the fins to effectively control the vehicle.
Gertler [14]. The hull radius $a$ varies with axial position by

$$a^2 = 0.0088x^6 + 0.0113x^5 + 0.0018x^4 - 0.0361x^3 - 0.0804x^2 + 0.0182x + 0.0736,$$

(3.1)

where the hull is defined on the domain

$$-1.2049 \leq x_{hull} \leq 0.9795. \quad (3.2)$$

The fins are modeled using a straight-line outline as shown in Figure 3.2. A single thruster is mounted axially at the rear of the vehicle. Cruciform fins are located fore of the propeller arrangement. The vertical fins are called rudders; the horizontal fins are elevators.

A vehicle-fixed reference frame $\{x, y, z\}$ is employed with the coordinate axes directed forward, starboard, and down. The vehicle origin is set at the centroid of the hull. There are six degrees of freedom for vehicle motion, encompassing linear and angular velocities along each of the vehicle axes. These are referred to as surge, sway, heave, roll, pitch, and yaw. The generalized velocities in these directions are $u$, $v$, $w$, $p$, $q$, and $r$, and the generalized forces are $X$, $Y$, $Z$, $K$, $M$, and $N$. For a survey-class vehicle, the surge velocity $u$ is large compared to the other velocity components. A first-order model is produced by discarding the terms which involve the other velocity components, $v$, $w$, $p$, $q$, and $r$, nonlinearly. The resulting model is linear in these
small velocities, but may include nonlinearities involving the surge velocity or vehicle attitude. This approach results in a model in which the vertical plane dynamics, involving surge, heave, and pitch, are decoupled from the horizontal plane dynamics, including sway, roll, and yaw. The model derivation will bear out this result.

This thesis focuses on controlling the vertical plane dynamics of the vehicle. Figure 3.3 illustrates the variables used in describing the vertical plane dynamics. The elevator can be turned to an angle $\delta$ with respect to the vehicle axis $x$. The vehicle frame of reference $\{x, z\}$ is rotated from the earth-fixed axes $\{\xi, \zeta\}$ with pitch angle $\theta$.$^1$ The total velocity in the vertical plane $V$ is

$^1$The relationship between the vehicle-fixed axes $\{x, y, z\}$ and the earth-fixed axes $\{\xi, \eta, \zeta\}$ for the general, coupled system is much more complex. See, for example, Waller [30].
the vector sum of the surge and heave velocities,

\[ V = \sqrt{u^2 + w^2}, \]  

(3.3)

and is directed at a sideslip angle \( \alpha \) with respect to the vehicle axis \( x \).

### 3.2 Vehicle Dynamics

#### 3.2.1 Hydrostatic Forces

Vehicle weight and buoyancy give rise to hydrostatic forces and moments. Weight is always directed along the positive \( \zeta \) axis (toward the ocean floor), while buoyancy always acts in the negative \( \zeta \) direction (toward the surface). The following assumptions are made in considering vehicle hydrostatics:

- the vertical plane and horizontal plane dynamics are decoupled,
- the vehicle is neutrally buoyant, and
- the vehicle is trim.

The assumption that the vertical plane dynamics are decoupled has been discussed already, and should hold if the vehicle has a relatively large surge velocity. Neutral buoyancy means that the vehicle weight is equal to its buoyancy. The vehicle is trim when there is no roll or pitch at rest; this means that the difference between the center of buoyancy and the center of gravity lies entirely in the \( z \) direction.

Because the vehicle is assumed to be neutrally buoyant, there are no net hydrostatic forces. The separation between the centers of buoyancy and gravity does, however, produce a moment,

\[ M_{\text{hydrostatic}} = -mgz_G \sin \theta, \]  

(3.4)

where \( z_G \) is the distance between the centers of buoyancy and gravity.

The weight of the vehicle is equal to the weight of the fluid displaced by the hull. This can be calculated by integrating (3.1):

\[ m = \int_{hull} \rho \pi a^2 dx = 359 \text{ kg}, \]  

(3.5)
CHAPTER 3. VEHICLE MODELING

where the domain of integration is the same as the domain over which the hull is defined (3.2). Rehling [27] estimates

\[ z_G = 0.05 \text{m}, \]  

resulting in

\[ M_{\text{hydrostatic}} = -175.91 \sin \theta. \]  

3.2.2 Inertial Forces

Inertial forces act on the vehicle due to the motion of the vehicle mass as well as the induced motion of the surrounding fluid. These forces can be represented using tensors of mass coefficients. The induced forces and moments acting on the vehicle due to an inertia tensor \( m_{ij} \) are

\[ F_j = -\dot{U}_i m_{ji} - \epsilon_{jkl} U_i \Omega_k m_{li}, \]  

and

\[ M_j = -\dot{U}_i m_{j+3,i} - \epsilon_{jkl} U_i \Omega_k m_{l+3,i} - \epsilon_{jkl} U_i U_{kmli}, \]  

where \( i = [1, 2, 3, 4, 5, 6], j, k, l = [1, 2, 3], \) and summation over repeated indices is implied.\(^2\)

**Body Mass Forces**

The body mass forces are forces on the vehicle due to the inertia of the vehicle itself. The following assumptions are made regarding the vehicle inertia:

- the difference between the centers of buoyancy and gravity lies entirely in the z direction, and
- the cross-products of inertia are negligible.

Applying equations (3.8) and (3.9) to the resulting body mass tensor

\[ m_b = \begin{bmatrix} m & 0 & 0 & 0 & m z_G & 0 \\ 0 & m & 0 & -m z_G & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & -m z_G & 0 & I_{xx} & 0 & 0 \\ m z_G & 0 & 0 & 0 & I_{yy} & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{zz} \end{bmatrix}, \]  

\(^2\)For a derivation of this result and a discussion of its use for body mass and added mass forces, see Newman [25, pp. 135-49].
and neglecting higher-order terms, the resulting body mass forces are

\[ X_{\text{body mass}} = -m\dot{u} - mzG\dot{q}, \]  
(3.11)

\[ Z_{\text{body mass}} = -m\dot{w} + muq, \]  
(3.12)

\[ M_{\text{body mass}} = -mG\dot{u} - I_{yy}\dot{q}. \]  
(3.13)

\( I_{yy} \) is estimated, as in Aguirre [2], using a homogeneous spheroid with the length and diameter of the vehicle,

\[ I_{yy} = m\frac{L^2 + D^2}{20} = 91\text{kgm}^2. \]  
(3.14)

The resulting body mass forces are

\[ X_{\text{body mass}} = -359\dot{u} - 17.95\dot{q}, \]  
(3.15)

\[ Z_{\text{body mass}} = -359\dot{w} + 359uq, \]  
(3.16)

\[ M_{\text{body mass}} = -17.95\dot{u} - 91\dot{q}. \]  
(3.17)

**Added Mass Forces**

There are also inertial forces due to fluid motion induced by the vehicle. When the vehicle moves, a potential flow field is created. Because these forces can be represented by an inertia tensor, they are called added mass forces. The vehicle is symmetric with respect to the \( x, y \)- and \( x, z \)-planes. Consequently, the added mass tensor reduces to

\[
m_a = \begin{bmatrix}
m_{11} & 0 & 0 & 0 & 0 & 0 \\
0 & m_{22} & 0 & 0 & 0 & m_{26} \\
0 & 0 & m_{33} & 0 & m_{35} & 0 \\
0 & 0 & 0 & m_{44} & 0 & 0 \\
0 & 0 & m_{35} & 0 & m_{55} & 0 \\
0 & m_{26} & 0 & 0 & 0 & m_{66}
\end{bmatrix}.
\]  
(3.18)

Applying equations (3.8) and (3.9) and neglecting higher-order terms, the vertical plane added mass forces are

\[ X_{\text{added mass}} = -m_{11}\dot{u}, \]  
(3.19)
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\[ Z_{\text{added mass}} = -m_{33} \dot{\omega} - m_{35} \dot{q} + m_{11} u q, \text{ and} \]
\[ M_{\text{added mass}} = -m_{35} \dot{\omega} - m_{55} \dot{q} + m_{35} u q + (m_{33} - m_{11}) u w. \]

The surge added mass coefficient \( m_{11} \) is determined by using a spheroidal approximation to the vehicle hull shape. Using potential flow theory, Blevins [3, p. 407] calculates the surge added mass coefficient of a prolate spheroid (a cigar shape) as

\[ m_{11} = \frac{4}{3} \pi \rho D^3 \beta, \]

where \( \beta \) is tabulated and depends on the length to diameter ratio. For the Odyssey hull shape,

\[ \beta = 0.3498, \]

yielding

\[ m_{11} = 30.59. \]

Slender body theory was used to determine the remaining added mass coefficients: \( m_{33}, m_{35}, \) and \( m_{55}. \) Since the vehicle forward velocity is assumed to be large compared with its heave and pitch velocities, and the vehicle has a large length to diameter ratio, the added mass coefficients involving heave and pitch may be approximated by considering the two-dimensional added mass at a particular cross-section of the hull at a position \( x_{\text{section}} \) on the \( x \) axis. The heave velocity at such a section is

\[ w_{\text{section}} = w - x_{\text{section}} q. \]

If the section has a two-dimensional added mass coefficient \( m_a(x_{\text{section}}), \) then the force acting on the section is equal to the change in the fluid momentum,

\[ Z_{\text{section}} = \left( \frac{\partial}{\partial t} - u \frac{\partial}{\partial x} \right) [m_a(x_{\text{section}}) w_{\text{section}}], \]

and the moment produced is

\[ M_{\text{section}} = x_{\text{section}} \left( \frac{\partial}{\partial t} - u \frac{\partial}{\partial x} \right) [m_a(x_{\text{section}}) w_{\text{section}}]. \]

Substantial derivatives are used here to account for momentum being convected along the hull. The total force and moment on the vehicle are the
integrals of the section forces and moments along the vehicle body.

\[ Z_{\text{slender body}} = \int_{\text{hull}} \left( \frac{\partial}{\partial t} - u \frac{\partial}{\partial x} \right) [m_a(x)w_{\text{section}}] \, dx. \] (3.28)

\[ M_{\text{slender body}} = \int_{\text{hull}} x \left( \frac{\partial}{\partial t} - u \frac{\partial}{\partial x} \right) [m_a(x)w_{\text{section}}] \, dx. \] (3.29)

The convected momentum term of (3.28) is a perfect differential. It accounts for a tail of nonvanishing radius and low aspect ratio lift from the hull.\(^3\) The Odyssey II tail comes to a point, so the former effect can be ignored. Since we will account for the lift force separately, the convected momentum term can be dropped altogether. The remaining terms identify the required added mass coefficients as

\[ m_{33} = \frac{\partial Z_{\text{slender body}}}{\partial \dot{w}} = \int_{\text{hull}} m_a(x) \, dx, \] (3.30)

\[ m_{35} = \frac{\partial Z_{\text{slender body}}}{\partial \dot{q}} = \frac{\partial M_{\text{slender body}}}{\partial \dot{w}} = \int_{\text{hull}} x m_a(x) \, dx, \text{ and} \] (3.31)

\[ m_{55} = \frac{\partial M_{\text{slender body}}}{\partial \dot{q}} = \int_{\text{hull}} x^2 m_a(x) \, dx. \] (3.32)

For most of the vehicle length, the hull cross-section is circular. The two-dimensional added mass coefficient of a circular section with radius \(a\) is

\[ m_{a_{\text{circle}}} = \rho \pi a^2. \] (3.33)

Near the tail, the fins must also be taken into account. Figure 3.4 shows the form of the vehicle cross-section in this region. The hull has a radius \(a\), and the hull and fins together have a maximum sectional radius \(s\). Nielsen [26, p. 372] calculates the translational added mass coefficient of this cross-section to be

\[ m_{a_{\text{circle with fins}}} = \rho \pi s^2 \left( 1 - \frac{a^2}{s^2} + \frac{a^4}{s^4} \right). \] (3.34)

The hull description (3.1) is used to integrate equations (3.30) through (3.32) numerically:

\[ m_{33} = 108.65, \] (3.35)

\(^3\)See Newman [25, p. 345] for a more in depth comparison of slender body and added mass theory.
The resulting added mass forces are then

\[
X_{\text{added mass}} = -30.59\dot{u},
\]

(3.38)

\[
Z_{\text{added mass}} = -108.65\dot{w} - 25.72\dot{q} + 30.59uq, \text{ and }
\]

(3.39)

\[
M_{\text{added mass}} = -25.72\dot{w} - 55.63\dot{q} + 25.72uq + 78.06uw.
\]

(3.40)

### 3.2.3 Viscous Forces

#### Drag

The axial drag on the vehicle was estimated using HYDAT [24]. HYDAT was used to ensure an accurate accounting for the fins and duct as well as the faired hull. The approach that HYDAT takes follows Hoerner [17]. The drag coefficient is the sum of contributions from the forebody and the base.
Since the afterbody of the Odyssey II is not truncated, there is no additional drag due to the base. The resulting estimate of the vehicle drag is

$$X_{\text{drag}} = -8.9u^2. \quad (3.41)$$

### Hull Lift

A vertical force, or lift, is developed on the hull because of momentum losses in the viscous boundary layer on the side away from the oncoming flow. This implies that the hydrodynamic derivative taken with respect to the angle of attack $\alpha$ of the hull lift force will look like a constant lift coefficient when referenced to the sideways projected area of the hull. Hoerner [18, p. 13-3] cites experimental results indicating that, indeed,

$$Z_{\text{hull lift}} = 0.003 \left( \frac{1}{2} \rho V^2 DL \right) \alpha. \quad (3.42)$$

Because the vehicle surge velocity is assumed to be large, the angle of attack can be approximated by its tangent,

$$\alpha \approx \frac{w}{u}, \quad (3.43)$$

and the total velocity can be approximated by the surge velocity,

$$V \approx u. \quad (3.44)$$

Hoerner [18, p. 13-4] also notes that the hull lift,

$$Z_{\text{hull lift}} = 0.003 \left( \frac{1}{2} \rho LD \right) uw = -1.83uw, \quad (3.45)$$

acts at roughly $x_{\text{hull lift}} = 0.6L = -0.25 \text{ m}$, providing a moment

$$M_{\text{hull lift}} = Z_{\text{hull lift}} x_{\text{hull lift}} = -0.46uw. \quad (3.46)$$

### Fin Lift

The main source of lift for the vehicle is of course the elevator fins. The fins each have a projected surface area $S$, span $s$, and aspect ratio $A$. Since the fins abut the hull, an image fin is included in the calculation of aspect ratio,

$$A = 2 \frac{s^2}{S}. \quad (3.47)$$
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The lift from the fins is due to the combined effect of the angle of attack of the elevators with respect to the vehicle hull $\delta$ and the angle of attack of the vehicle $\alpha$. The total lift provided by the fins is

$$Z_{\text{fin lift}} = \frac{1}{2} \rho u^2 S \frac{\partial C_L}{\partial \alpha} (\alpha + \delta),$$  \hspace{1cm} (3.48)

where the marginal lift coefficient can be estimated by

$$\frac{\partial C_L}{\partial \alpha} = \frac{1}{2 \pi a^2} + \frac{1}{\pi A} + \frac{1}{2 \pi A^2},$$  \hspace{1cm} (3.49)

with $a = 0.9$. The Odyssey II elevator fins have a span $s = 0.2604$ m, a projected surface area $S = 0.0252$ m$^2$, and an aspect ratio $A = 5.3856$, resulting in

$$\frac{\partial C_L}{\partial \alpha} = 4.422.$$  \hspace{1cm} (3.50)

The elevator fins have a moment arm $x_{\text{fin lift}} = -0.7331$ m. The elevator lift, assuming small angle of attack, is

$$Z_{\text{fin lift}} = -112.13 \left( u(\omega - x_{\text{fin lift}}) + u^2 \delta \right).$$  \hspace{1cm} (3.51)

The moment arm of the elevator fins supplies a moment

$$M_{\text{fin lift}} = -82.2 \left( u(\omega - x_{\text{fin lift}}) + u^2 \delta \right).$$  \hspace{1cm} (3.52)

3.2.4 Thruster Model

Vehicle speed is controlled using a single, axially-mounted thruster. The thruster model contains two parts: a motor model and a propeller model. The motor model describes the conversion of the input voltage signal into a propeller shaft torque and angular velocity. The propeller model identifies the loading characteristics of the thruster, that is, it provides a relationship between the propeller angular velocity and torque. The propeller model determines the provided thrust as well. The thruster model parameters have been estimated using data from AUV Odyssey I.
Thruster Motor Model

The thruster is controlled by providing an input voltage signal $V$. As shown in Figure 3.5, the motor is modeled as a voltage source, an electrical resistance $R_E$, an electrorotational gyrator with conversion constant $K_T$, a mechanical resistance $\tau_{SF}$, and a propeller load. The mechanical resistance is nonlinear due to static friction. $\tau_{SF}$ refers to this nonlinearity. The remaining, linear, portion of the mechanical resistance is combined with the electrical resistance in the model. The electrical side of the gyrator has a common current and the rotational side has a common angular velocity. These are common-flow junctions and can be described by the effort balances

$$V = R_Ei + K_T\omega, \quad \text{and} \quad \tau = K_Ti - \tau_{SF}. \quad (3.53)$$

Combining these effort balances, we obtain the delivered torque

$$\tau = \frac{K_T}{R_E}V - \frac{K_T^2}{R_E}\omega - \tau_{SF}. \quad (3.55)$$

Propeller Model

Yoerger, Cooke, and Slotine [32] have developed a thruster model for use during hovering maneuvers. This model is extended to include the effects of a constant flow. The propeller is modeled as fixed in a free stream of velocity
The propeller sweeps out an area $A$. Fluid exits the propeller with a volumetric flowrate $Q$, producing an exiting velocity

$$u_{out} = \frac{Q}{A}. \quad (3.56)$$

The action of the thruster is described in terms of the inflow and outflow velocities without specifying the details of the flow near the propeller.\(^4\) The free stream has a specific kinetic energy (kinetic energy per unit volume)

$$K_{in} = \frac{1}{2} \rho u^2. \quad (3.57)$$

Through the actions of the thruster, the exiting flow has a specific kinetic energy

$$K_{out} = \frac{1}{2} \rho \left( \frac{Q}{A} \right)^2. \quad (3.58)$$

Following the analysis of Yoerger, et al. [32, p.169], the thruster is assumed to work on an effective volume of fluid $\nabla$ such that there is a total kinetic energy

$$T = \frac{1}{2} \rho \left( \frac{Q}{A} \right)^2 \nabla \quad (3.59)$$

stored by the fluid in the thruster system. The propeller dynamics are derived by balancing the power flowing into the thruster system with the change in kinetic energy of the fluid in the thruster,

$$\frac{dT}{dt} = \omega \tau + (K_{in} - K_{out}) Q. \quad (3.60)$$

Power is added to the thruster through the propeller shaft and the incoming fluid flow and is lost though the exiting fluid flow. Carrying out the power balance yields

$$\frac{\rho \nabla}{A^2} \dot{Q} = \omega \tau + (K_{in} - K_{out}) Q. \quad (3.61)$$

\(^4\) This approach to modeling propeller action is called actuator disk theory. See the Principles of Naval Architecture [9, p. 373-85] for a more detailed development and comparisons to other propeller modeling methods.
CHAPTER 3. VEHICLE MODELING

As the vehicle moves through the water, there is some slip between the flow and the propeller. The propeller rotation is related to the fluid exiting velocity;

\[ \eta_p \omega = \frac{Q}{A}, \]  

(3.62)

where \( \eta_p \) is the effective pitch of the propeller. Substituting for the volumetric flowrate, the propeller dynamic equation

\[ \dot{\omega} = \frac{\tau}{\rho \nabla (\eta_p)^2} + \frac{A}{2 \nabla \eta_p} u^2 - \frac{\eta_p A}{2 \nabla} \omega^2 \]  

(3.63)

results.

Incorporating the motor model from (3.55), the thruster model becomes

\[ \dot{\omega} = \frac{K_T}{R_E \rho \nabla (\eta_p)^2} V - \frac{K_T^2}{R_E \rho \nabla (\eta_p)^2} \omega - \frac{\tau_{SF}}{\rho \nabla (\eta_p)^2} + \frac{A}{2 \nabla \eta_p} u^2 - \frac{A \eta_p}{2 \nabla} \omega^2 \]  

(3.64)

The thrust provided by the thruster is given by the change in linear momentum in the fluid convected through the thruster

\[ T = \rho \left( \frac{Q}{A} - u \right) Q = A \rho \left( (\eta_p \omega)^2 - \eta_p u \omega \right). \]  

(3.65)

### Determination of the Thruster Parameters

There are no means currently in place for measuring the dynamic response of the thruster. In order to estimate the parameters involved in the thruster model, Bollard tests were performed with AUV Odyssey I. During a Bollard test, the vehicle is restrained, setting

\[ u \equiv 0. \]  

(3.66)

The resulting steady state vehicle thrust and current drawn are measured for a range of input voltages. Combining (3.53), (3.54), (3.64), and (3.65), we can relate these quantities by

\[ \sqrt{\frac{T}{A \rho}} = \left( \frac{\eta_p}{K_T} \right) V - \left( \frac{\eta_p}{K_T} R_E \right) i, \]  

(3.67)

\[ \frac{T}{2} = \left( \frac{K_T}{\eta_p} \right) i - \left( \frac{\tau_{SF}}{\eta_p} \right). \]  

(3.68)
CHAPTER 3. VEHICLE MODELING

The thruster parameters $\eta p$, $K_T$, $R_E$, and $\tau_{SF}$ cannot be uniquely determined from the measured data. Because of this, an effective propeller pitch is assumed. We set the effective propeller pitch to be equal to the actual propeller blade pitch, which is directly measured as

$$\eta p \equiv p = 0.0485 \frac{m}{\text{rad}}.$$  \hspace{1cm} (3.69)

To see how this can be justified, we consider what the effective pitch is telling us in this case. The thruster model incorporates two types of power losses:

- electrical to shaft power losses due to the electrical resistance and shaft static friction, and

- shaft to mechanical power losses due to propeller slip.

Setting the effective pitch of the propeller in effect sets the ratio of these losses in the model. In particular, setting the effective pitch equal to the measured propeller pitch results in a model in which all losses obtain in going from electrical power $V_i$ to shaft power $\tau \omega$. The steady state relationship between the electrical input $(V, i)$ and the mechanical output $(T, u)$ is uniquely estimated by the data, but the shaft output $(\tau, \omega)$ depends on the chosen value of $\eta p$. Since our purpose in modeling the thruster is primarily to determine the vehicle thrust, this is sufficient. Experiments in which the propeller angular velocity is measured will provide an estimate of $\eta p$ once the vehicle is equipped with a functional means of measuring $\omega$.

The effective thruster volume $\nabla$ also remains undetermined, since it plays no role in steady state propeller motion. Yoerger, et al. [32] empirically determined $\nabla$ for a thruster similar the one on AUV Odyssey I to be roughly twice the enclosed thruster volume. Following this, $\nabla$ was estimated at twice the enclosed volume of the thruster on AUV Odyssey I. Given the other thruster parameters, $\nabla$ determines the speed at which the thruster reaches a steady state, but has no effect on the shape of the response. Because the situations we are considering involve a constant input voltage and a roughly constant surge velocity, errors in estimating the effective thruster volume should have little effect on predicted vehicle behavior.

Table 3.1 indicates the parameters used in the thruster model and whether they have been determined through direct measurement, estimated using the results of the Bollard tests, or set, in the case of effective pitch $\eta$ and effective thruster volume $\nabla$. 


Table 3.1: Thruster Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.08 m²</td>
<td>measured</td>
</tr>
<tr>
<td>p</td>
<td>0.0485 m/rad</td>
<td>measured</td>
</tr>
<tr>
<td>KT</td>
<td>0.4762 Nm/rad</td>
<td>estimated</td>
</tr>
<tr>
<td>RE</td>
<td>4.8383 Ω</td>
<td>estimated</td>
</tr>
<tr>
<td>τSF</td>
<td>0.0741 Nm</td>
<td>estimated</td>
</tr>
<tr>
<td>η</td>
<td>1</td>
<td>set (see text)</td>
</tr>
<tr>
<td>Δ</td>
<td>0.02 m³</td>
<td>set (see text)</td>
</tr>
</tbody>
</table>

3.3 Summary of Vertical Plane Dynamics

The vehicle dynamic equations in the vertical plane result from summing all of the forces acting on the vehicle. These dynamic equations are written in terms of hydrodynamic derivatives. The vertical plane dynamics of the vehicle are fully specified by these equations:

\[ X_{\delta} \dot{u} + X_{q} \dot{q} = X_{u} u^2 + Ap \left( (\eta p \omega)^2 - \eta p \omega u \right), \]  
\[ Z_{\omega} \dot{w} + Z_{q} \dot{q} = Z_{u} uw + Z_{q} uq + Z_{\delta} u^2 \delta, \]  
\[ M_{\delta} \dot{u} + M_{\omega} \dot{w} + M_{q} \dot{q} = M_{u} uw + M_{q} uq + M_{\delta} u^2 \delta + M_{\theta} \sin \theta, \]  
\[ \dot{\theta} = q, \]  
\[ \dot{\zeta} = -u \sin \theta + w \cos \theta, \]  

and,

\[ \dot{\omega} = \frac{K_T}{R_E \rho (\eta p)^2} V - \frac{K_T^2}{R_E \rho (\eta p)^2} \omega - \frac{\tau_{SF}}{\rho (\eta p)^2} + \frac{A}{2 \eta p} u^2 - \frac{A \eta p}{2 \eta p} \omega^2 . \]

The values of the hydrodynamic derivatives are summarized in Table 3.2. The forces which contribute to each derivative are also indicated.

3.3.1 Steady State Dynamics

A steady dive can be executed by setting the elevator to a fixed angle \( \delta_0 \). The vehicle settles to a steady dive as the hydrostatic restoring force balances the
### Table 3.2: Vehicle Hydrodynamic Derivatives

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
<th>Drag</th>
<th>Hydrostatic</th>
<th>Body Mass</th>
<th>Added Mass</th>
<th>Hull Lift</th>
<th>Fin Lift</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_i$</td>
<td>389.59 kg</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_q$</td>
<td>17.95 kgm</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_u$</td>
<td>-8.90 kg/m</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{iv}$</td>
<td>467.65 kg</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{iq}$</td>
<td>25.72 kgm</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{iw}$</td>
<td>-113.96 kg</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_q$</td>
<td>307.39 kg/m</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_\delta$</td>
<td>-112.13 kg/m</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$M_i$</td>
<td>17.95 kgm</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_{iv}$</td>
<td>25.72 kgm</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_q$</td>
<td>146.63 kgm$^2$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_w$</td>
<td>-4.60 kg</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_q$</td>
<td>-34.54 kgm</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_\delta$</td>
<td>-82.20 kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$M_\delta$</td>
<td>-175.91 kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 3. VEHICLE MODELING

lift moment resulting from elevator deflection and angle of attack. During a steady dive, that is, once the vehicle has settled in this situation, all of the accelerations and angular velocities vanish. The remaining terms in the heave and pitch equations are

\[ Z_w u w + Z_\delta u^2 \delta = 0, \quad \text{and} \]
\[ M_w u w + M_\delta u^2 \delta + M_\theta \sin \theta = 0. \]

These equations provide a characterization of the steady dive in terms of two parameters. Solving the heave equation (3.76) for the steady state heave yields

\[ w_{ss} = -\frac{Z_\delta}{Z_w} u_{ss} \delta_0 = -\sigma u_{ss} \delta_0, \]

where the sideslip ratio \( \sigma \) is the ratio of the hydrodynamic derivatives corresponding to forces due to the angle of attack \( \alpha \) and forces due to the elevator angle \( \delta_0 \). Similarly, the pitch equation (3.77) can be solved for the steady state pitch,

\[ \sin \theta_{ss} = -\frac{M_\delta - M_w Z_L }{M_\theta} u_{ss}^2 \delta = -\mu u_{ss}^2 \delta_0, \]

where the dive angle coefficient \( \mu \) represents the balance between moments due to lift and hydrostatics. Using the values from Table 3.2,

\[ \sigma = 0.9839, \quad \text{and} \]
\[ \mu = 0.4416. \]

Note that the sideslip ratio \( \sigma \) and the dive angle coefficient \( \mu \) completely characterize the vehicle's steady state vertical-plane behavior.

Unmodeled vehicle dynamics and environmental forces may introduce small perturbations to the system. We can introduce a set of new variables to examine the stability of the vehicle while in a steady dive: \( \hat{w} = w - w_{ss}, \hat{q} = q, \) and \( \hat{\delta} = \delta - \delta_{ss} \). The elevator angle is assumed to remain constant, \( \delta \equiv \delta_0 \), throughout. The vehicle dynamics for small perturbations are then

\[
\begin{bmatrix}
Z_{\hat{w}} & Z_{\hat{q}} & 0 \\
M_{\hat{w}} & M_{\hat{q}} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\dot{w} \\
\dot{\hat{q}} \\
\dot{\hat{\delta}}
\end{bmatrix}
= \begin{bmatrix}
Z_w u & Z_q u & 0 \\
M_w u & M_q u & M_\theta \cos \theta_{ss} \\
0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{w} \\
\dot{\hat{q}} \\
\dot{\hat{\delta}}
\end{bmatrix}
+ \begin{bmatrix}
Z_\delta u^2 \\
M_\delta u^2 \\
0
\end{bmatrix} \delta_0.
\]
The natural frequencies of the system can be determined by finding the eigenvalues of the state matrix

\[
A = \begin{bmatrix}
Z_w & Z_q & 0 \\
M_w & M_q & 0 \\
0 & 0 & 1
\end{bmatrix}^{-1} \begin{bmatrix}
Z_w u & Z_q u & 0 \\
M_w u & M_q u & M_\theta \cos \theta_{ss} \\
0 & 1 & 0
\end{bmatrix}.
\] (3.83)

Figure 3.6 shows the natural frequencies of the vehicle as poles in the s-plane as a function of the surge velocity with the elevator angle set \( \delta_0 = 0 \). Figure 3.7 shows the effect of elevator angle \( \delta_0 \) on the natural frequencies for given surge velocity \( u = 2 \text{ m} \). The vehicle is marginally stable at zero velocity, but as the steady forward velocity \( u \) increases, the poles move further into the left half-plane, indicating exponential stability. Since the poles are complex, disturbances will cause an exponentially decaying sinusoidal response. As the constant elevator angle \( \delta_0 \) is increased, the damping is increased due to the magnitude of the steady portion of the hydrostatic restoring force.

Another important aspect of the steady-state dive is the dive rate \( \zeta \). In
Figure 3.7: Vehicle natural frequencies for perturbations around a steady dive as a function of elevator angle $\delta_0$. $u = \frac{2}{3}$. The dotted curve shows the speed dependance of one of the poles, the bottom curve in Figure 3.6. The complex part of the natural frequency is reduced as the elevator angle is increased, as the curve extends from the circle to the cross.
steady-state, the depth rate equation (3.74) becomes

$$\dot{\zeta} = -u \sin \theta_{ss} + w_{ss} \cos \theta_{ss} \approx \mu u^3 \delta_o - \sigma u \delta_o.$$  

(3.84)

Figure 3.8 shows how the steady state depth rate $\dot{\zeta}$ depends upon the steady forward velocity of the vehicle and the set elevator angle. Note in particular that there is a region in which $\dot{\zeta}$ remains small for all elevator angles. This velocity can be solved for by setting $\dot{\zeta} = 0$ in (3.84):

$$u_{no\_dive} = \sqrt{\frac{\sigma}{\mu}} = 1.49 \text{ m/s}.$$  

(3.85)

Because of the lack of vehicle responsiveness during steady state near this speed, any vehicle control mechanism will necessarily rely mainly on transients to accomplish timely maneuvers. The use of steady diving will not be useful in this regime.

Figure 3.9 illustrates this effect. The steady state depth rate is shown for a fixed elevator angle of 20 degrees throughout the speed range of the
Figure 3.9: The dependence of steady-state depth rate on vehicle steady forward velocity. $\delta_o$ is set at 20 degrees.
vehicle. The achievable steady state depth rate is small near the critical velocity $u_{no\;dive}$. 
Chapter 4

Developing a Dynamic Controller for General Transit

The problem posed at the beginning of this thesis was to provide a mechanism for action selection and control in the presence of a wide range of possibly varying goals and behaviors. The scenario of general transit helps to further motivate this problem. In many of the envisioned missions for the Odyssey vehicles, the main activity for the agent occurs at a substantial depth or range. The vehicle must of course first get itself to the appropriate location in order to proceed with the mission. For example, if the vehicle is investigating the environs of a hydrothermal vent, it must first situate itself close to the vent, a location at considerable depth and possible fairly distant from the launch site. A similar situation is encountered during underice missions, where a deployment hole at the base camp is used to attain access to events of interest up to ten kilometers away. This general transit to and from the primary focal point of the mission entails different behaviors, and different control needs, than the behaviors which are most likely to be used while on location.

General transit refers to this type of situation, in which the agent is not required to spend a great deal of effort on precise movement, but instead maintains adequate control while attempting to minimize power consumption. We examine a solution to the general transit problem, and its integration with the rest of the vehicle architecture, as an illustration of the use of an asynchronous action hierarchy. Additionally, some of the basic connections between control theoretic and action selection approaches to structuring ve-
hicle intelligence are exposed. Specifically, a fully action-selection oriented scheme is used for vehicle dynamic control during general transit. The are several features of the general transit problem which make this feasible. The temporal and spatial resolution required of the controller is reduced. Vehicle responsiveness is more appropriately event-oriented, as opposed to a continuous dependance on sensory feedback. The environment in which the general transit dynamic controller is to be used can be stereotypically described. Finally, the dominant dynamics of the vehicle are simple and stable.

4.1 Basic Actions

In analyzing animal behavior, ethologists often attempt to identify basic, atomic activities, quanta of behavior from which the more global behavior of an agent is constructed. Such behavioral quanta are usually described as fixed action patterns or motor programs [16] [21] [28]. In the synthesis of the general transit controller, a complementary approach is adopted. Specific forms of actuation will provide basic actions for the vehicle. We examine the dynamic response of the vehicle for a number of basic actions, or control inputs, and attempt to construct a suitable general transit controller from such a set of actions.

This ethological focus on actions rather than control laws may at first seem primarily semantic. The reason such a paradigm is useful stems from the control trade-offs of general transit. The important things for a general transit controller, roughly in order of importance, are:

1. don’t lose control,

2. don’t waste power, e.g. by moving the elevators more than necessary, and

3. don’t be too picky about the vehicle state.

Good control is needed to maintain the vehicle state within safe bounds, but the specifics, such as the exact depth trajectory, are largely irrelevant. Because of this, the most appropriate information is in the form of discrete events rather than continuous feedback. Monitoring the depth isn’t as useful as just knowing when the vehicle reaches a target depth. It is because discrete
events are more useful than continuous feedback in general transit that the focus on actions is useful and appropriate.

4.1.1 Gliding

The first basic action truly spends the least power on elevator actuation; the elevator simply isn’t moved. In this case, the vehicle settles in a glide. In Section 3.3.1, it was shown that the vehicle is stable during a glide. It was also noted that the steady state dynamics can be characterized by two parameters, the side slip ratio $\sigma$ and the dive angle coefficient $\mu$. We will occasionally draw a distinction between a glide involving a change in depth, which we call a dive, and a level run. This basic action is nice for a number of reasons. First, power is conserved by not operating the elevator. Second, the vehicle dynamics are stable. Third and finally, because the steady state response is easily characterized, such an action can be readily adapted to changing parameters. The only problem comes when the vehicle isn’t headed in the right direction.

4.1.2 Transitioning Between Glides

An obvious first attempt at transitioning between glides is commanding a step change to the appropriate elevator angle. There are, however, problems with this approach. The transition is not smooth, and there can be considerable overshoot. Figure 4.1 shows the simulated response of the vehicle to a step change in commanded elevator angle. The bandwidth of a step change provides excitation of unwanted dynamic modes, resulting in the excessive pitch overshoot. To prevent this, transitions are made by approaching the desired elevator angle exponentially:

$$\delta_{\text{command}} = \delta_0 + (\delta_f - \delta_0) \left(1 - e^{-\frac{1}{\tau}(t-t_0)}\right)$$

(4.1)

where $\delta_0$ is the current elevator angle, $\delta_f$ is the target elevator angle, $\tau$ is the decay time constant, and $t_0$ is the time at which the transition is begun. This basic action provides a control signal of limited bandwidth, so that unwanted dynamics can be eliminated.
4.1.3 Depth Changes

The depth change command presents a command modality too complex to be accomplished by the basic actions described above. This modality is easily accommodated by creating a higher-level action within the asynchronous action hierarchy. A change in depth is constructed as follows. The appropriate elevator angle for diving is calculated, depending on the maximum permissible vehicle pitch and the current vehicle speed, and the elevators are transitioned to this angle. The vehicle glides without elevator motion until it has reached the desired depth less the draft required to pull out of the dive. At this point, a transition to level running is executed. This depth change covered in a transition from a dive to a level run is called the recovery draft.
CHAPTER 4. CONTROLLER DEVELOPMENT

4.2 The Structure of the General Transit Controller

In this section, we consider the structure of the general transit dynamic controller. Recall that the controller module accepts input commands from the command mode modules at the base of the asynchronous action hierarchy, as shown in Figure 4.2. It responds to these commands and provides, as output, elevator commands. Figure 4.3 illustrates the functioning of the general transit controller module as a finite state machine. There are two possible states for the controller: gliding and transitioning. While gliding, the controller module is essentially asleep. No commands need to be sent to the elevators, and no processing is necessary at this level. The general transit controller leaves the gliding state just in case it receives a new command from the activity hierarchy. If the general transit controller is not gliding, it is commanding a transition between two glides. This state continues until a new command is received or the new gliding state is achieved. If a new command is received, the general transit controller re-enters the transitioning state. When the target elevator angle is reached, that is, when the transitioning action has been completed, the general transit controller enters the gliding state.

When the transitioning state is entered, the general transit controller responds to the module requesting the transition. This response serves as acknowledgement of receipt of the request, and indicates whether the controller is implementing the requested action. The general transit controller implements all requested actions provided they have sufficient priority to override the current state. If the transitioning request was sent by the depth change command mode module, the general transit controller also includes an estimate of the necessary recovery draft for the dive. At this point, the controller evaluates the requested transition (depending on the command mode) and determines the target elevator angle. If the request is received from the pitch command mode module, for example, the current estimates of the vehicle speed and dive-angle coefficient are used to calculate the appropriate elevator angle to achieve the requested vehicle pitch. Using the controller decay time, the elevator is commanded to exponentially approach the target elevator angle. The decay time is currently specified for the controller, but could be defined through an endogenous variable to provide more controller...
Figure 4.2: The general transit dynamic controller situated in the asynchronous action hierarchy. The dynamic controller receives input from the command mode modules and produces elevator commands as output.
Figure 4.3: Finite state representation of the general transit dynamic controller. The controller has two states: gliding and transitioning between glides.
flexibility in the future. Once the commanded elevator angle has reached the target elevator angle, the general transit controller enters the glide state, waiting for a new transition request.

4.2.1 Command Modes

The relationship between the general transit dynamic controller, the command mode modules and the remainder of the asynchronous action hierarchy is shown in Figure 4.2. Most of the command modes currently used require only a single transition to achieve the desired action. The depth change and altitude command modes, however, require two: an initial transition to the appropriate diving angle and a recovery transition to regain level running at the desired depth or altitude. These command modes illustrate the use of releasing mechanisms in the asynchronous activity hierarchy. When a depth change request is sent from the depth change or altitude command mode modules to the general transit controller, an acknowledgement is returned indicating whether the controller is implementing the request and estimating the recovery draft necessary for the vehicle to return to level running at the conclusion of the depth change maneuver. When this recovery depth estimate is received, the command mode module uses a releasing mechanism to trigger the second transition (from the diving portion of the maneuver to the recovery portion of the maneuver).

4.2.2 Controller Parameters

With the structure of the general transit dynamic controller defined, we will now consider the parameters which are used in implementing the controller. First, the controller has an internal model of the dynamics it uses. This does not consist of a full dynamic model of the vehicle, rather, a much simpler model pertaining the dynamics exploited by the controller is maintained. This model includes the sideslip ratio $\sigma$ and the dive angle coefficient $\mu$. As mentioned in Section 3.3.1, these two parameters completely characterize the steady state behavior of the vehicle as modeled in Chapter 3. They are used in determining the target elevator angle when a transition request is received. The general transit controller also needs a way to estimate the recovery draft needed when returning to level running after a dive. This recovery draft model is based on simulation results of the full vehicle model.
(as developed in Chapter 3). In addition to these model parameters, the controller has factors which impact the controller performance: decay time constant and elevator resolution. The decay time constant $\tau_{\text{decay}}$ is the time constant of the exponential fin motion used by the general transit controller. There are obvious performance implications due to decay time. If the time constant is too small, excessive pitch overshoot may result, as was the case with the step input discussed in Section 4.1.2. If the time constant is too large, the controller will react too slowly, resulting in wasted time, and thus energy expenditure. The angular resolution of the elevators is not entirely a controller issue. Due to motor gearing and mechanical give in the elevator system, there is a physical limit to the accuracy of the elevator angle. It would be useless to try to control the elevators at an accuracy greater than they are physically capable of, wasting bandwidth on the agent's network bus. Also, the elevator angular resolution may be reduced below the physical limit, providing a trade-off between communications bandwidth and performance.

4.3 Performance Metrics

Because the general transit controller relies on discrete events for feedback, typical performance metrics are unusable for its evaluation. We will look to more global aspects of vehicle dynamic behavior to provide an evaluation of the controller performance. The question at hand is how well the general transit controller is meeting its objectives: maintaining stability and conserving power. In order to provide stable control, the controller should maintain vehicle state with certain bounds. The reason for the action-based approach for the general transit controller is to provide flexibility in the vehicle state when precise control is unnecessary. However, the controller must be able to operate the vehicle to within certain bounds. The major trade-off for the general transit controller comes in choosing the bandwidth of the control signal, specifically, the decay time constant of the transitioning action. Rapid response is played off against excessive vehicle motion and oscillation. Four metrics are used to evaluate the controller performance: depth undershoot, depth overshoot, pitch overshoot, and settling time. When the vehicle begins a dive, there is often a dip in the opposite direction as the pitch of the vehicle is changed. The extent of this dip in the undesired direction is the depth undershoot. Depth overshoot is distance beyond the final depth that the
Figure 4.4: Example of the performance metrics used to evaluate the general transit dynamic controller. (a) Settling time is the time from the beginning of a transition until the vehicle remains within 0.5 m of its final depth. (b) Pitch overshoot is the amount of pitch beyond the target pitch to which the vehicle swings. (c) Depth overshoot is the vertical excursion beyond the target depth. (d) Depth undershoot is the vertical excursion in the direction opposite the target motion. Note that all times are relative to the beginning of a transition and depths and pitches are relative to either the initial or target depth or pitch.
vehicle reaches as it settles into a level run. Pitch overshoot is the amount of vehicle pitch beyond that desired that the vehicle swings through. Settling time refers to the amount of time between initiating a transition to a level run and the restriction of vehicle motion to within one half meter of the final depth. These performance metrics are illustrated in Figure 4.4.

4.4 Choosing the Transition Decay Time Constant

To simplify the analysis, the possible transitions will be restricted. It is assumed that transitions run to completion (steady state) for this analysis. It is further assumed that all transitions involve either leaving a level run or entering a level run. In other words, we look at the vehicle’s dynamic behavior transitioning between a level run and a dive and between a dive and a level run, but will not consider transitions between two dives or transitions which are interrupted by either a new transition or a change of dynamic controller. This retains focus on the typical operation of the general transit dynamic controller. Vehicle behavior was simulated for the following parameter ranges:

- motor input voltage: 12, 18, 24, 30, 36, 42, and 48 volts,
- transition decay time constant: 1, 2, 4, and 6 seconds, and
- elevator angle: five equally spaced angles between zeros and the smaller of the maximum commandable angle (45 degrees) and the angle at which the maximum vehicle pitch angle (30 degrees) is achieved.

For each run, the settling time, recovery draft, overshoot, undershoot, and pitch overshoot were calculated. For transitions to dives, the settling time, recovery draft, and overshoot were ignored. For transitions to level runs, the undershoot was ignored. The desired characteristics for the controller are

- overshoot: less than one meter,
- undershoot: less than one meter,
- pitch overshoot: less than five degrees, and
Figure 4.5: Maximum pitch overshoot versus transition decay time constant. The dashed line at 5 deg indicates the maximum desirable pitch overshoot.

- settling time: as fast as possible given the other constraints.

The overshoot and undershoot remained within these bounds for all of the simulations. Therefore, the general transit controller transition decay time constant was chosen on the basis of pitch overshoot performance and settling time. Figure 4.5 shows the maximum pitch overshoot for each of the tested decay time constants. The 1 s decay time constant resulted in excessive pitch overshoot. Figure 4.6 shows the maximum settling times for each time constant. Shorter decay time constants produce more rapid settling. A decay time constant of $\tau_{\text{decay}} = 2$ s was chosen for the general transit controller because it provided the most rapid response while keeping the vehicle within the desired behavioral limits.
Figure 4.6: Maximum settling time versus transition decay time constant.
Chapter 5

Evaluating the Performance of the General Transit Dynamic Controller

The design of the general transit dynamic controller results in gliding when possible to save energy and ensuring a stable range of operation for the agent. In this chapter, the performance of the controller is examined. First, the performance of the controller will be considered assuming the dynamic model of the vehicle which was developed in Chapter 3 is correct. An estimation scheme for predicting the recovery draft of dive to level run transitions is also developed. Next, the effects of finite resolution in the fin actuators are examined. Finally, the sensitivity of the controller to various sources of error in the model is considered. The impact of parametric error and measurement noise is discussed, and controller performance in the presence of process noise is noted. Section 5.4 provides a brief summary of the results and draws some conclusions about the general transit dynamic controller and the asynchronous action hierarchy.

5.1 Controller Performance with an Accurate Model

The performance of the general transit dynamic controller, using a transition decay time constant of 2 seconds, is considered in Figures 5.1 - 5.4. In all
Figure 5.1: General transit controller settling time performance.

of these figures, the data from transitions from level running to diving at the maximum permissible elevator angle and transitions from the maximum angle to level running are combined. Figure 5.1 shows the maximum settling time as a function of vehicle surge velocity \( u \). Note the small settling times realized when the vehicle is operating at a medium speed. This corresponds to the velocity at which the vehicle doesn’t dive. Recall from Chapter 3, (3.85),

\[
\text{\text{\( u_{\text{no\,dive}} = 1.49 \frac{m}{s} \)}}
\]

Operation near this velocity is difficult for the general transit dynamic controller because of its reliance upon the vehicle steady state behavior, which in this case involves a very small depth rate. Depth overshoot and undershoot present further problems to operating near this speed. Figure 5.2 shows the maximum overshoot of the vehicle when transitioning to level as a function of vehicle surge velocity. The depth overshoot is essentially zero below the critical speed \( u_{\text{no\,dive}} \), but increases as the surge velocity approaches \( u_{\text{no\,dive}} \) from above. The undershoot performance, shown in Figure 5.3, follows a similar trend. Small depth undershoots are present in level to dive transitions executed above the critical speed, however as the vehicle surge velocity approaches the critical speed from below, undershoot also becomes a prob-
Figure 5.2: General transit controller depth overshoot performance.

Figure 5.4 shows the effects of vehicle forward velocity on the maximum pitch overshoot during transitions from dive to level running. Note that the first two speeds are the result of saturating the elevator angle, that is, the elevator angle during the dive is 45 degrees, but the vehicle remains below its maximum permissible pitch of 30 degrees. The remaining data result from the vehicle achieving 30 degrees pitch with the elevator set at less than 45 degrees.

Table 5.1 summarizes the performance of the general transit dynamic controller across the range of vehicle velocities.

Figures 5.5 - 5.7 show the details of the vehicle behavior during transitions for three representative speeds. The three vehicle speeds chosen are due to a supplied motor voltage of 12 V, 24 V, and 48 V, respectively. These vehicle speeds were chosen to illustrate the upper and lower limits of the vehicles capabilities, as well as data near the critical speed $u_{\text{no dive}}$.

Note that in all of these cases, the vehicle dynamic response is well within the desired behavioral limits of one meter depth overshoot and undershoot and five degrees pitch overshoot. Also, the controller is able to effectively treat the entire speed range of the vehicle using a very simple model of the vehicle dynamics. The response of the vehicle, in terms of amount of
CHAPTER 5. CONTROLLER PERFORMANCE

Figure 5.3: General transit controller depth undershoot performance.

Figure 5.4: General transit controller pitch overshoot performance.
Figure 5.5: Controller performance during slow speed transitions. The motor is supplied 12 V, resulting in a vehicle speed of 0.8 m/s. Plots (a) and (b) show the depth and pitch, respectively, during a dive to level run transition. Plots (c) and (d) show depth and pitch during a level run to dive transition. Note that time is relative to the beginning of a transition, depth is relative to the initial depth, and pitch is relative to the target pitch.
Table 5.1: General Transit Dynamic Controller Performance

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Velocity</th>
<th>Elevator Angle</th>
<th>Settling Time</th>
<th>Depth Overshoot</th>
<th>Depth Undershoot</th>
<th>Pitch Overshoot</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>u</td>
<td>δ</td>
<td>ts</td>
<td>ζ_{over}</td>
<td>ζ_{under}</td>
<td>θ_{over}</td>
</tr>
<tr>
<td>V m/s</td>
<td>deg</td>
<td>s</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>deg</td>
</tr>
<tr>
<td>12</td>
<td>0.80</td>
<td>45</td>
<td>10.77</td>
<td>0</td>
<td>0</td>
<td>1.41</td>
</tr>
<tr>
<td>18</td>
<td>1.12</td>
<td>45</td>
<td>7.16</td>
<td>0</td>
<td>0</td>
<td>2.14</td>
</tr>
<tr>
<td>24</td>
<td>1.40</td>
<td>33</td>
<td>3.58</td>
<td>0</td>
<td>45.72</td>
<td>1.68</td>
</tr>
<tr>
<td>30</td>
<td>1.65</td>
<td>24</td>
<td>0.41</td>
<td>48.66</td>
<td>25.17</td>
<td>0.99</td>
</tr>
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<td>1.89</td>
<td>18</td>
<td>2.23</td>
<td>0.12</td>
<td>16.08</td>
<td>0.52</td>
</tr>
<tr>
<td>42</td>
<td>2.10</td>
<td>15</td>
<td>3.15</td>
<td>0.05</td>
<td>11.38</td>
<td>0.17</td>
</tr>
<tr>
<td>48</td>
<td>2.31</td>
<td>12</td>
<td>3.81</td>
<td>0.03</td>
<td>8.46</td>
<td>0.08</td>
</tr>
</tbody>
</table>

damping, and even the presence of depth undershoot, varies across the vehicle's dynamic range, but the general transit dynamic controller is capable of maintaining control in each of these situations. Of course, the trade-off for the simplicity and range is precise tracking. Small oscillations are present even before the addition of noise. However, such effects are unimportant for the vehicle while operating in a general transit setting.

### 5.1.1 Estimating the Recovery Draft

In order to complete a depth change behavior, the general transit controller must be able to estimate the recovery draft, or the vertical excursion of the vehicle when executing a dive to level running transition. The model used for estimating recovery draft is entirely empirical; it is based on the data from the simulated transitions. The recovery draft may be estimated as

\[
ζ_{rd} = \left(7.1701u^2 - 10.4774u - 0.5973\right) δ. \tag{5.2}
\]

This estimate is based upon the observations that

- the recovery draft increases nearly linearly with the elevator angle while diving, and
Figure 5.6: Controller performance during medium speed transitions. The motor is supplied 24 V, resulting in a vehicle speed of 1.4 m/s. Plots (a) and (b) show the depth and pitch, respectively, during a dive to level run transition. Plots (c) and (d) show depth and pitch during a level run to dive transition. Note that time is relative to the beginning of a transition, depth is relative to the initial depth, and pitch is relative to the target pitch.
Figure 5.7: Controller performance during high speed transitions. The motor is supplied 48 V, resulting in a vehicle speed of 2.3 m/s. Plots (a) and (b) show the depth and pitch, respectively, during a dive to level run transition. Plots (c) and (d) show depth and pitch during a level run to dive transition. Note that time is relative to the beginning of a transition, depth is relative to the initial depth, and pitch is relative to the target pitch.
Figure 5.8: Estimated recovery draft as a function of vehicle surge velocity and elevator angle.

* the marginal draft based on elevator angle varies approximately quadratically with speed.

Although this estimate, shown in Figure 5.8, is empirically based, it provides a good estimate of the recovery draft with a small number of parameters. Figure 5.9 shows the errors in the recovery draft estimate as a function of speed incurred by each of these assumptions. The lower, dashed line of Figure 5.9 indicates the RMS error in recovery draft due to assuming a linear relationship between recovery draft and elevator angle, and the upper, solid line indicates the total RMS error in the recovery draft estimation scheme from (5.2).

The RMS error of the recovery draft estimate remains less than 20 cm for the entire speed range of the vehicle, and improves considerably at high speeds.
5.2 The Effects of Elevator Angular Resolution

The elevators are not perfect actuators. There is some amount of give in the mechanism by which the fins are actuated, and there may additionally be errors in the positioning of the elevator. To explore the effect this has on the general transit dynamic controller, the elevator command specified by the controller was limited to a finite resolution. The vehicle was simulated performing transitions (both level run to dive and dive to level run) at three speeds: 0.8 m/s, 1.4 m/s, and 2.3 m/s. These speeds correspond to motor supply voltages of 12 V, 24 V, and 48 V, respectively. At each speed, the vehicle was transitioned to and from the maximum permissible vehicle pitch. This was done with the elevator able to resolve commands to within 0, 0.5, 1, 2, and 4 degrees. Note that a 0 deg resolution represents infinite resolution, the same as the performance tests carried out in Section 5.1. The results for the three speeds are shown in Figures 5.10 - 5.12.

Elevator angular resolution does not seem to have a very large effect on the performance of the general transit dynamic controller. The performance metrics remain within the desired envelope even with a 4 deg angular reso-
Figure 5.10: Slow speed performance with angular resolution effects. The motor is supplied with 12 V, resulting in a vehicle surge velocity of 0.8 m/s. The plots show the effects of angular resolution on (a) settling time, (b) pitch overshoot, (c) depth overshoot, and (d) depth undershoot.
Figure 5.11: Medium speed performance with angular resolution effects. The motor is supplied with 24 V, resulting in a vehicle surge velocity of 1.4 m/s. The plots show the effects of angular resolution on (a) settling time, (b) pitch overshoot, (c) depth overshoot, and (d) depth undershoot.
5.3 Controller Sensitivity to Errors

Thus far, we have considered how the general transit dynamic controller performs using the model of the vehicle developed in Chapter 3. However, there are most likely discrepancies between the model developed and the real-world dynamics of the vehicle. In this section, we examine the sensitivity of the general transit dynamic controller to such discrepancies. Variations from the model are broadly categorized into three types: parametric error, measurement noise, and process noise. Parametric error is error in the model hydrodynamic values. Parametric errors imply that the model is wrong quantitatively, but not qualitatively; the form of the model is correct (vis a vis

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1Personal communication with James Bellingham.
Figure 5.13: Errors and noises in modeling. Differences between a real-world vehicle and its dynamic model can be categorized into parametric error, measurement noise, and process noise.

the parametric error), but the values of the hydrodynamic coefficients in the model may be incorrect. Measurement noise is noise introduced into the controller dynamics due to noise in the measurement of vehicle state. Process noise, on the other hand, is noise resulting from unmodeled vehicle dynamics or environmental forces. Figure 5.13 illustrates how each of these forms of modeling error relates to the dynamic controller.

5.3.1 Parametric Errors

Errors in estimating the hydrodynamic coefficients for the vehicle dynamic model are parametric errors. These affect the performance of the general transit dynamic controller in a number of ways. The general transit controller has been characterized using the model as presented in Chapter 3; if this model contains errors, the resulting dynamics of the vehicle will be different, and the results predicted during simulation will not be borne out in real-world trials. Specifically, the controller's limited model of the vehicle dynamics will be flawed. If the values of the sideslip ratio $\sigma$ and the dive
angle coefficient $\mu$ are uncertain, then the general transit controller will not be able to accurately calculate the proper elevator angle for a dive. If the model is incorrect, the recovery draft estimate will be less accurate. However, the general transit dynamic controller depends on a relatively small number of parameters, much smaller than the number of hydrodynamic coefficients in the model, for example. Additionally, the quantities involved in these parameters are fairly easily measured. For this reason, the general transit dynamic controller can be fairly easily recalibrated to a real-world vehicle.

5.3.2 Measurement Noise

Measurement noise arises from inaccuracies in measuring the vehicle state. This can be caused by physical limitations of the sensors, noise in the electronics used to process and store the sensor measurements, and errors in estimating vehicle state from measurable quantities. Because the general transit dynamic controller does not use continuous state feedback, its performance is largely immune to measurement noise, with a few notable exceptions. First, the controller must know the vehicle's speed in order to calculate the proper elevator angle and estimate the recovery draft. The speed required for this, however, need only be the steady vehicle velocity, that is, the average surge velocity of the vehicle. There is noise present in the measurement of vehicle speed, but by averaging the data, a good portion of this noise can be eliminated. Second, the controller must be able to place the elevator accurately. This issue is dealt with in the section on elevator resolution above. Third and finally, the vehicle must have an accurate sense of depth or altitude in order to trigger a transition from diving to level running. Depth sensor accuracy falls well within the envelope of controller performance.

5.3.3 Process Noise

Now consider the case of process noise. The noise we are concerned with here is the product of unmodeled forces on the vehicle. These include nonlinear drag and lift terms, crossflow effects, and higher-order effects of angle of attack, for example. It is somewhat difficult to simulate such forces, since they are, by definition, not modeled. The main concern, however, is that the general transit dynamic controller not be too sensitive to process noise. In other words, we would like for the performance of the general transit
Figure 5.14: Controller performance with added process noise at slow speed. The motor is supplied with 12 V, resulting in a vehicle surge velocity of 0.8 m/s. The plots show the effect of a stochastic force on (a) settling time, (b) pitch overshoot, (c) depth overshoot, and (d) depth undershoot. The added force is a random percentage of a nominal force. The percentage is a zero-mean normally distributed series with the indicated standard deviation.
dynamic controller to degrade gracefully as the effects of process noise increase. To investigate the controller sensitivity to process noise, a stochastic force term was added to the surge, heave, and pitch equations of the vehicle. This stochastic force term was constructed as a random percentage of some nominal force. The idea is to perturb the existing force balance by a small percentage, and evaluate the controller performance. Recall that we restricted testing to transitions between diving and level running. The nominal force upon which the process noise term was based was calculated as follows. For the surge equation, a nominal drag force was used:

\[ X_{\text{nom}} = X_u \tilde{u}^2, \]  

where \( \tilde{u} \) is the nominal surge velocity of the vehicle, that is, the steady state surge velocity given the applied motor voltage. For the heave and pitch equations, the steady state heave velocity \( \tilde{w} \) is also used define the nominal force:

\[ Z_{\text{nom}} = Z_w \tilde{w} \tilde{w}, \text{and} \]
\[ M_{\text{nom}} = M_w \tilde{w} \tilde{w}. \]

At each time step, these nominal forces were multiplied by independent random percentages \( \nu \),

\[ \nu = N(0, \sigma_{\text{noise}}), \]

with a given standard deviation \( \sigma_{\text{noise}} \). Simulations were run at the same three speeds as were used in the angular resolution tests. At each speed, the maximum permissible elevator angle was used during the dive. Process noise standard deviations of one, five, and ten percent were used. At each noise level, ten transitions of each type (dive to level running and level running to dive) were carried out. Figures 5.14 - 5.16 show the average performance metrics for these runs as a function of process noise standard deviation.

The general transit dynamic controller handles the process noise quite well. The vehicle response remains within the desired envelope even when process noise with a standard deviation of ten percent of the nominal force is added. Any degradation in controller performance seems to be graceful.

5.4 Conclusions

The general transit dynamic controller accomplishes the control goals set for it. The controller is capable of providing low-power control which maintains
Figure 5.15: Controller performance with added process noise at medium speed. The motor is supplied with 24 V, resulting in a vehicle surge velocity of 1.4 m/s. The plots show the effect of a stochastic force on (a) settling time, (b) pitch overshoot, (c) depth overshoot, and (d) depth undershoot. The added force is a random percentage of a nominal force. The percentage is a zero-mean normally distributed series with the indicated standard deviation.
Figure 5.16: Controller performance with added process noise at high speed. The motor is supplied with 48 V, resulting in a vehicle surge velocity of 2.3 m/s. The plots show the effect of a stochastic force on (a) settling time, (b) pitch overshoot, (c) depth overshoot, and (d) depth undershoot. The added force is a random percentage of a nominal force. The percentage is a zero-mean normally distributed series with the indicated standard deviation.
the vehicle within the envelope of desired motions consisting of no more than one meter overshoot or undershoot in depth and no more than five degrees overshoot in pitch. By acknowledging that precise control of the vehicle state is unnecessary during general transit, we have developed a simple, easily adapted controller suitable over the entire speed range of the vehicle in such a situation. Furthermore, by implementing the general transit dynamic controller in the context of an asynchronous action hierarchy, the possibility of implementing multiple dynamic controllers has been opened up. The asynchronous action hierarchy provides the flexibility to expand the capabilities of an AUV while maintaining enough structure to allow an organized implementation.
Chapter 6

Implementation Issues and Future Research Directions

In this thesis, a general intelligence architecture for autonomous agents has been described. The use of this architecture has been illustrated through the development of a dynamic controller within the framework of an asynchronous action hierarchy. The flexibility of the asynchronous action hierarchy provides a number of directions for immediate expansion.

6.1 Vehicle Modeling

6.1.1 Refining the Vehicle Dynamic Model

The dynamic model of the Odyssey vehicles developed in Chapter 3 could be refined in several ways. The first assumption that should be relaxed is that of neutral buoyancy. While the vehicles are often configured so as to be close to neutrally buoyant at their target depth, the relative amount of buoyancy will vary as the vehicle moves through the water column and is reconfigured for other missions. Empirical data from Odyssey missions should also be used to determine the accuracy of this model and provide better estimates of the vehicle parameters. Using a better dynamic model of the vehicle could provide a more accurate estimate of the recovery draft and controller performance.
CHAPTER 6. FUTURE RESEARCH DIRECTIONS

6.1.2 Adaptive Modeling

Providing adaptivity to the general transit controller model of the vehicle will make the controller more robust to changes in the vehicle dynamics due to reconfigured sensor suites or environmental variations. Adaptive maintenance of the sideslip ratio and dive angle coefficient is an easy initial step in this direction. A good estimate of these parameters is necessary for the proper functioning of the dynamic controller. Their empirical measurement is quite simple, however. Measurements of the vehicle pitch and depth rate provide good estimates, with the possible complication that vehicle velocity is not trivially measured. Beyond maintaining this basic model adaptively, the more difficult issues of vehicle performance and recovery draft estimation may be monitored.

6.2 The Asynchronous Action Hierarchy

We have provided the skeleton of the asynchronous action hierarchy for the vehicle. Further developments will take advantage of the flexibility this intelligence architecture affords and provide a richer repertoire of agent behavioral response.

6.2.1 Utilizing Endogenous Variables

We have not implemented any endogenous variables in this thesis, and the use of releasing mechanisms is quite limited. Several aspects of the general transit controller could be handled using endogenous variables. These include the transition decay time, elevator angular resolution, and dynamic controller selection by the command mode modules. The use of releasing mechanisms to signal discrete events to behaviors could also be expanded. However, I think that some more work will need to go into the software implementation of both releasing mechanisms and endogenous variables to ensure that they can provide modularity without excessive overhead.

6.2.2 Expanding the Action Repertoire

Perhaps the most exciting area for expansion is the addition of new actions. Experimentation with the vehicle dynamic model and creative control inputs
can provide useful motions. These might include quick dodges for use in obstacle avoidance. In addition to designing such actions by hand, there is the possibility of training the agent through the discovery and refinement of new actions and maneuvers. One can imagine specifying the goal of a particular action and a set of performance metrics, and, in much the same way as the general transit controller was developed here, derive a set of actions which meets such a goal. The agent, operating in the real world or through a simulation, could adapt the control sequence in order to refine the action, similar to an athlete being coached. The current work on directed evolution using genetic algorithms suggests such a scenario is quite feasible.

6.2.3 Adding Dynamic Controllers

There are many control techniques available for a system such as an AUV. The asynchronous action hierarchy provides the framework for including many dynamic controllers in the vehicle architecture. In this way, the dynamic controller which best suits the agent's situation and environment can be used.

6.3 Other Research Areas

6.3.1 Combining Model Information

All dynamic controllers have an implied plant model in them. Each is designed with a specific plant model in mind. These models vary widely in terms of depth of the model, whether noise is accounted for, etc. It would be nice if the information present in these models could be combined, particularly if they are adaptive. For example, the adaptive extension of the general transit dynamic controller discussed above can readily identify changes in the sideslip ratio and the dive angle coefficient. These parameter estimates imply certain relationships among the hydrodynamic coefficients of more complex models. Such information could be used to help tune more complex controllers using another controller's model which is more easily identified, albeit simpler.
6.3.2 Software Implementation

In discussing the agent's intelligence architecture, we have intentionally abstracted away from any particular software implementation. The best implementation of the asynchronous action hierarchy depends on a number of factors, including the operating system and microprocessor being used. Most of the implementations for this thesis have been partial and in environments not likely to be used on an AUV, such as MATLAB. In designing the intelligence architecture, we have, however, tried to keep certain programming features in mind. These include object encapsulation, inheritance, event-driven processing, and polymorphism. The asynchronous action hierarchy (and the general transit dynamic controller within it) is designed to allow easy extension while maintaining enough structure to make organized expansion feasible.
Bibliography


[24] Naval Coastal Systems Center, Panama City, Florida. *HYDrodynam  


