

Automated Bathymetry Mapping Using an Autonomous Surface Craft

by

Claudia Doria Rodriguez-Ortiz

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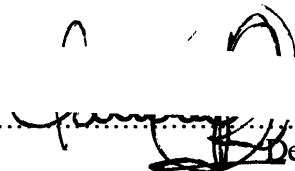
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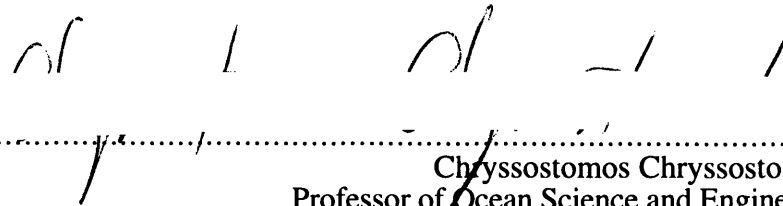
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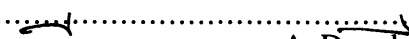
Author


.....
Department of Ocean Engineering
September 3, 1996

Certified by


.....
Chryssostomos Chryssostomidis
Professor of Ocean Science and Engineering
Thesis Supervisor

Accepted by


.....
A. Douglas Charmichael
Chairman, Departmental Committee on Graduate Studies

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Abstract

In this research, a need for autonomous, economic, time-efficient and accurate bathymetry surveying is identified. To meet this need, ARTEMIS, a prototype Autonomous Surface Craft (ASC), was developed to perform automated bathymetric-data-collection. ARTEMIS contains all the components required to generate bathymetric maps autonomously in real-time. The systems in ARTEMIS were tested individually (with an emphasis on the navigation, guidance and control systems – critical elements for bathymetry surveying) and then integrated into the total system. The GPS-based navigation technique employed in ARTEMIS was found to be adequate for typical bathymetric surveys. A waypoint-following controller based on fuzzy logic was used to guide and control the vehicle. The waypoint-following strategy proved very useful for transect-defined bathymetry surveying. The controller was robust to large external disturbances even on complex survey paths. ARTEMIS has performed automated bathymetry mapping in real-time, creating a high-resolution bathymetry map of a portion of the Charles River in Cambridge, MA. It is demonstrated that real-time automated bathymetry mapping using ASC have the potential to perform high-quality bathymetry surveys faster and more economically than conventional methods.

Thesis Supervisor: Chryssostomos Chryssostomidis
Title: Professor of Ocean Science and Engineering

*A mi abue Margarita, la más linda de todo el universo,
y a mis maravillosos papás, Doria y Orlando.*

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¹ Murphy's Law: If something *can* go wrong, it *will* go wrong.

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Nomenclature

Symbol	Definition or Meaning
AI	Artificial Intelligence
ASC	Autonomous Surface Craft
AUV	Autonomous Underwater Vehicle
AV	Autonomous Vehicle
C	programming language
CPU	Central Processing Unit
CTD	Conductivity-Temperature-Depth
DAMOS	Disposal Area Monitoring System
DGPS	Differential GPS
DR	Dead Reckoning
EPA	Environmental Protection Agency
FLC	Fuzzy-Logic Controller
FM	Frequency Modulated
GB	Giga-Byte
GPS	Global Positioning System
hr	hour
I/O	input/ output
kHz	kilo-Hertz
m	meter
NL	Negative Large
NM	Negative Medium
NMEA	National Marine Electronics Association
NOAA	National Oceanographic and Atmospheric Association
NS	Negative Small
PAH	Polycyclic Aromatic Hydrocarbons
PCB	Poly Chlorinated Biphenyls
PID	Proportional Integral Derivative

Symbol	Definition or Meaning
PL	Positive Large
PM	Positive Medium
PPS	Precise Positioning Service
PS	Positive Small
PWM	Pulse Width Modulation
RC	Remote Control
rms	Root mean square
ROV	Remotely-Operated Vehicle
RTCM	Radio Technical Commission for Maritime Services
SA	Selective Availability
sec	seconds
SPS	Standard Positioning Service
SV	Space Vehicle
TPU	Time Processing Unit
TT7	TattleTale microcomputer Model 7
TTL	Transistor-Transistor Logic
UART	Universal Asynchronous Receiver/Transmitter
UTM	Universal Transverse Mercator
V	Volts
ZE	Zero

CHAPTER ONE

Introduction

1.1 Motivation

This research develops a novel surveying system capable of autonomously creating high-resolution bathymetric maps in real-time. Autonomy has the potential of increasing scientific access to the oceans and coasts, and will aid in maintaining the navigation channels and updating nautical charts, both necessary for safe and efficient marine transportation. Marine transportation plays a key role in promoting trade around the world. In particular, 95% of all U.S. international trade moves through ports [1]. Consequently, a great part of the economy depends on the successful modernization of the water transportation system. This modernization must include expanding navigation channels for larger ships as well as updating nautical charts for enhanced navigation safety, both of which depend on reliable bathymetry information. However, the current methods for surveying bathymetric data are slow and expensive, limiting the areas that can be surveyed. As a result, half of inshore bathymetry surveys that support U.S. nautical charts rely on bathymetric data obtained before World War II [2; 3]. To meet the need for more efficient and cost-effective bathymetric surveys, an autonomous bathymetric-data-collection-system was developed and successfully tested in the field. Increasing bathymetric data acquisition rates can help modernize the marine transportation system, which is essential for efficient trade.

1.2 Bathymetry

1.2.1 Definition and Brief History

Bathymetric data are measurements of the depth of the water column. The word 'bathymetry' is derived from the Greek *bathos*, which means depth. A bathymetry chart represents the topography or the contours of bottom depths. Figure 1 shows an example of a bathymetry chart.

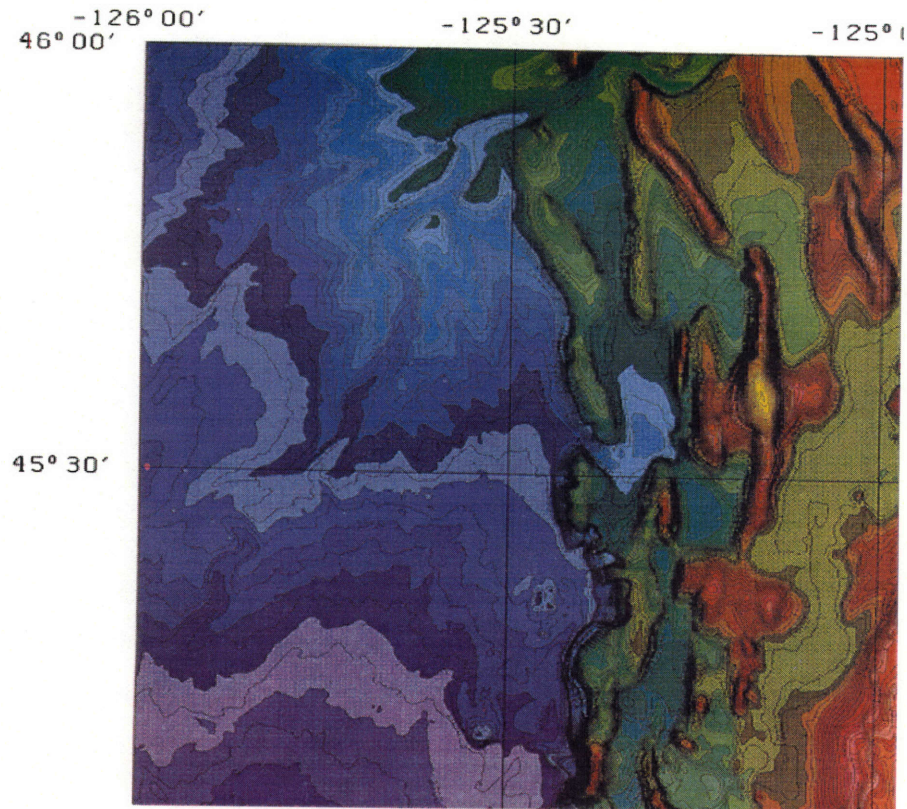


Figure 1 Seabeam Bathymetry of a portion of Oregon Continental and Adjacent Abyssal Plain. Shades of color represent various depths. Pacific Marine Environmental Laboratory, NOAA and Oregon Sea Grant Program.

Bathymetric charts have existed for centuries. An Egyptian temple decoration dating from about 1600 BC shows a ship on which a member of the crew is measuring the depth of the water with a long pole [4]. The Viking sailors took soundings (water depth measurements) by hauling in a lead weighted line and measuring it by the span of their arms [4]. Depths are still cited in six-foot (1.8-meter) intervals called fathoms from the Old Norse word *fathmr*, which means "outstretched arms" [4]. The water depth continued to be measured with the sounding line until the introduction of the depth sounder (or echo sounder) more than half a century ago [5; 6]. To create a chart, the lead-line measurements were correlated with a specific location and annotated by a person.

With the depth sounder (described in detail in Section 2.4), we are now able to remotely probe the oceans through acoustic means [5; 7; 8]. A depth sounder can be used to measure water depth data in a surveying grid to create a bathymetry chart. Unlike the sounding line, which offers only depth measurements at a single point, the depth sounder can record a continuous profile of the water column along a line.

Today, the depth measurements can be recorded digitally, allowing data processing and permanent storage. Depth sounding techniques now include equipment other than the conventional depth sounder [9; 10]. Sub-bottom profilers provide information about the layers beneath the bottom floor through the emission of high-power low-frequency signals [11]. With electronic sound navigation ranging or *sonar*, the location of objects within the water column can be determined. Side-scan sonars can provide high resolution images of the sea bed by towing a torpedo-like body with a pair of narrow beam acoustic transducers (an acoustic transducer converts mechanical, electrical or other form of energy into acoustical energy) along the sides [12].

1.2.2 Bathymetry Needs and Limitations

Scientists use bathymetric information for developing water circulation models in littoral regions [13]. Bathymetry maps are used in geophysical map-based navigation for underwater vehicles [14; 5]. The military uses bathymetric data for mine-countermeasure operations [15]. Commercial enterprises use bathymetry information to help locate new fisheries and identify regions with possible petroleum accumulations [13]. In particular, bathymetric data are essential for the successful operation of waterborne commerce, which is crucial to the U.S. economy. Commercial marine transport requires accurate and reliable nautical charts, as well as deep navigation channels to accommodate large vessels. Nautical charts consist of bathymetry charts and other information required for safe navigation. Dredging of navigation channels and disposing the dredged material also depend on bathymetric data because the depth of a channel must be known to ensure the quality of the dredging operation.

The nautical charts for U.S. waters are produced by the National Oceanographic and Atmospheric Administration (NOAA). NOAA is responsible for the charting and updating of approximately 95,000 miles of coastline and 3.5 million square nautical miles of oceans, inland rivers, and lakes [3]. However, nautical charts are outdated mainly due to a lack of efficient and economic hydrographic surveying techniques. In addition to commercial transport, nautical charts are an underpinning of a wide range of enterprises including naval operations, commercial fishing industry, recreational boating and fishing [3]. Non-navigational users include real-estate developers, coastal-zone planners, wetland managers, research scientists, and state coastal regulatory agencies [3; 2].

Nationwide, there is a need to update existing nautical charts and to survey uncharted areas. Sixty percent of the bathymetric data in NOAA's present nautical charts were obtained prior to 1940 [3]. Previous depth measurements taken with lead-line methods are inaccurate and cover less than one percent of the surveyed area [2]. At the same time, these surveys were performed with less sophisticated navigation systems leading to positional errors of 15 to 50 meters [2]. Moreover, there are over 20,000 reported but unsurveyed wrecks and obstructions around the U.S. [2]. As a result of uncharted features, three major vessels have grounded since 1987 [2]. A total of 43,200 square nautical miles have been identified as critical survey areas or areas with inadequate charts that may lead to marine accidents; however, it would take 40 years to survey these critical areas with the current surveying techniques and assets [2].

For the water transportation system to be efficient and to remain competitive in the world market, not only the nautical charts have to be updated but also its navigation channels must undergo periodic dredging for maintenance and improvement. Container ships and tankers have become wider and deeper to meet the increased demand for goods that accompany the rise in human population. Deeper navigation channels are required to accommodate the new generation of vessels. The U.S. Army Corps of Engineers is responsible for dredging over 400 ports and 25,000 miles of navigation channels throughout the U.S. [1]. Bathymetric surveys are necessary before, during, and after dredging to ensure the quality of the dredging operation.

Bathymetry surveys are also required for operations involving the disposal of dredged material. In the U.S. every year there are approximately 400 million cubic yards of dredged material, of which 5% to 10% contain heavy metals and organic compounds such as PAH's and PCB's [16]. The disposal of these contaminated sediments is an issue of

great debate [17] since the contaminated material can be resuspended and dispersed. One method of disposing the dredged material is 'capping' the contaminated sediments with clean sediments in near-coastal waters. Most commonly, the material is placed at offshore sites approved by the Environmental Protection Agency (EPA). For all of these cases, bathymetric surveys are necessary throughout the procedure: before deposition to select a site, during the deposition process to verify that the material is adequately placed, and periodically afterwards to ensure on a long-term basis that the dredged material remains at the site [1].

Whatever the need for bathymetry may be, a common thread is that the current bathymetric surveying methods are time-consuming, labor-intensive and expensive. During a typical offshore bathymetry survey at a disposal site, a research vessel follows track lines roughly 25 meters apart over an area of approximately two miles by two miles while gathering bottom information. With this method, it takes eight weeks to survey four square miles at a cost of approximately \$80,000, which includes the research vessel, crew, equipment and data analysis [18]. The costs rise with the area and the accuracy requirements. Channel surveying can use smaller vessels, but still require a significant number of personnel. The Corps, NOAA, and other organizations that have bathymetry surveying programs are constrained by the limited financial resources available for these purposes.

In response to the need for cost-effective, accurate and time-efficient bathymetric surveying, a mobile platform for autonomous bathymetric data collection was developed. Automated bathymetry mapping using a small Autonomous Surface Craft (ASC) proved to be economic, time-efficient, and accurate. Before introducing the ASC, other methods for gathering bathymetric information are briefly examined.

1.3 Bathymetry Survey Platforms

Existing survey platforms include surface vessels, manned submersibles, towed sensors, remotely operated vehicles (ROVs), remote-sensing satellites, and autonomous underwater vehicles (AUVs). The methodology chosen to collect bathymetric data depends on the particular application and the resolution and accuracy requirements. Surveys range from searching for large objects on a flat and smooth bottom to trying to locate fisheries on a rocky seafloor. The site to be surveyed may vary in terms of depth, current, slope, contour, rockiness, among other characteristics.

1.3.1 Existing Platforms

By far the most common bathymetry survey platforms are ships or small vessels operated by a crew. Surface vessels as survey platforms have been, and are today, largely indispensable. Nevertheless, their use is limited due to costs of operation and complicated logistics.

Submarines with crew offer deep measurements and excellent maneuverability. The drawbacks are the risk posed to the human lives aboard and the high operation costs. When bathymetric data is collected from a manned submersible, there is usually another task involved because the high costs cannot be justified for routine bathymetry survey work.

ROVs and towed platforms have proven to be very useful surveying tools for microbathymetric studies in relatively limited areas [5]. Power, as well as high-bandwidth real-time data such as acoustic and video images can be transmitted through the tether attached to the ROV. However, ROVs and towed sensors require support vessels and personnel for their operation, making the process slow, especially for surveying large areas. In addition, the operation of a research vessel with crew and scientists can be very costly.

A more recent technology involves the use of remote-sensing satellites to make observations of the ocean over long distances. In this fashion, two-dimensional synoptic views can be created such as temperatures of surface waters, sea state and ice conditions, and surface currents [5; 19]. However, neither visual nor radar photographic techniques have great potential for deep bathymetric work [5; 19]. Satellite remote-sensing may prove beneficial for shallow harbor surveys, yet it needs to be ground-truthed with other methods.

Autonomous marine vehicles are emerging technologies that introduce a whole new concept in data collection. The following section describes the advantages and disadvantages of this technology.

1.3.2 Autonomous Vehicles

Advances in robotics and automation have made possible the construction of autonomous vehicles (AVs) for scientific and industrial uses. Here 'autonomous' denotes an unmanned, untethered vehicle with an onboard guidance computer.

An autonomous system has an advantage over towed vehicles and ROVs in that there is no tether that may limit the performance of the vehicle by complicating the dynamic behavior, snagging or becoming tangled. Free from physical attachments an AV can travel faster and more efficiently. The trade-off is that there is limited energy since most AVs are battery-operated, which imposes power constraints on both propulsion and the sensors that can be carried. Without a tether, data can be transmitted via radio link or acoustic modem but at a much lower bandwidth [20]. Because not all data are transmitted, an AV needs a large onboard data storage capacity.

Bathymetry surveying with autonomous vehicles can be economical. By building small AVs, the support equipment and the size of the support vessel can be reduced [22]. Depending on the degree of autonomy, little or no human intervention is required during a preset mission. For bathymetry data collection this is particularly useful because an AV can be commanded to survey an area in fine grid spacing – repeatedly if necessary – a tedious and time-consuming task for a human being. With less support personnel and equipment an AV survey can be done at minimal operation costs.

Though surveying with AVs is a very attractive concept, achieving autonomous behavior is a challenging task. State-of-the-art control and navigation systems are needed to carry out a fully autonomous mission, which includes surveying, path following, obstacle avoidance, rendezvous and docking, and failure detection and recovery [14].

Although research and development of AVs have significantly increased in the past two decades, very little has been done with autonomous surface vehicles. Several Autonomous Underwater Vehicles (AUVs) are being built in the United States, Japan and other countries [23]; however, previous work regarding autonomous surface boats is sparse.

An autonomous surface vehicle embodies all the advantages mentioned above plus the additional feature that it can provide a bridge between the air and the water. Unlike an underwater vehicle, an autonomous boat is not shielded by sea water and can be equipped with a radio modem, allowing a two-way communication in real-time with a land-based station. Similarly, a surface vehicle can use the Global Positioning System (GPS) or a radio-based navigation technique, options generally not available to an underwater vehicle.

1.4 ASC ARTEMIS

The aim of this research project is to develop a prototype autonomous surface craft (ASC) and to demonstrate its capabilities for economical collection of bathymetric data. The long-term goal of this research is to develop future generations of low cost, high-efficiency, autonomous surface vehicles for oceanographic, industrial and environmental surveys. The intent is not to replace existing technologies, but to create an additional surveying method for the scientific, industrial, and governmental communities that may prove more convenient and economic. In some situations ASC may assist other surveying methods to jointly provide marine data. The success of such innovative technologies rests on the realization of prototype development projects. With this motivation, the ASC ARTEMIS – a first generation autonomous surface craft – was designed, constructed and tested.

ARTEMIS is a battery-operated mobile instrument platform that is able to navigate autonomously and collect bathymetric data (See Figure 2).



Figure 2 The 1.4-meter-long Autonomous Surface Craft (ASC) ARTEMIS configured for automated bathymetry mapping. ARTEMIS is equipped with a microcomputer for autonomous guidance, a GPS system for navigation, a depth sounder for bathymetric-data-collection, and a radio modem for data transmission in real-time.

The hull of ARTEMIS is a 1/17th scale model of a 76-foot New England fishing trawler with a length of 1.4 meters, a beam of 0.4 meters and a displacement of 27.3 kilograms. This model was previously used for resistance tests at the M.I.T. Ocean Engineering Testing Tank. An aft compartment houses the batteries while a waterproof enclosure containing all the electronic components is mounted in the forward compartment (Figure 3). The hull's small size and weight greatly simplify the deployment reducing the support personnel and hence the operation costs.

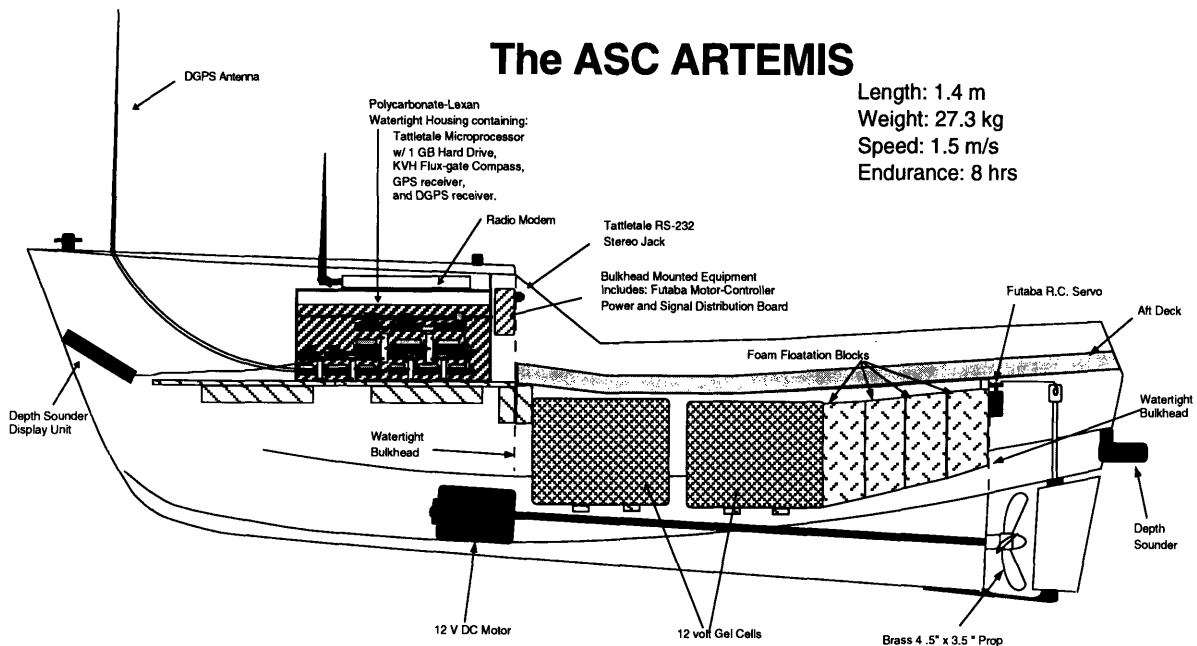


Figure 3 Schematic of ARTEMIS in cross-section. The aft compartment houses the batteries. Most of the electronic components are kept in a water-proof housing in the forward deck.

1.5 Automated Bathymetry Mapping

To demonstrate the vehicle's capabilities it was used to obtain a high-spatial-resolution bathymetry map of a portion of the Charles River in Cambridge, Massachusetts. This bathymetry map is particularly useful for an on-going research project in which the AUV *Odyssey* (See Appendix A) will navigate by following bottom features. Acquiring high-resolution bathymetric data involves accurately tracking the vehicle's position while measuring the water column depth. To operate autonomously effective navigation, guidance, and control schemes were developed.

Bathymetric data is useless without precise knowledge of the vehicle location at the times of data collection. The determination of the vehicle's location within a prescribed grid is referred to as 'navigation'. GPS was the most convenient, accurate, and economic option to obtain position information for ARTEMIS. For this purpose a GPS-based navigation technique was developed, which is described in Section 2.2.

Once position is determined, the next problem is to maneuver the vehicle along a prescribed path while compensating for vehicle drifts due to environmental disturbances. This is carried out by a guidance controller. In this context, guidance refers to the action of *determining* the course to be followed by the vehicle, while control refers to the *actions* taken to move the vehicle along a specified path [24]. Control can be achieved by using model-based approaches; however, for this application a 'model-free' control theory based on fuzzy logic is applied. Fuzzy-logic control provided fast development time of an accurate guidance controller for ARTEMIS. The fuzzy guidance-controller is described in detail in Section 2.3. The design of the vehicle hardware and software focused on attaining accurate navigation and control.

1.6 Organization of this Thesis

This chapter is an overview of bathymetry, the needs for bathymetric data collection, and various approaches to bathymetry surveying. Chapter 2 explains how concepts in navigation and control and existing instrument technologies are synthesized into a novel bathymetric-data-collection system. Chapter 3 discusses the results of the field experiments and compares automated bathymetry mapping to a conventional bathymetry surveying method. Finally, Chapter 4 states the conclusions of this research project and identifies areas of future work.

CHAPTER TWO

System Integration

Automated bathymetry mapping is achieved by coupling an accurate navigation technique, an effective control system, a water depth sensor, and data storage. The first step in the development of the ASC ARTEMIS involves the integration of the hardware components, among these, a main onboard computer with large data storage capability, a GPS system, a compass, a radio modem, and a depth sounder. The second step is to design the control software. The third step involves preliminary testing of the navigation and control systems. The final step is to integrate all the elements into an automated-bathymetry system to be operated in the field. The field experiments that demonstrate the capabilities of ARTEMIS are presented in Chapter 3.

The vehicle's hardware is described in Section 2.1.1. The software to control the vehicle is discussed in Section 2.1.2. The details regarding navigation and control are described in sections 2.2 and 2.3 respectively. Finally, the operation of the depth sounder and the limitations to the accuracy of the bathymetric data are discussed in Section 2.4.

2.1 System Description

Figure 4 shows a cartoon of the automated-bathymetry system. In a bathymetry surveying mission ARTEMIS is programmed to follow a survey grid. During the mission bathymetric and position data are collected by ARTEMIS and transmitted to a land-based computer via a radio link. At the land-based station, a color-coded bathymetry map is created in real-time using a MATLAB[®] script. This allows continuous monitoring of both

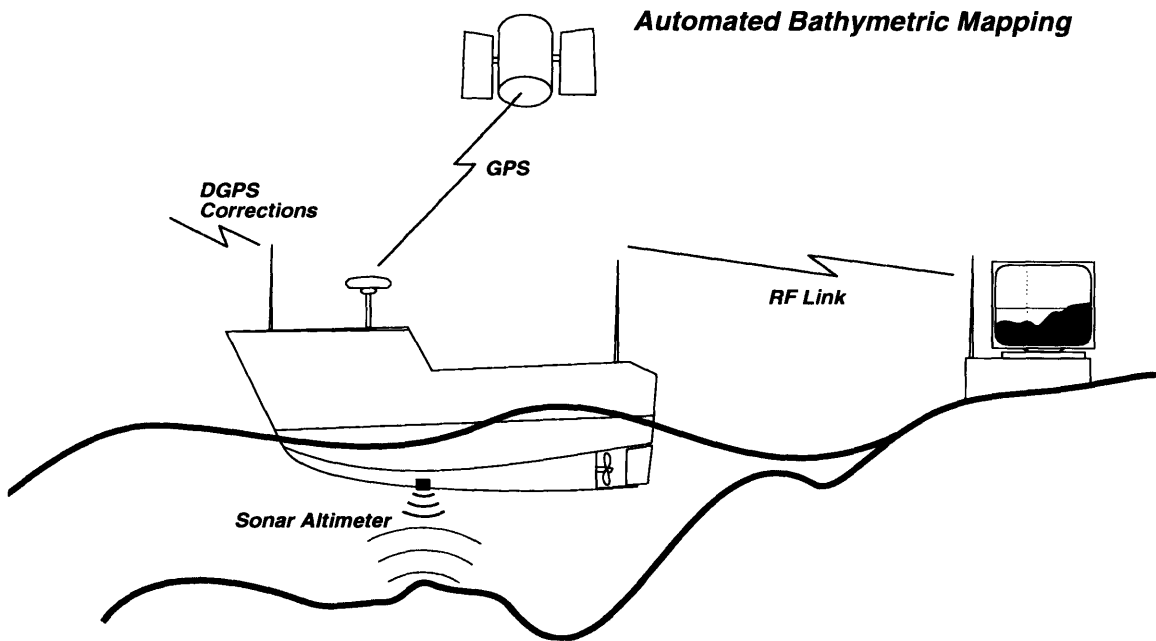


Figure 4 Real-time Automated Bathymetry Mapping using ARTEMIS. ARTEMIS navigates using DPGS position information while collecting bathymetric information with a depth sounder. Position and bathymetric data are transmitted to a land-based station via radio link, where a bathymetry map is created in real-time.

the position of the vehicle and the bathymetry beneath it. At the same time data is recorded onboard ARTEMIS for later retrieval. Although surveying can be done fully autonomously, a human operator at the land-based station can send basic control commands to ARTEMIS to modify the mission while in progress.

2.1.1 Vehicle Hardware

To reduce development time, minimize cost, and to allow an easy transition to the construction of multiple vehicles, ARTEMIS is built primarily with commercially-available components. In this section, the electronic components of the ARTEMIS system are described. The main subsystems that comprise the hardware in ARTEMIS as adapted for bathymetric surveys are shown in Figure 5.

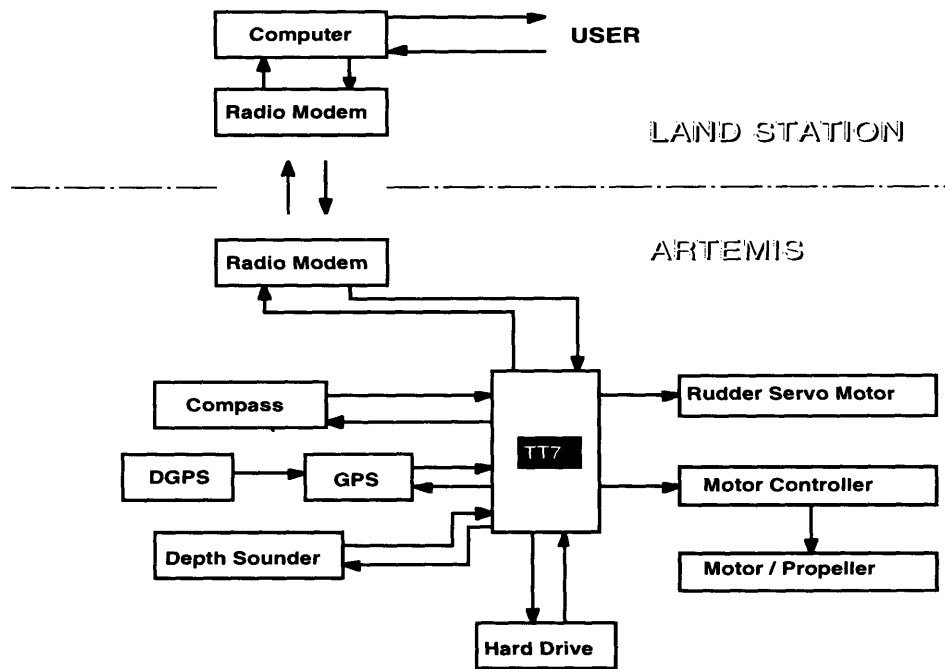


Figure 5 Block diagram showing the electronic components in the ARTEMIS system configured for bathymetric-data-collection. The main computer onboard is a Tattletale® Model 7 (TT7), which communicates with the other electronic components through its 16-channel Time Processing Unit (TPU).

The Tattletale[®] Model 7 (TT7) microcomputer runs the control software in ARTEMIS. The user downloads the mission to the TT7's through an RS-232 cable, which is detached after completion of the download. Throughout the mission the TT7 obtains heading information from the compass and position information from the GPS. Using these data, the control program in the TT7 computes the appropriate steering commands for the rudder servo motor (see Section 2.1.2). As this is being done, bathymetric data is collected with the depth sounder and transmitted to a land-based station, consisting of a computer and a radio modem, where a bathymetric map is generated in real-time. All data are stored on the ASC in a 1-GB hard drive and can be retrieved upon recovery of the vehicle.

ARTEMIS obtains heading information with a KVH[®] C100 SE-10 fluxgate compass. The fluxgate consists of a magnetic field sensor, in this case an inductor, which senses the horizontal component of the Earth's magnetic field. The KVH[®] sensor is gimballed, permitting operation through ± 45 degrees of tilt (pitch and roll). The compass communicates with the TT7 through its RS-232 serial port.

An Ashtech[®] GPS receiver and an Accqpoint[®] FM Differential GPS (DGPS) data receiver provide position information (the operation of the GPS and DGPS systems are described in Section 2.2.2). The Ashtech[®] sensor can track up to 12 satellites (SVs or Space Vehicles) at a time. With three SVs in view, the GPS receiver can compute and time tag the two-dimensional position of its antenna. Position accuracy is typically 16 meters rms [25]. Because this accuracy does not suffice for high-resolution bathymetry surveying, the GPS data is corrected with real-time differential measurements.

The Accqpoint[®] DGPS receives the differential corrections transmitted by a commercial service. It transmits differential corrections to the GPS receiver in RTCM format through

one of the two RS-232 serial ports in the GPS receiver. The second serial port in the GPS receiver is used to communicate with the Tattletale[®] microcomputer.

The TT7's TPU can generate pulse width modulation (PWM) waveforms with a duty cycle range from 0 to 100%. A PWM message is transmitted by modulating the signal's amplitude, thus changing the characteristics of the carrier wave (e.g., the length of the pulse). The PWM signals drive the servo motor which actuate the rudder. The propulsion system consists of a 12-volt brushed DC motor, a PWM-controlled motor control system, and a four-bladed brass propeller.

The bathymetric data is collected using a West Marine[®] D100 echo sounder with a 200 KHz, 12°-beam transducer. It provides depth readings from 1 to 130 meters in NMEA format. For communication in real-time with ARTEMIS from a land-based station, a pair of ProxLink[®] PL radio modems are used. The ProxLink[®] radio modems allow wireless RS-232 communication over a range of up to 1000 feet [26].

An attractive feature of the TT7 is its sixteen channel time processing unit (TPU) and built-in library of interrupt-driven, asynchronous, serial I/O functions. Each of the channels in the TPU can be opened independently for UART input or output and the TTL logic levels can be converted to the RS-232 standards. This furnishes enough channels to permit serial communication with the heading sensor, the GPS receiver, the radio modem, and the depth sounder. Currently, the TT7 uses ten out of the sixteen channels in the TPU (eight for the electronic components and two for the PWM signals used for motor and rudder control). Therefore, it is possible to obtain two-way communication from three additional environmental sensors capable of outputting over a serial (RS-232) port.

Power is supplied by two 12-volt, 26-Amp/hr lead-acid gel-cell batteries. One battery powers the electronics, the other provides propulsion power. With the present configuration the boat can cruise at approximately 1.2 m/sec with an endurance of approximately 8 hours, affording multiple, long-duration runs between recharges.

2.1.2 Vehicle Software

In this section, the general structure of the control software is discussed at a high level leaving the details of the control algorithm for Section 2.3. The software for the TT7 is developed in C on a Macintosh® computer then cross-compiled and downloaded to the TT7. Before each mission, the user must create an input mission file, which contains all the necessary parameters to run a mission. These parameters include the desired motor speed and a list of waypoints that determines a survey path. The main program that runs the vehicle is described in Section 2.1.2.1. The interaction between ARTEMIS and the land-based station via radio link is described in Section 2.1.2.2.

2.1.2.1 Main Program

The structure of the software is shown in Figure 6. After the initialization routine, the first waypoint in the list is selected. The current position and heading of the vehicle are determined and compared to this waypoint. If the vehicle has not reached the waypoint, the guidance controller computes a new rudder command for the rudder servo. The program loops until the waypoint is reached, at which point the next waypoint is activated. Once the last waypoint in the list is reached, the program exits.

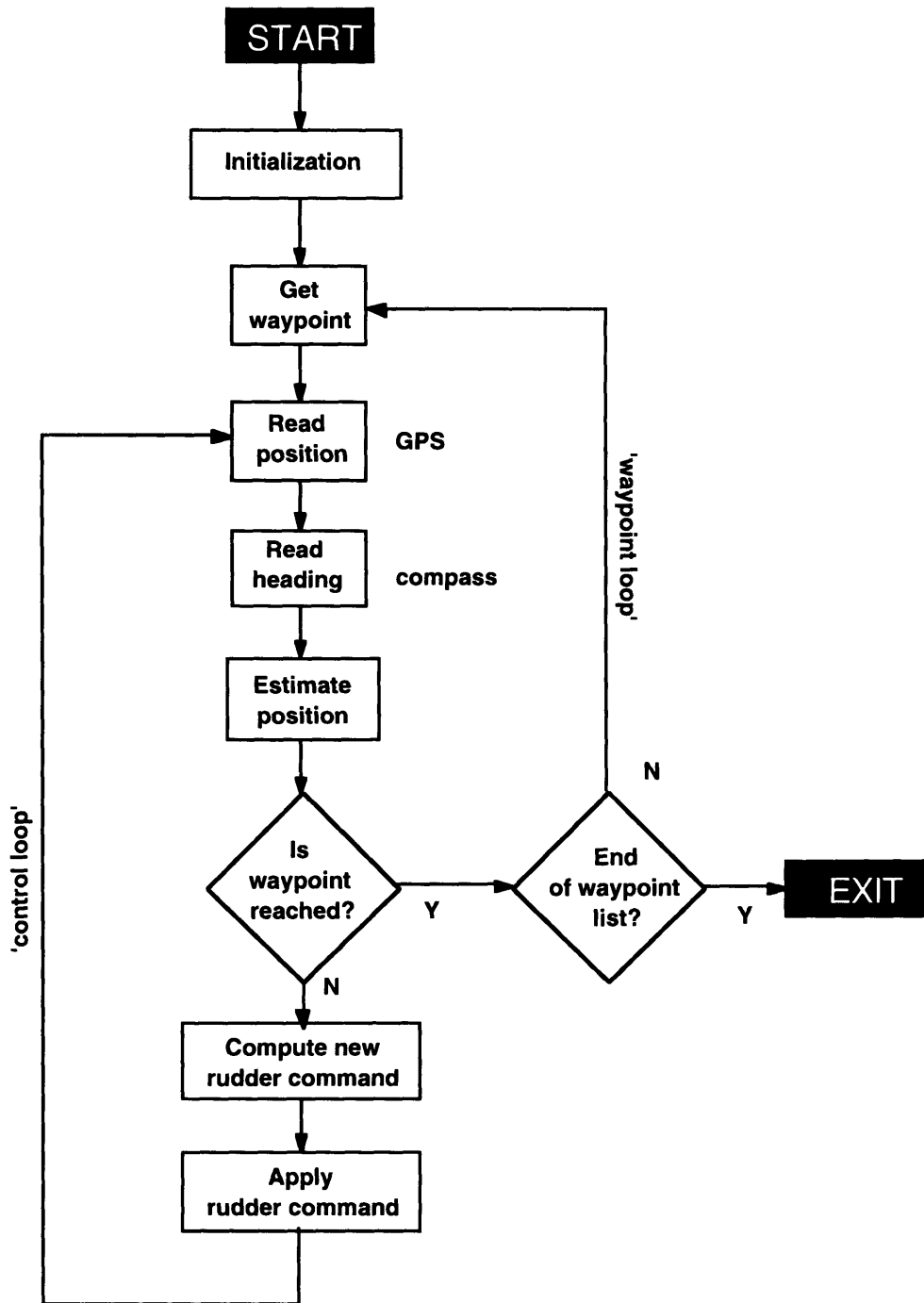


Figure 6 Software Architecture. The location of the vehicle is estimated, and the rudder angle required to reach the desired position and heading is computed. The program loops until a list of waypoints is completed.

In the initialization phase, two TPU pins are configured for rudder and motor control. Eight more TPU pins are configured as the serial inputs and outputs for the compass, GPS, radio modem, and depth sounder. At the start of a mission, the compass and the GPS are initialized, and an initial heading and GPS position fix are obtained. The desired speed is obtained from the input file, and the appropriate PWM signals are sent to the motor controller. The calculations to obtain the parameters that define the PWM waveforms (for both motor and rudder servo motor) are shown in Appendix B. At this point, the list of waypoints is obtained from the input file and the waypoint loop begins.

At the beginning of each execution of the control loop, the position of the boat is estimated by using a dead-reckoning algorithm updated with a GPS position fix (the position estimator is described in Section 2.2). To obtain heading and position information, query commands are sent to the compass and GPS respectively. A parsing routine extracts position and information from the GPS and compass NMEA response messages. Estimated position and heading are the inputs to a guidance controller that computes the rudder angle necessary to steer the boat to its destination. (The details of the controller are described in Section 2.3.) Each new commanded rudder angle is sent by the TT7 to the rudder servo motor in PWM waveforms.

All relevant information in a mission is permanently stored in the hard disk drive. Table 1 shows all the elements contained in the output data file. Before the program terminates, a routine disables all the PWM lines and serial ports, and closes all files.

Table 1. Data recorded during each control cycle loop

<p>Waypoint number</p> <ul style="list-style-type: none"> The number of the active waypoint in the list of waypoints downloaded to the boat at the start of the mission. 	<p>Y position, DR/DGPS</p> <ul style="list-style-type: none"> The current y-position of the boat in UTM coordinates computed from DGPS-updated DR algorithm.
<p>Waypoint- X position</p> <ul style="list-style-type: none"> The UTM x-position of the active waypoint. 	<p>Range to active waypoint</p> <ul style="list-style-type: none"> Distance to active waypoint in meters.
<p>Waypoint- Y position</p> <ul style="list-style-type: none"> The UTM y-position of the active waypoint. 	<p>Speed provided by GPS</p> <ul style="list-style-type: none"> Boat's speed computed by the GPS receiver.
<p>Waypoint crossing heading</p> <ul style="list-style-type: none"> The active waypoint's desired crossing-heading. 	<p>X position, GPS</p> <ul style="list-style-type: none"> The current x-position of the boat as read from the GPS receiver.
<p>Mission time</p> <ul style="list-style-type: none"> A running clock generated by the onboard computer. 	<p>Y position, GPS</p> <ul style="list-style-type: none"> The current y-position of the boat as read from the GPS receiver.
<p>GPS time</p> <ul style="list-style-type: none"> Universal time read from the GPS receiver. 	<p>Water depth</p> <ul style="list-style-type: none"> Water depth measurement read from the depth sounder.
<p>Heading</p> <ul style="list-style-type: none"> Magnetic heading read from the fluxgate compass. 	<p>DGPS flag</p> <ul style="list-style-type: none"> A 1 indicates that GPS position fixes are differentially corrected, a 0 indicates that GPS position fixes are not differentially corrected (contain SA errors).
<p>X position, DR/DGPS</p> <ul style="list-style-type: none"> The current x-position of the boat in UTM coordinates computed from the DGPS-updated DR algorithm 	<p>Number of satellites-in-view</p> <ul style="list-style-type: none"> The number of satellites used to compute the current position fix.

2.1.2.2 Supervisory Control

Although ARTEMIS may remain autonomous at all times, basic commands can be sent to the vehicle while a mission is in progress. The supervisory control mode consists of a series of control commands listed below:

START- This command allows starting the mission remotely after the control program is downloaded onto ARTEMIS and the tether is detached.

SKIP WAYPOINT- When the vehicle receives this command, it omits the next waypoint in the list.

HOME- Upon receipt of this command, ARTEMIS returns to the mission starting point.

PAUSE/ RESUME- With these commands, the mission can be suspended and restarted.

STOP- This command terminates the mission, i.e., the program is halted

2.2 Navigation System

This section describes the position estimator previously mentioned in the context of the software architecture. Navigation in ARTEMIS evolved from being a pure dead-reckoning (DR) system to a more elaborate system that employs the Global Positioning System (GPS). An overview of DR and GPS navigation is given as well as a description of the integration of the two techniques.

2.2.1 Dead-Reckoning Navigation

In the initial stages of the development of ARTEMIS, dead-reckoning² (DR) was the most obvious choice for navigation because it is simple and self-contained, i.e, it does not require external positioning references, such as acoustic beacons, radio stations or satellites. A DR estimation of the vehicle's position is merely the integration of the vehicle velocity in time. If the speed, the heading, and the travel time are known, the current position relative to the previous position can be estimated with simple kinematics.

In short range surveys and under favorable conditions, fairly accurate results can be acquired with an accurate compass and speed log. However, this method does not account for velocity components added by external forces such as winds and currents. For example, when a constant current causes the boat to drift, as shown in Figure 7, the DR calculation does not reflect the true position.

² The term DR comes from "deduced" positioning, spelled as "dead" it also means "certain" or "exact" as in the expression "dead ahead" [27].

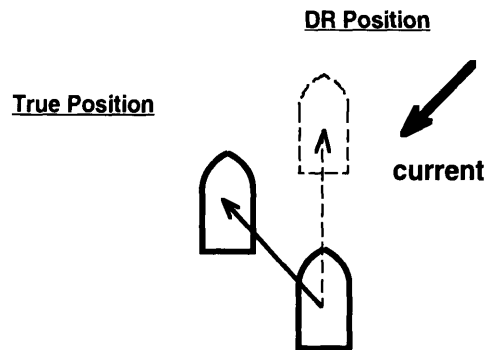


Figure 7 Dead-reckoning (DR) error. A boat travel course is affected by a current. DR estimation and true position differ from each other because the force from the current is not being accounted for in the DR estimation.

These environmental factors may generate position inaccuracies that propagate with time. Since the determination of the current position requires knowledge of the previously determined position, any errors in heading and speed measurements accumulate even if subsequent measurements improve. One way of preventing this error accumulation is to obtain periodic position updates using an external navigation method. For this purpose, a GPS-based system provides an additional measurement of position. Before describing this technique in Section 2.2.3, the basic concepts of GPS are introduced.

2.2.2 GPS and Differential GPS Navigation

Global Positioning Systems are space-based radio-positioning systems that provide all-weather, 24-hour, three-dimensional position, velocity and time information to suitably equipped users virtually anywhere in the world [28]. There are two satellite-based navigation systems in operation: NAVSTAR provided by the U.S., and GLONASS

developed by the Russian Federation. Equipment can be purchased by civilians around the world for restricted access to either or both systems. ARTEMIS is equipped with a GPS receiver that observes the NAVSTAR system.

A GPS receiver computes a radial distance from the center of the Earth using GPS satellites as navigation references. The range to the satellite is obtained by measuring the travel time of the satellite signal to the GPS receiver. When four space vehicles (SVs) are observed simultaneously, the receiver can determine three-dimensional position. Three SVs can be used to compute a two-dimensional position with a constant height.

The NAVSTAR system, operated by the U.S. Department of Defense, offers the Standard Precision Service (SPS) and the Precise Positioning Service (PPS). SPS is the standard specified level of positioning and timing accuracy that is available to any civilian user on a continuous worldwide basis. For national security reasons, this signal (denoted as S-code) is degraded through a process called Selective Availability (SA). When SA is turned on, the civilian user is able to obtain a horizontal positioning accuracy of order 100 meters. The P-code provided by the PPS is more accurate and it is not subject to SA; however, it is limited to authorized governmental and defense uses. The P-code is encrypted to prevent unauthorized use.

GPS signals may be degraded by sources of error other than SA or may be blocked in an urban environment. Multipath signals, e.g., reflecting from nearby objects such as buildings, can introduce large errors in the range. Errors can also be introduced when the GPS receiver changes the set of satellites used for position computation. At times, buildings may block GPS signals and the receiver may not find enough satellites to compute a two-dimensional position. During our experiments, at least three satellites were

in view most of the time. Additional sources of error include clock deviation and changing radio propagation conditions in the ionosphere [28].

One method to improve the accuracy of GPS navigation is a Differential GPS (DGPS) system. DGPS is based on the principle that most errors seen by GPS receivers in a local area are common errors and can be filtered with an appropriate technique. A stationary reference station with known coordinates continuously receives GPS position updates. Due to SA and other errors, the computed position is changing even though the base station is not moving. The difference between the known position and the computed position reflect the bias errors in the GPS signal.

Once the error in a local area is known, it can be subtracted from the GPS solution obtained from a GPS receiver at a nearby unknown location. This can be done during post-processing, or in real-time if the error is transmitted to the moving GPS receiver. One way of obtaining real-time differential corrections is through commercial services that use radio or television subcarriers to transmit DGPS corrections. These signals are received by the DGPS data receiver on ARTEMIS which transmits them to the onboard GPS receiver.

2.2.3 Integrated DR/DGPS System

To reduce the error in a dead-reckoned position, differentially-corrected GPS position fixes are used as an additional source of position information. GPS data is external to the system, thus preventing the unbounded error in DR navigation. A block diagram of the integrated DR/DGPS system is shown in Figure 8. The DR position propagator (Loop 1) is active until a full data-set is received from the GPS sensor. In this loop, the last GPS-derived boat speed and the time between position estimates (approximately 0.2 seconds) are

passed to the DR propagator to obtain the current position estimate. The GPS receiver provides a position update approximately every second in the form of geodetic latitude and longitude. The GPS NMEA string is parsed and converted to flat surface coordinates by using the UTM (Universal Transverse Mercator) mapping-projection technique. Because the error in the raw GPS position fix is not acceptable, the software in the boat uses only differentially-corrected position fixes for navigation. Every differentially-corrected GPS position update resets the initial conditions in the DR algorithm and the subsequent position estimate is computed based on the current information from the DGPS (Loop 2). The speed employed in the DR calculation is also derived from GPS information (position and time). By changing the DR point of reference and the vehicle's velocity with each DGPS update, the unbounded error propagation inherent to DR is prevented. The integrated DR/DGPS position estimator does not filter either the DGPS position fixes or the DR position estimates. Field tests have shown that this system works well with little or no noticeable jumps in the estimated position when a new GPS position fix is received.

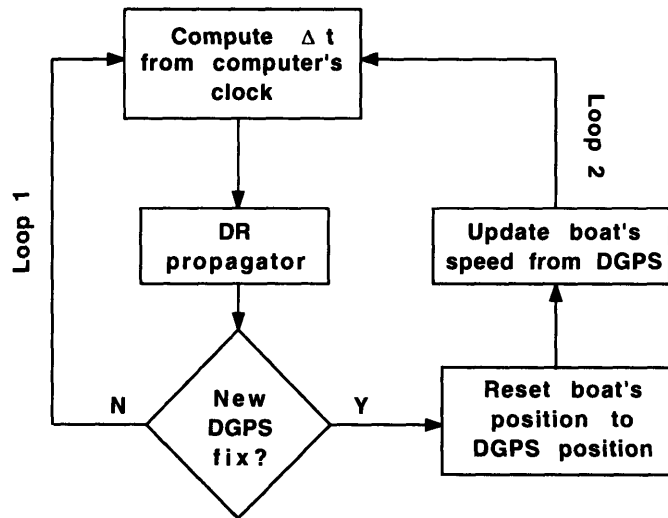


Figure 8 DR/DGPS Position estimator block diagram. This diagram shows the control flow in the position estimator.

2.3 Guidance and Control

In the absence of automation a person trying to take a boat from one position to another first considers her present position and course in relation to the desired position and course. Then she chooses a specific speed and heading. To maintain the course of her boat she uses her expert knowledge. That is, her experience and intuition tell her how much the helm needs to be turned and when to straighten it. She checks the heading and position periodically and makes appropriate corrections. An ASC is expected to perform this operation reliably without human interaction. The problem is broken down into navigation, guidance and control. This is shown in Figure 9. The previous section described the navigation system in ARTEMIS. This section presents the fuzzy-logic approach to guidance and control.

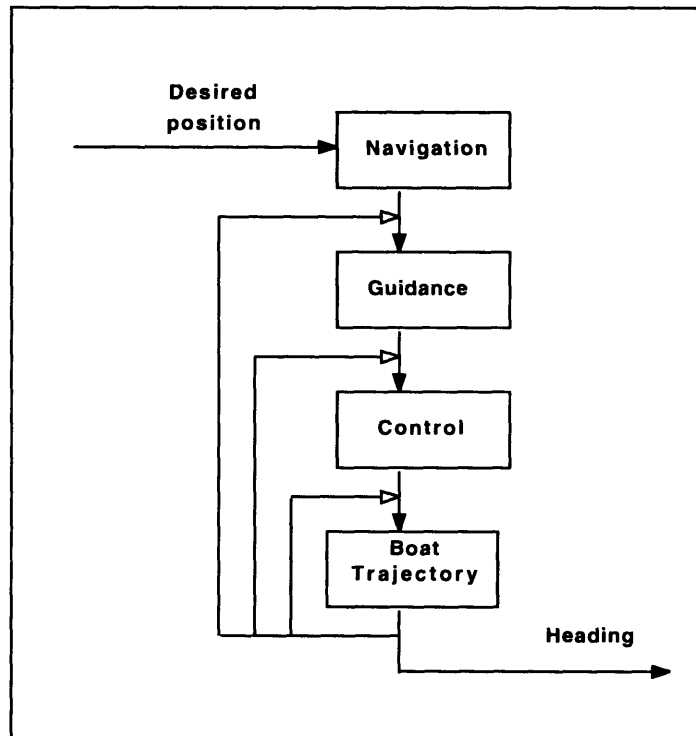


Figure 9 Navigation, guidance and control as nested loops, as applied to a boat.

2.3.1 Waypoint-Following Strategy

In a conventional bathymetry survey, a vessel guided by a helmsman follows track lines or transects. For each transect, the helmsman steers the vessel in a straight line to an imaginary point at a distance. The control strategy for autonomous operation is to form the desired trajectory by connecting a series of waypoints. A waypoint is defined by a position, a crossing heading and an 'arrival' circle. To reach a waypoint, the boat must enter the arrival circle on the specified heading (Figure 10). When a waypoint has been reached, the next waypoint in the list is activated. By forcing the vehicle to cross at a specific heading, smooth trajectories can be accomplished with only a few waypoints. For bathymetry surveying, the waypoints can be defined with opposite consecutive headings, as shown in Figure 10, which allows for closely-spaced transects.

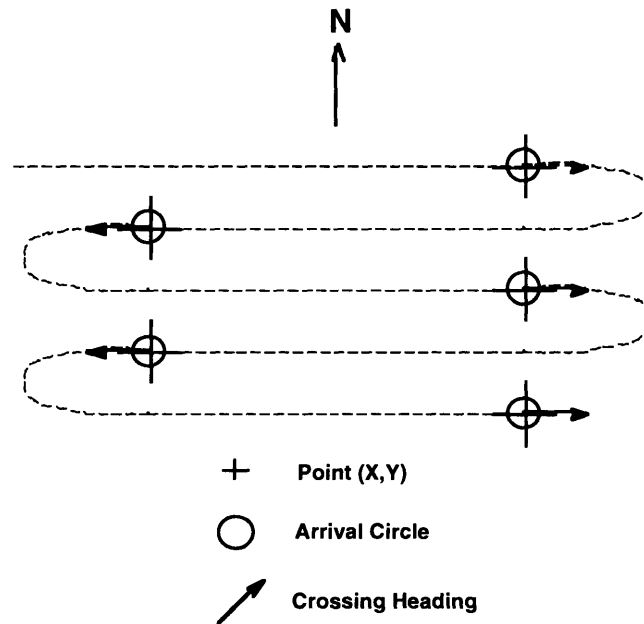


Figure 10 Waypoint-following strategy. A bathymetry survey can be performed by connecting a series of waypoints defined by their position coordinates, an arrival circle, and a crossing heading.

2.3.2 Control Methodologies

Autonomous control can be achieved in many different ways. Model-based approaches have proved effective and successful in solving well-defined problems [29]. A more recent control methodology is intelligent control, such as neural networks, genetic algorithms and fuzzy logic.

Model-based control relies on a mathematical model to predict the behavior of a system. A model, however, is always a simplification of reality, requiring assumptions. For example, Nomoto's first order model for a ship's motion [24] is:

$$T\phi'' + \phi' = K\delta$$

where ϕ is the yaw angle, T is the system's time constant, K is the gain, and δ is the disturbance. Using this model, a course-keeping autopilot can be designed with a simple proportional-integral-derivative (PID) controller. However, the vehicle's kinematics and dynamics change with the vehicle's configuration, making modeling difficult. If at a later stage in the evolution of the vehicle there are size or weight modifications that change the dynamics of the vehicle, a reevaluation of the time and gain constants will be necessary. If the environmental disturbances such as wind, waves and currents deviate from those modeled, the performance of the controller will be affected. This means that conventional controllers must be designed very conservatively to ensure robustness. As more inputs affecting the system response need to be considered, the mathematical model becomes more complex and detailed. In particular, a robust controller for a ship may require including nonlinearities that are difficult to model and control.

An alternative to model-based control is intelligent control, where the control algorithms are developed by emulating certain characteristics of intelligent biological systems [30]. For

instance, an artificial neural-network can learn by observing the system's behavior and can be used to control highly-nonlinear systems [30; 31]. Genetic algorithms can artificially "evolve" a controller to produce better solutions to a specific control problem [30]. For the objective of this thesis, which is to build a test platform to prove the concept of bathymetric surveying with ASC, fuzzy-logic control offers the most favorable and time-efficient way of developing a robust controller. The 'model-free' nature of fuzzy systems allows for rapid design and implementation of control laws without having to develop nonlinear dynamic models or complex control-system-architectures [32]. The fuzzy-logic controller is not as sensitive to changes in the vehicle configuration and it is robust to environmental disturbances.

2.3.3 Notions of Fuzzy Logic

In conventional (or bivalent) logic statements are either true or false, 1 or 0, white or black, nothing in between. Fuzzy logic, on the other hand, allows fractions, partial truths, shades of gray. Black and white are the extremes in a wide spectrum. The essence of fuzziness lies in that opposites are identical in nature, but different in degree [33; 34]. For example, there is no difference between "light" and "darkness" or between "large" and "small". The truth of any statement is a matter of degree.

The notions of fuzzy logic have been known for centuries. Hermetic philosophy of ancient Egypt and Greece clearly revealed fuzzy ideas in the 'Principle of Polarity' [33]. The *sorites* paradox of ancient Greek philosopher Zeno questioned bivalency [34]. Modern philosophers like René Descartes, David Hume, Werner Heisenberg, Bertrand Russell have also stated fuzzy concepts in one way or another [34]. Fuzzy logic theory as it is known and used today was introduced in 1965 when Lofti Zadeh published his work on

"Fuzzy Sets" [35]. During the 1980's the ideas of fuzzy set theory were more fully developed with some initial applications to show the fruits of this approach to control. The 1990's is a period of "fuzzy boom", in which fuzzy appliances and products have generated billions of dollars, particularly in Japan and more recently in the U.S. [36].

2.3.4 Fuzzy-Logic Control

The controller in ARTEMIS is designed to emulate a human's deductive process when steering a boat. A person manually steering a boat would check the heading periodically and correct it by turning the helm. The person knows that a hard turn of the rudder causes the boat to make a sharp turn. In the person's mind, the intuitive knowledge of how much the boat turns by turning the helm does not have a precise numerical value or a *crisp* value, in other words, it is *fuzzy*. In computing and reasoning, humans employ words that are relative and vague. These words can be represented with fuzzy sets [37], which are sets whose members belong to them to some degree. A fuzzy set is multivalent, which is essential to capture the vagueness in words.

A fuzzy control-system consists of an input-fuzzification interface, a Fuzzy-Associative-Memory (FAM) mechanism, and an output-defuzzification interface. To illustrate how a fuzzy-logic controller (FLC) works, a course-keeping controller is considered. The input to such controller is the measured heading.

The words that a helmsman would use to describe the difference between the measured heading and the desired heading do not have a clear distinction between one another and can be represented by the fuzzy sets: ZERO (ZE), POSITIVE SMALL (PS), POSITIVE MEDIUM (PM), POSITIVE LARGE (PL) and the mirror image for the negative side.

These fuzzy sets can be expressed in membership functions centered at the desired heading (180° in this example). The membership function for the input heading variable are shown in Figure 11. Adjacent membership functions overlap because of the vagueness in the linguistic terms. For example, an expert would say that a measured heading of 135° (a heading error of 45°) is more than “Negative Small” but is less than “Negative Medium” (NM). This error can be said to have attributes of both of these sets: it is to some degree both negative small and negative medium. This concept of belonging to both of these sets is graphically illustrated by the overlap shown in the figure.

The form of the membership functions (both number and placement) used in the ARTEMIS fuzzy control code were developed by first using intuition and then testing using simple simulations. Part of the ‘art’ of designing a fuzzy controller is deciding on the number of membership functions, their shape, and their placement. More precise control require more and thinner sets. Contrary to artificial intelligence (AI) based on bivalent logic, fuzzy logic allows gradual transitions without a large number of rules.

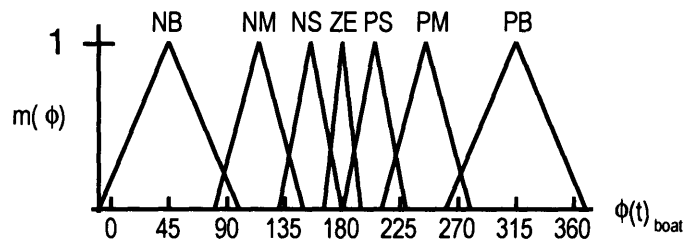


Figure 11 Membership function for the heading variable $\phi(t)$ centered at the desired heading (180°).

In the input-fuzzification interface, the crisp input values are categorized qualitatively with fuzzy sets. Each input belongs to a fuzzy set with a degree of membership, $m(\bullet)$. For a

particular input, most of the degrees of membership will be zero, except for one or at most two non-zero degrees of membership, which must add to unity.

When asked what action she would take given a heading error, a helmsman would respond using linguistic terms such as: small amount of right rudder (POSITIVE SMALL, PS), medium amount of right rudder (POSITIVE MEDIUM, PM), hard right rudder (POSITIVE BIG, PB). As before, these fuzzy sets are expressed in membership functions (Figure 12).

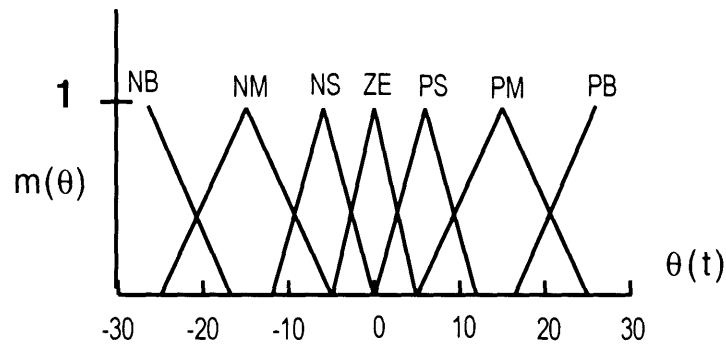


Figure 12 Membership functions for rudder angle.

Input fuzzy sets and output fuzzy sets are related through the FAM mechanism. In a FAM system, the 'experts' knowledge is quantified in a bank of IF-THEN rules. For example, if the heading error is NS (indicating that the boat is slightly to the left of the desired course), the rudder needs to be turned to a PS angle (rudder would be turned slightly to the right). Another way of expressing this is:

If (heading error is NS) then (turn rudder PS).

Each input fuzzy set is mapped to an output fuzzy set in this way. For this simple example, a complete FAM matrix would appear as:

		rudder command
	PB	NB
	PM	NM
	PS	NS
heading error	ZE	ZE
	NS	PS
	NM	PM
	NB	PB

The FAM rules are fired parallelly and partially [34], meaning that they are applied all at once to some degree.

Going back to the example, if the input to the course-keeping controller is 135° , it belongs to the fuzzy set 'NS' with a degree of membership of 0.4 and to the set 'NM' with a degree of membership of 0.6. These input fuzzy sets are mapped to the output fuzzy sets (rudder command) through the FAM matrix, in this case activating the 'PS' set to a level of 0.4 and the 'PM' set to a level of 0.6. The crisp (scalar) rudder command angle is found by computing the centroid (referred to as centroidal defuzzification) of the activated output fuzzy sets. In this example, the CD yields a crisp rudder angle of 12° . A flow chart for the FLC for course-keeping is shown in Figure 13.

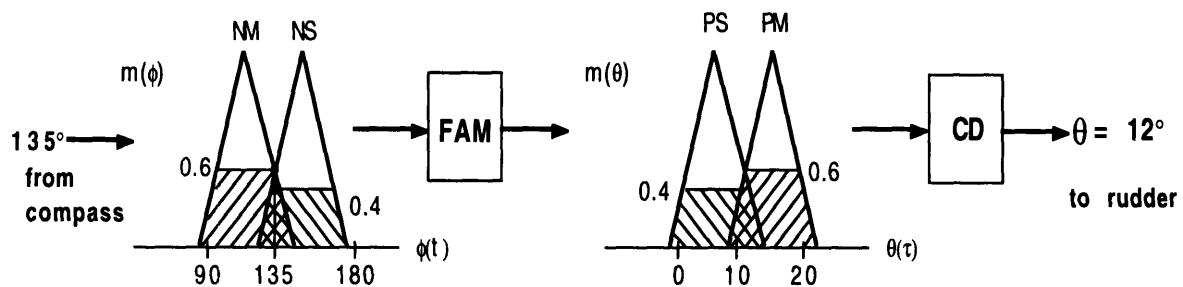


Figure 13 Hypothetical case of a FLC for course-keeping when the desired heading is 180° . A measured heading of 135° has degrees of membership, $m(\phi)$, of 0.4 NS and 0.6 NM in the variable heading membership function $\phi(t)$. The FAM rules relate the heading fuzzy sets with the output fuzzy set for rudder angle $\theta(t)$, resulting in degrees of membership, $m(\theta)$, of 0.4 PS and 0.6 PM. Centroidal defuzzification (CD) yields the commanded rudder angle 12° .

2.3.5 Waypoint-Following Fuzzy-Controller

To provide steering guidance for ARTEMIS, a fuzzy logic controller was developed based on a human's intuition of navigating to a waypoint and crossing it on a specified heading. Figure 14 shows how the waypoint-following FLC in ARTEMIS computes the output rudder angle. In addition to measured heading (ϕ), the FLC in ARTEMIS receives crisp numerical inputs for estimated position (x,y), which are fuzzified and associated to a rudder angle through the FAM rules. Centroidal defuzzification of the output fuzzy set results in the angle commanded to the rudder servo.

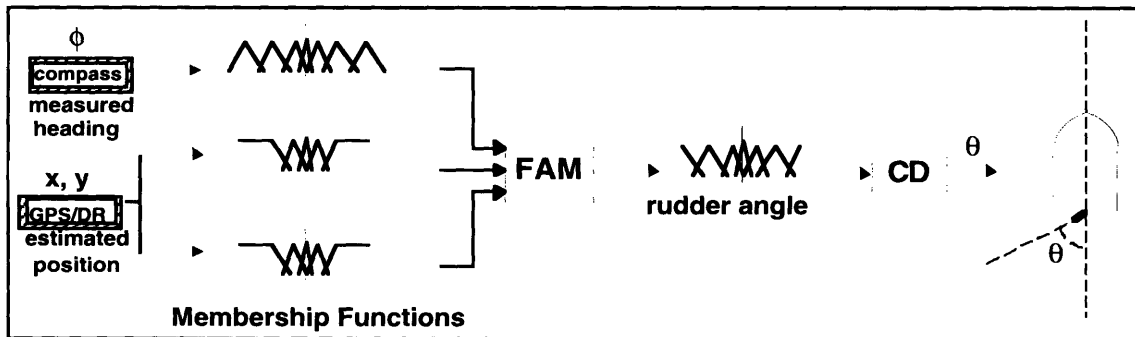


Figure 14 Cartoon showing the process in the fuzzy-logic waypoint-following controller in ARTEMIS. Crisp values of heading (ϕ), and position (x,y) are fuzzified and related to rudder angle through the FAM mechanism. Centroidal defuzzification yields the commanded rudder angle (θ).

As in the course-keeping-controller example, these inputs are fuzzified by assigning them degrees of membership in fuzzy sets. There are five fuzzy sets for x , five for y , and seven for heading angle. The fuzzy-logic controller (FLC) in ARTEMIS uses triangular and trapezoidal membership functions. Figure 15 shows the memberships functions for the y position variable. (The membership functions for the x position variable are identical.)

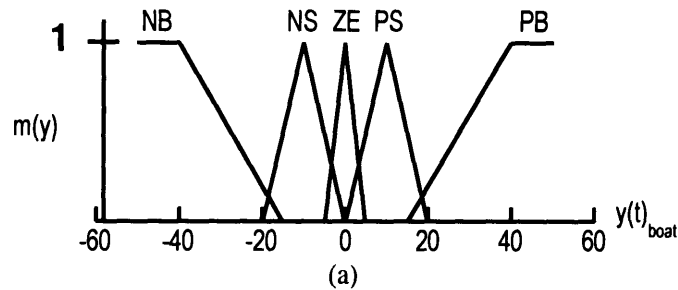


Figure 15 Membership functions for the y position variable. (The membership functions for the x position variable are identical.)

The FAM rules relate the fuzzy values of position (x,y) and heading angle (ϕ) with rudder angle (θ). The FAM system correlates each group of input fuzzy sets (x , y and ϕ) with an output fuzzy set (θ) in the form of IF-THEN rules. The waypoint follower controller uses 175 FAM rules, corresponding to $5 \times 5 \times 7$ different combinations of the three input sets. The FAM rule bank is shown in Figure 16. These rules were based on a paper model of desired boat trajectories near a waypoint, and they were tuned with computer simulations and preliminary in-lab tests.

The output rudder angle has membership functions shown in Figure 17. For finer rudder control, the fuzzy set is narrower around zero degrees, whereas in the extremes, the rules are less precise. To prevent stalling, the rudder angle is limited to $\pm 25^\circ$. In this work, the degree to which the rule is fired is determined by the correlation-minimum inference procedure. This procedure 'clips' or truncates the output fuzzy set depending on the degree of the input membership. Once the fuzzy output set is obtained, the crisp output – a numerical value for commanded rudder angle – is obtained by centroidal defuzzification.

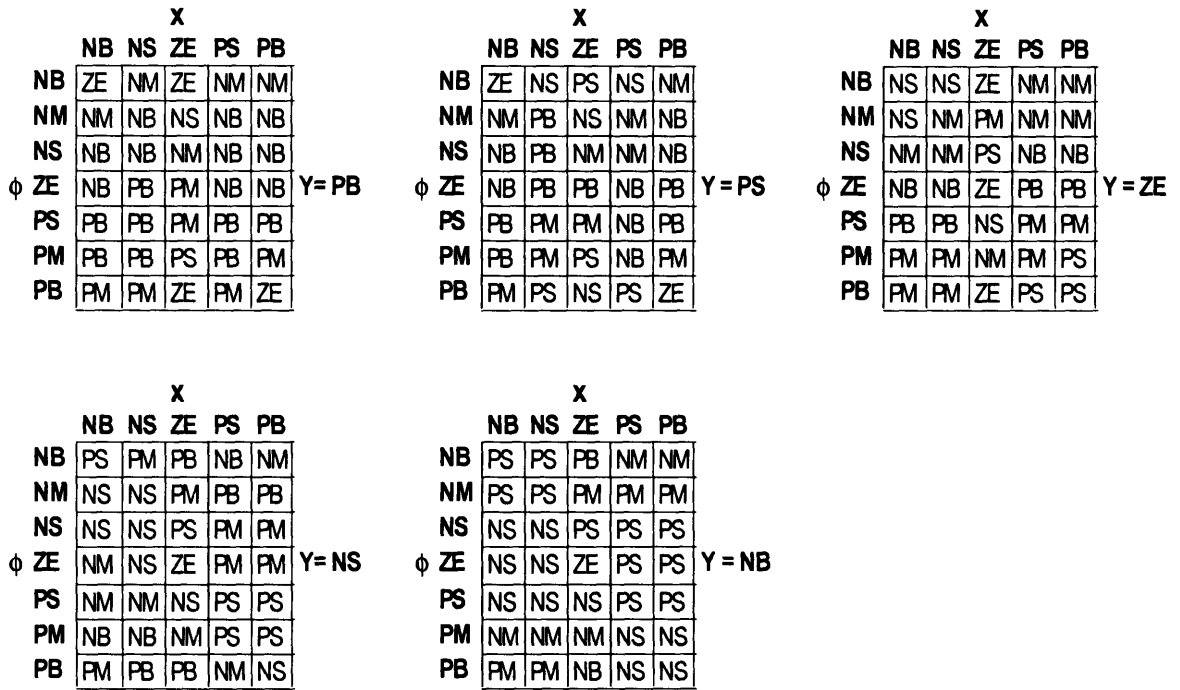


Figure 16 FAM rule bank associates input fuzzy sets (x, y and φ) with an output fuzzy set (θ).

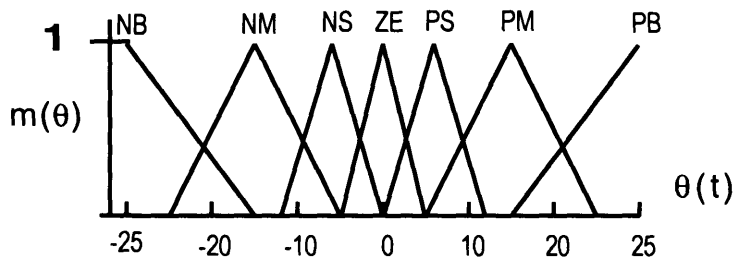


Figure 17 Membership functions for rudder angle. To prevent the rudder from stalling, the rudder angle is limited to $\pm 25^\circ$.

2.4 Depth Sounder

Depth sounding instruments vary in resolution, range and power but they all operate under the same principle. It is not the intent of this thesis to go deep into the theory of underwater acoustics; however, the fundamental idea behind the operation in depth sounding is presented.

2.4.1 Principles of Depth Sounding

A depth sounding instrument has a source that projects sound into the water, typically using transductive systems. The acoustic pulses travel through the water until reflected and backscattered from the seafloor or any other target. Each returning echo is picked up by a hydrophone, which converts it into an amplified electrical signal. The round trip time of the acoustic signal becomes a measure of depth, assuming a speed of sound in water.

The sound waves emitted by the depth sounder can be thought of as cone of sound pointing towards the sea bottom. The size of the sound cone is dependent on the beamwidth characteristic of the instrument. The beamwidth and the depth of the water determine the effective scan range or the area that the depth sounder is able to cover at one time [38]. Figure 18 shows a depth sounder with beamwidth θ over a plane horizontal bottom. The horizontal distance covered by the echosounder at one time is $X = 2 * D * \tan(\theta/2)$, where D is the earliest return or the depth of the water .

Some depth sounders have a beamwidth of approximately 60° , providing only an average depth over a large area . For applications needing wide coverage with little bottom detail, a wider beam may be used. Narrower beam widths increase the directivity at the expense of

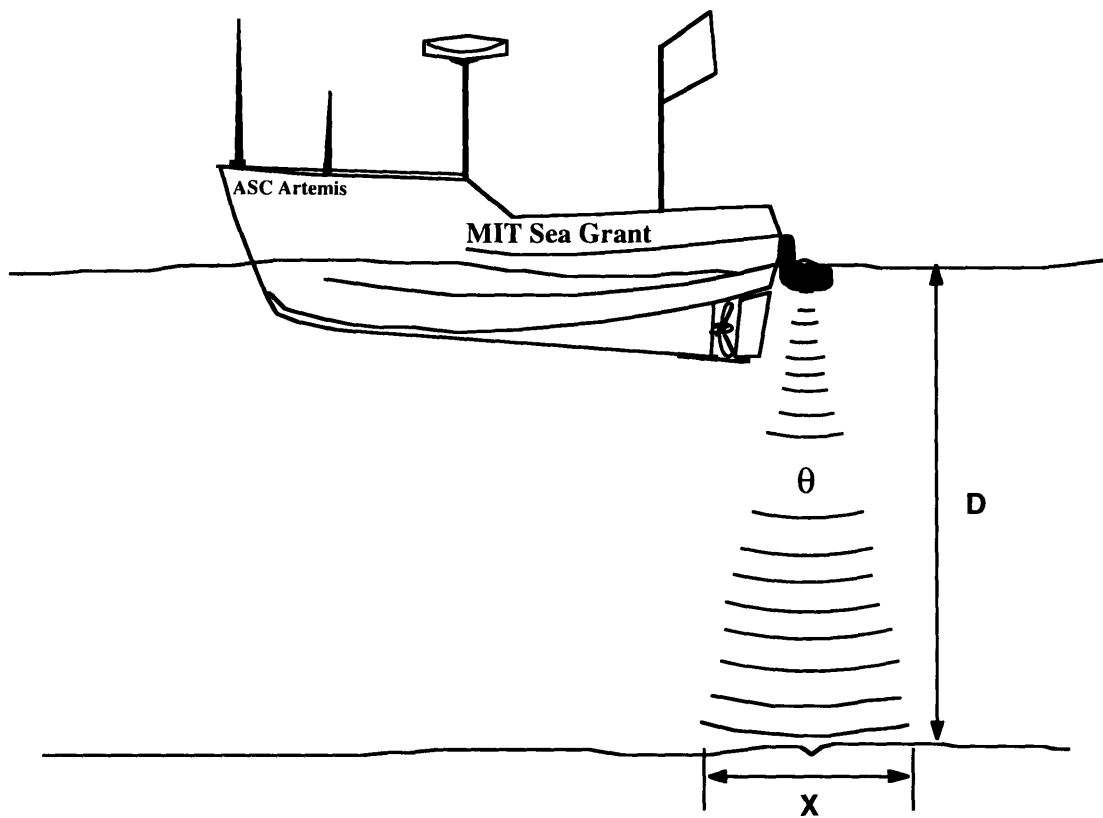


Figure 18 Representation of the depth sounder beamwidth (θ) projected in a horizontal plane. D is the depth and X is the effective scan range.

coverage [5]. High resolution depth sounders have beamwidths as small as 3° [38]. The echo sounder on ARTEMIS used for collecting bathymetric data in the Charles River has a beamwidth of 12°. This means that this echo sounder detects a circle of about 0.5 meters in radius at the 5-meter average-depth of the Charles River. Therefore, survey transects separated on the order of a meter are required to ensure full coverage. It is important to recall that this parameter should not be taken as an absolute measure of ARTEMIS bathymetry collection capabilities because a more capable sensor can be easily replaced should more accuracy be needed.

The resolution increases with the frequency of the acoustic pulse. The depth-ranging instrument in ARTEMIS has a 200 kHz transducer capable of resolving to 10 centimeters. The maximum detection range depends on the absorption of sound in water. Absorption increases with the frequency of the acoustic pulse [38; 7]. For operations in 10°C temperature waters, the total absorption is 67.1 dB/km, which yields a maximum range of approximately 400 feet.

2.4.2 Limitations to Bathymetry Accuracy

Besides the intrinsic limitations on accuracy imposed by the specific depth sounder used, bathymetry mapping is also subject to factors external to the instrument itself. These include navigational and attitudinal errors, speed of sound changes, and false sounding.

The spatial resolution of the bathymetry survey is directly tied to the accuracy of the positioning mechanism. Each sounding must be paired to an accurate geographic position for the chart to be accurate. Thus, accurate position control is necessary for applications where the survey lines must be closely spaced.

The calculations in the depth sounder assume that the energy is beamed straight downwards. The first return is from the bottom nearest to the boat and the successive returns are from all other points in the ocean bottom within the area of the sound cone, termed side echoes. Rocking of the boat due to waves caused by winds or wakes of passing boats can cause errors. If the pitch or roll angles are greater than the beamwidth, the range will be different from that one just below the vehicle. This problem can be solved through a gimbaled mechanism to stabilize the echo sounder. Another approach is to make corrections to the data with vehicle attitude information. If a motion sensor provides pitch and roll angles, the attitudinal errors can be compensated geometrically. This problem is not currently being addressed in ARTEMIS; however, the errors are less critical because the bathymetric data was collected during calm conditions in the river in shallow water.

Some errors are introduced with the variations of sound speed with salinity, temperature and pressure. For precision depth sounding, extremely precise knowledge of the sound velocity is needed. There are expressions for sound velocity in terms of salinity, temperature and depth [7]. These variables can be measured with a conductivity-temperature-depth (CTD) sensor. The bathymetric data can be corrected using the CTD-calculated speed of sound. These corrections are not made in the present ARTEMIS system because they are less notable in the tested shallow water environment.

In shallow waters with highly reflective bottom, such as sand and gravel, bottom-surface reverberation can cause multiple false echoes. Other causes of false sounding include phase differences, deep scattering layers and schools of fish [5]. The depth sounder used on ARTEMIS returns a zero if a false sounding is suspected. Zero depth values are removed from the data as the bathymetric map is plotted.

CHAPTER THREE

Field Experiments Results and Discussion

As discussed previously, there are several key elements involved in the development of an automated-bathymetry-mapping system, in particular, the navigation technique, the control algorithm, and the bathymetric-data-collection instrument. Numerous experiments were performed to progressively validate the components of the ARTEMIS system. In particular, the field tests shown here evaluate four important factors that concern the creation of a bathymetry map:

- 1) the accuracy of the navigation technique,
- 2) the performance of the guidance controller,
- 3) the quality of the depth sounder instrument, and
- 4) the successful integration of all of the above into an automated bathymetry system.

3.1 Experimental Setup

Field tests were conducted at the MIT Sailing Pavilion on the Charles River in Cambridge, Massachusetts (See Figure 19). The deployment can be carried out by two persons because of the small size of the vehicle. A typical test mission begins by sealing the boat for water-tightness. The control program is then downloaded to the TT7 computer from a portable computer through a serial communication tether. The missions are pre-planned in the lab but they can be easily modified in the field. A single mission is downloaded to ARTEMIS, the serial tether is detached and ARTEMIS is free to perform its mission. Although ARTEMIS can perform fully autonomously, basic supervisory control commands such as **START**, **STOP**, **PAUSE/RESUME**, **SKIP WAYPOINT** and **HOME** can be sent via radio modem (as explained in Section 2.1.2.2.).



Figure 19 Experimental Setup. Frame 1: Control software being downloaded into ARTEMIS before tether is detached. Frame 2: After tether is detached, ARTEMIS is launched (it is light enough that two persons can carry it). Frame 3: ARTEMIS under way performing automated bathymetry.

During a bathymetry survey, ARTEMIS autonomously navigates along predefined tracks while recording readings from the depth sounder. The track spacing is chosen to provide the desired spatial resolution of the map. While the boat is surveying, bathymetric and geodetic position data are sent to the dock computer through a radio link and a bathymetry map is created in real-time. All data are also stored onboard ARTEMIS. Upon completion of a mission, the boat is recovered and the data are retrieved.

3.2 Navigation Tests

The accuracy of the navigation technique employed in the survey is paramount, as the bathymetric data must be associated with the proper geographic location to be useful. To determine the accuracy of the DR/DGPS navigation technique used in ARTEMIS, position data was collected at a stationary point. The second experiment presented here tries to explain some discontinuities found in the position data.

Although differential corrections are meant to remove the errors due to SA, the position information obtained with DGPS navigation still include some inaccuracies. These inaccuracies may be caused by fact that the system that provides the differential corrections may be using a different set of satellites for calculating position than the GPS receiver in ARTEMIS. At the same time, the environmental conditions (e.g., ionospheric conditions) where the antennas of the DGPS system are located may differ from the those where the GPS receiver is located. The signals sent by the satellite may be reflected off nearby buildings before reaching the GPS receiver, i.e., multipath, adding noise to the signal.

To assess the accuracy of the navigation system in ARTEMIS, data was recorded at a stationary position for 27 minutes, as shown in Figure 20. Some discontinuities found in the position data (explained in the next experiment) were removed. Assuming that the data

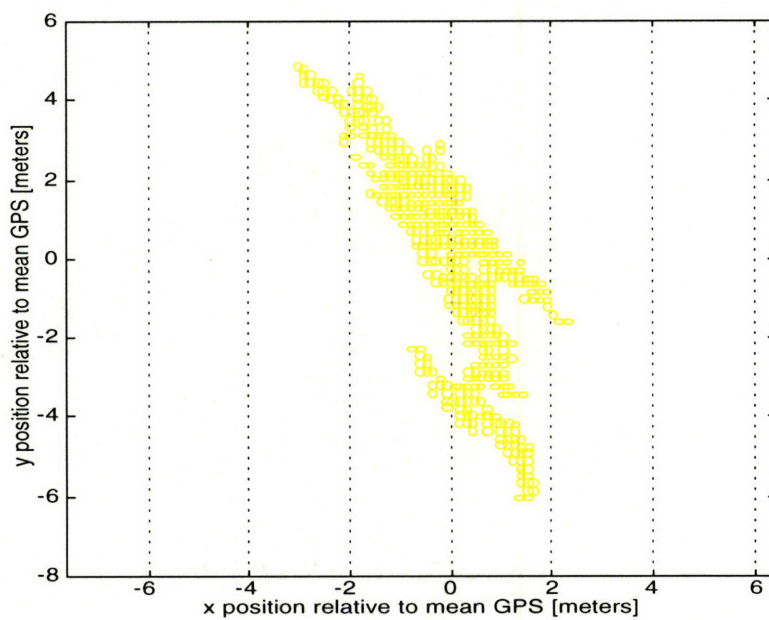


Figure 20 DGPS position fixes recorded over 27 minutes. Maximum error from the mean value is 6.75 meters. Two-dimensional rms error (typically called ‘accuracy’ by GPS manufacturers) is 2.5 meters.

points are randomly distributed a mean position is found. From the mean position, the maximum error is 6.75 meters. The two-dimensional rms value (typically called accuracy by GPS manufacturers) is ± 2.5 meters.

During the test runs, discontinuities were observed in the DGPS position data. In the present version of ARTEMIS, these jumps in position are not being addressed. The cause of this error was determined to be a change in the number of satellites used by the GPS receiver to compute a position. When the GPS receiver uses a different set of satellites for its position computation it can cause errors in the position data. In Figure 21, the GPS receiver in ARTEMIS had 6 satellites in view (red circles), 7 satellites in view (green circles), and 8 satellites in view (blue circles). There is a clear discontinuity in the position data when the number of SVs change.

Because these abrupt changes in position data coincide with the change in satellite number, we believe that this is the source of error. This is an area that requires attention in the near future. Discontinuities in the position data can also be attributed to multipath noise; however, during these experiments no clear signs of multipath were noticed.

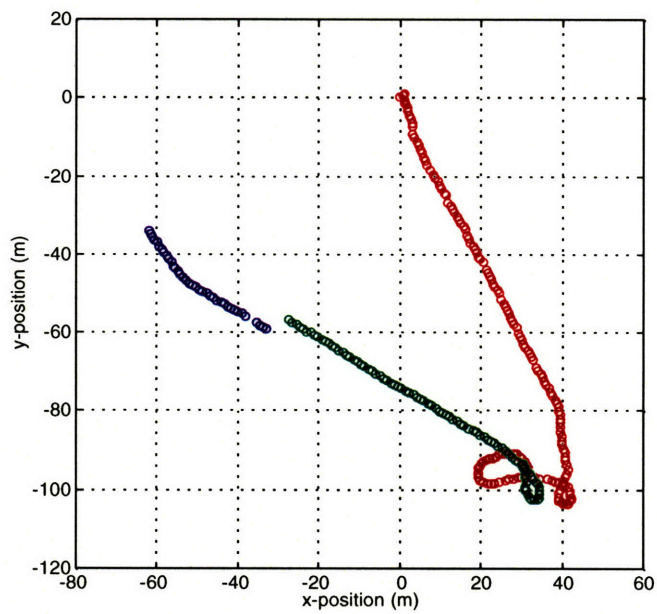


Figure 21 ASC path and the number of satellites or Space Vehicles (SVs) seen by the GPS receiver during a mission. The starting position has been translated to (0,0). Red dots represent 6 SVs, the green dots represent 7 SVs, and the blue dots represent 8 SVs. Discontinuities in position data coincide with changes in number of satellites in view.

3.3 Waypoint-Following Controller Tests

To evaluate the performance of the waypoint-following fuzzy-logic controller, the results of five field test are presented. These tests displayed the typical vehicle behaviors. The waypoint-following strategy used is that described in Section 2.3.1. In all figures, the circles represent the ‘arrival’ circle, the long arrow represents the crossing heading, the dotted line is the vehicle’s position, and the small arrows represent the boat’s heading.

As an initial test to verify that the controller was capable of handling waypoints requiring sharp turns, the vehicle was commanded to navigate through two waypoints with opposite headings as shown in Figure 22. We can appreciate how ARTEMIS executes a sharp turn when passing through waypoint 1 and heading towards waypoint 2. This ability enables ARTEMIS to perform bathymetry surveys with very tight track spacing.

A useful behavior in the fuzzy-logic controller is a turn-anticipation behavior. As soon as the boat crosses a waypoint, the guidance controller anticipates the turn required to cross the next waypoint on the specified heading. The controller ensures that the prescribed heading is crossed, even if the boat has to deviate from the most direct route. Because the turns are not done near the waypoints, the trajectories are smooth. This behavior is shown in Figure 23 and in Figure 24.

Figure 25 shows a waypoint-following mission where a sample survey-type pattern was created. The waypoint-following approach allows the creation of surveying paths with various levels of complexity. Because ARTEMIS has accurate navigation and control, it can return to the same position on a different survey. Repeatability is important when multiple surveys are run over several days.

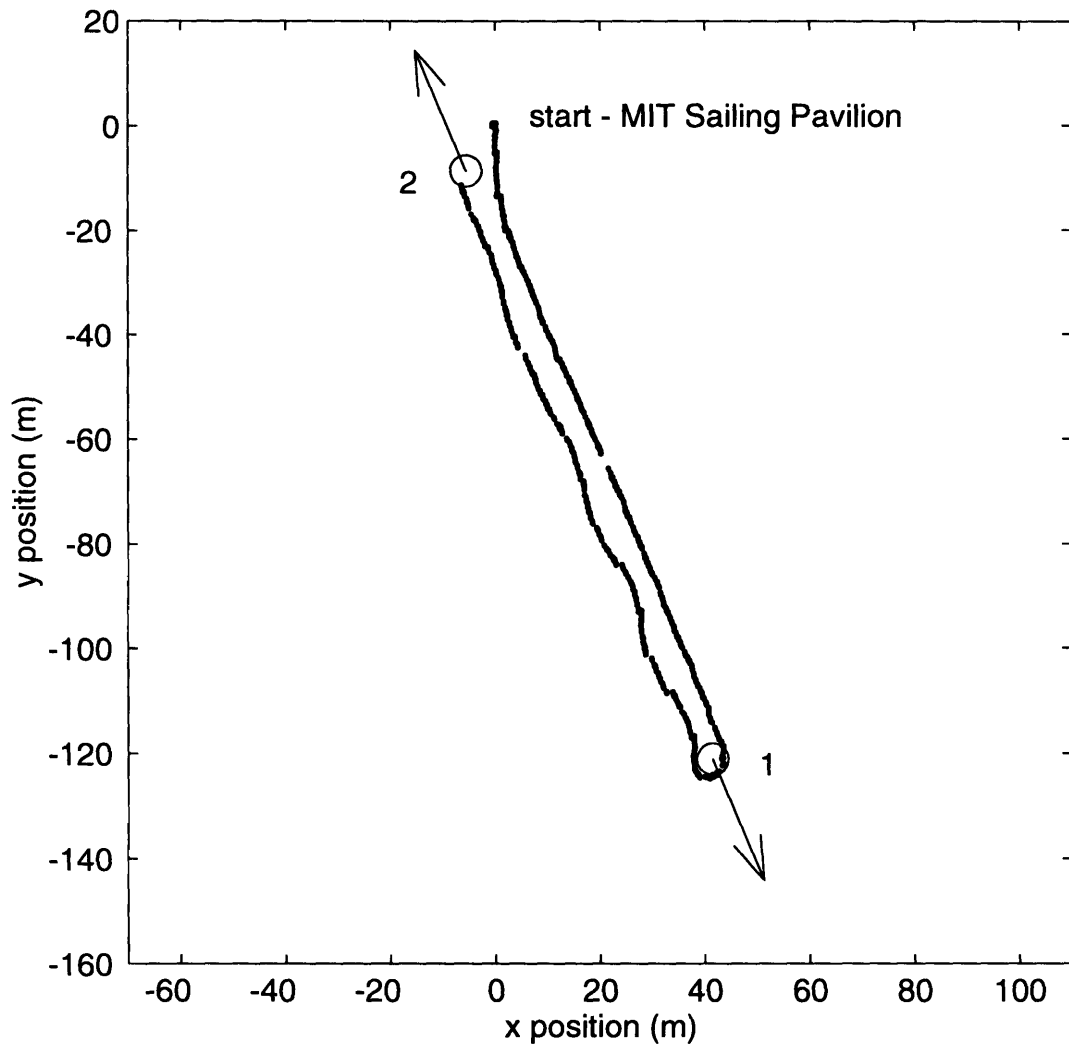


Figure 22 ARTEMIS executing a sharp turn. ARTEMIS executes a sharp turn to track to two waypoints with opposite heading. The radius of the arrival circle is 3 meters.

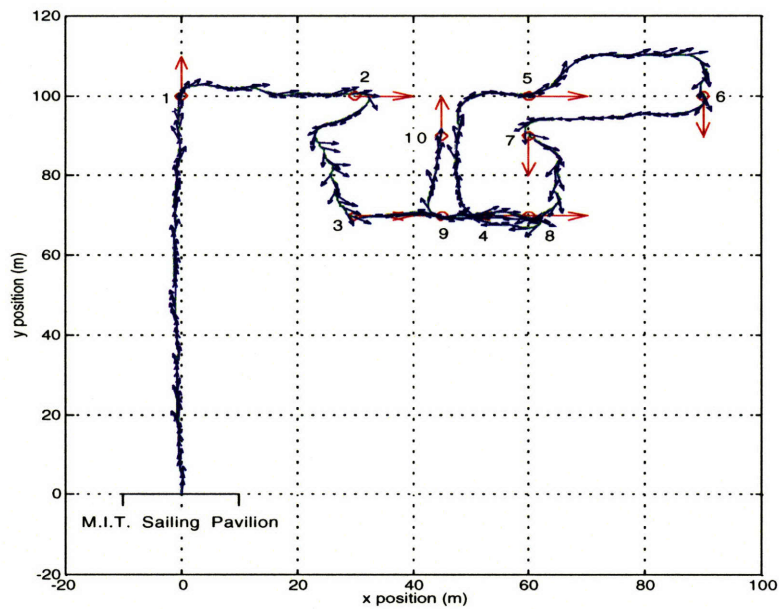


Figure 23 Survey showing turn-anticipation behavior. The circles represent the waypoint's 'arrival' circle, the large arrows are the specified crossing headings, the small arrows are the boat's heading every tenth of a recording cycle. When navigating from waypoint 5 to waypoint 6, it is clear how the boat deviates from the most direct route in order to achieve the prescribed crossing heading. The large oscillations in heading between waypoints 2 and 3, and 7 and 8 were caused by vehicle motions due to the wakes of passing motorboats.

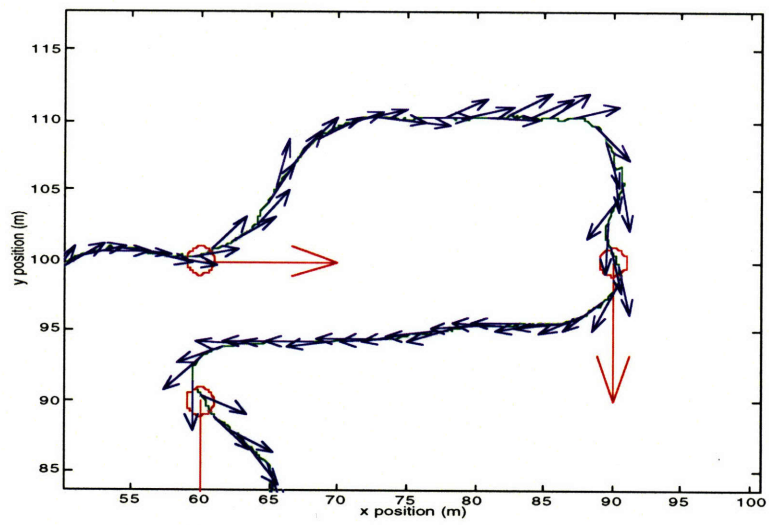


Figure 24 Enlarged view of previous figure showing turn-anticipation behavior. In navigating from waypoint 6 to waypoint 7, the boat anticipates the turn required to achieve the crossing heading.

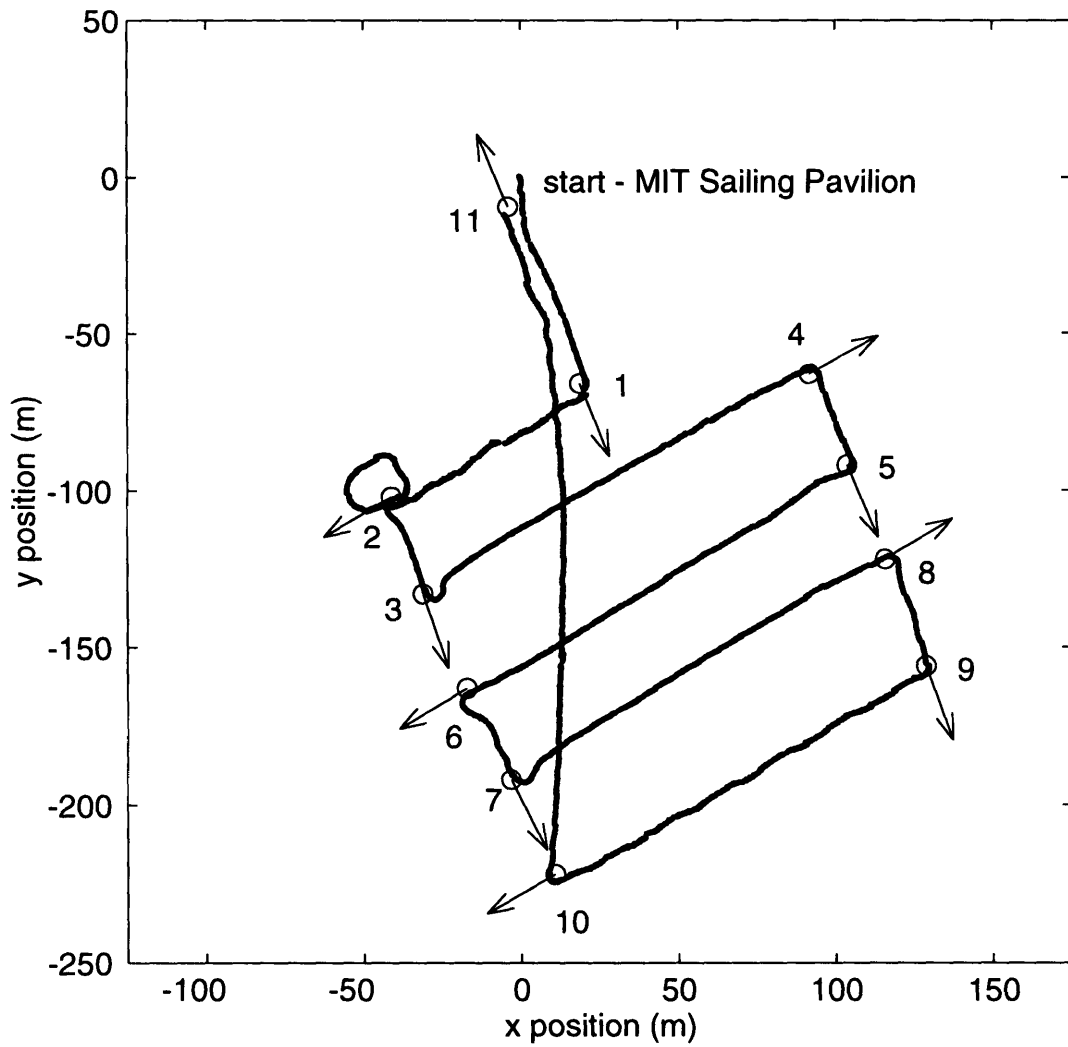


Figure 25 ARTEMIS performing a survey grid formed with eleven waypoints. This test also shows an interesting behavior of the controller, the missed-approach behavior, where the vehicle returns to a missed waypoint.

The sample survey path in Figure 25 also shows an interesting feature of the fuzzy controller: the missed-approach behavior. On several occasions, the boat encountered large disturbances causing the boat to miss a waypoint. For instance, in approaching the second waypoint, the boat fails to cross the arrival circle by approximately 20 centimeters. In the event of a missed approach, the controller guides the vehicle back to the missed waypoint for another attempt.

The missed-approach behavior is simply an extension of the fuzzy controller described in Section 2.3.5. The FAM rules have been selected to command the boat to always re-approach a waypoint after crossing it (Figure 26). The guidance controller overrides this feature by activating the next waypoint in the list after the current waypoint has been ‘hit’ (Figure 27).

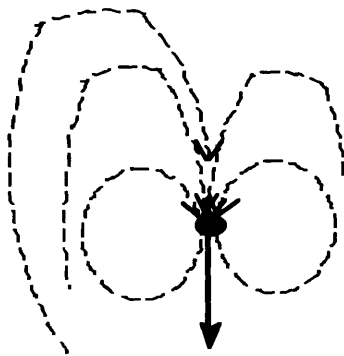


Figure 26 A waypoint without an arrival circle. The boat would continually circle back and re-approach a waypoint after crossing it.

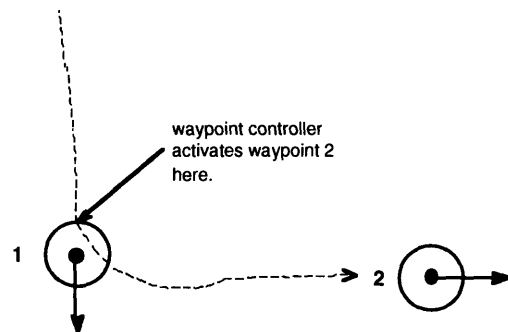


Figure 27 Waypoints with arrival circles. After entering the arrival circle in waypoint 1, ARTEMIS’ controller activates waypoint 2.

ARTEMIS turns back for a re-approach after it has passed a line through the waypoint perpendicular to the desired crossing heading as shown in Figure 28.

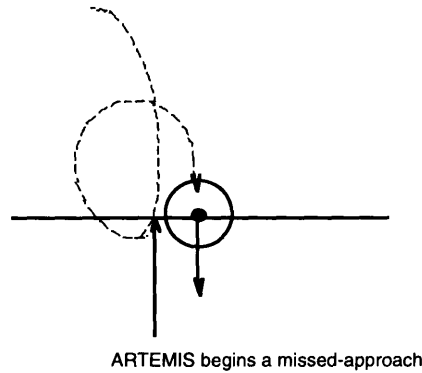


Figure 27 Missed approach. ARTEMIS turns back after passing a line through the waypoint perpendicular to the desired crossing heading.

Figure 29 is an enlarged view of Figure 25 near the second waypoint. When ARTEMIS failed to enter the 'arrival' circle due to a large disturbance, the fuzzy controller simply commanded the missed-approach maneuver. The missed-approach behavior may be undesirable for surveying because it would slow down the process. However, if the radius of the arrival circle is enlarged when there are strong winds and currents, the likelihood of a missed approach is reduced. There is a limit to the number of missed approaches that the boat will attempt, which can be modified according to the situation. The dimensions of the 'arrival' circle and the maximum number of attempts may also be adjusted.

In general, it was found that ARTEMIS was able to follow complex path geometries with little control effort despite sometimes large environmental disturbances such as wakes from passing motor boats. The fuzzy control system proved to be robust under various environmental conditions, from calm water to choppy water with high winds and currents.

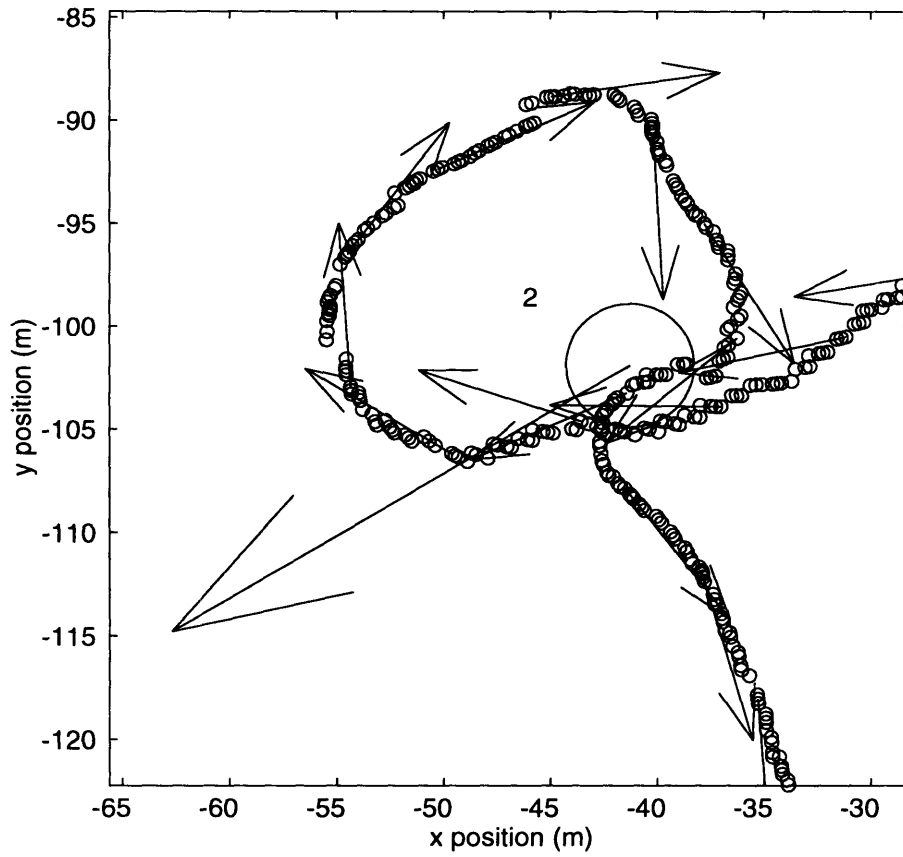


Figure 28 Enlarged view of the boat's trajectory showing a re-approach to a missed waypoint. In the event that the boat misses to enter the 'arrival' circle, the fuzzy controller commands the missed-approach maneuver. The circle is the 'arrival' boundary, the large arrow is the prescribed crossing heading, the small circles are the boat's position at each control cycle, and the small arrows show the boat's heading at every sixth control cycle.

3.4 Depth Sounder Test

The depth sounder in ARTEMIS is capable of resolving to 10 centimeters. To determine the accuracy of the instrument, measurements were taken with the depth sounder and compared to a measurement taken with a sounding line. The sounding line measurement was approximately 4.5 meters next to the depth sounder which measured 4.2 meters.

The difference in the depth measurements can be explained by the fact that the Charles River bottom consists for the most part of loose mud. At the bottom of the Charles River there are layers of decaying debris that become thicker with depth. This not-clearly-defined bottom can cause erratic readings in the depth sounder. While the sounding line penetrates into the mud, the depth sounder may obtain reflections from the top and middle layers, as well as from the hard bottom. The fact that the depth sounder was calibrated in sea water lead to additional depth errors.

For the purposes of typical bathymetry mapping, the accuracy of the instrument is adequate. For most applications requiring bathymetric maps, an error of 30 centimeters is not significant. As an example, the navigation channels are dredged a few additional meters to ensure safety. In the event that more accurate readings are required, the depth sounder in ARTEMIS can be replaced by a high-accuracy altimeter.

3.5 Bathymetry Data Collection

Automated bathymetry surveys were conducted in a portion of the Charles River off the M.I.T. Sailing Pavilion. Preliminary tests were performed to locate the area to be mapped. Once the area was located, several surveys were performed to generate the bathymetric map of a portion of the Charles River shown in Figure 30.

Initially an area with interesting topography was selected. The preliminary tests consisted of missions with wide-spaced transects across the Charles River to locate the area to create a bathymetry map. An area of approximately 120 by 100 meters was selected. This area has sufficient topography variation to be seen in a map and it is located directly off the M.I.T. Sailing Pavilion, which made operations easy. In the figure, the shades of color represent the different depths. We can see that the bottom slopes down with a depth variation ranging from 1.5 to 7.5 meters.

The map shown in Figure 30 is a compilation of multiple surveys over several days. Initial experiments were performed, and upon data processing, the surveying grid was adapted to collect bathymetric data with higher spatial resolution in areas of high variation. Repeatability of position is not an issue because the navigation and control in ARTEMIS yield repeatable results (within 2.5 meters as shown in Section 3.2). Therefore, after finding unsurveyed areas, transects were added to fill missing details in the map. Track lines perpendicular to each other were formed to ensure full coverage. The bathymetric map was created with four different missions lasting a total of 95 minutes (38 minutes, 30 minutes, 14 minutes, and 13 minutes respectively) shown in Figure 31.

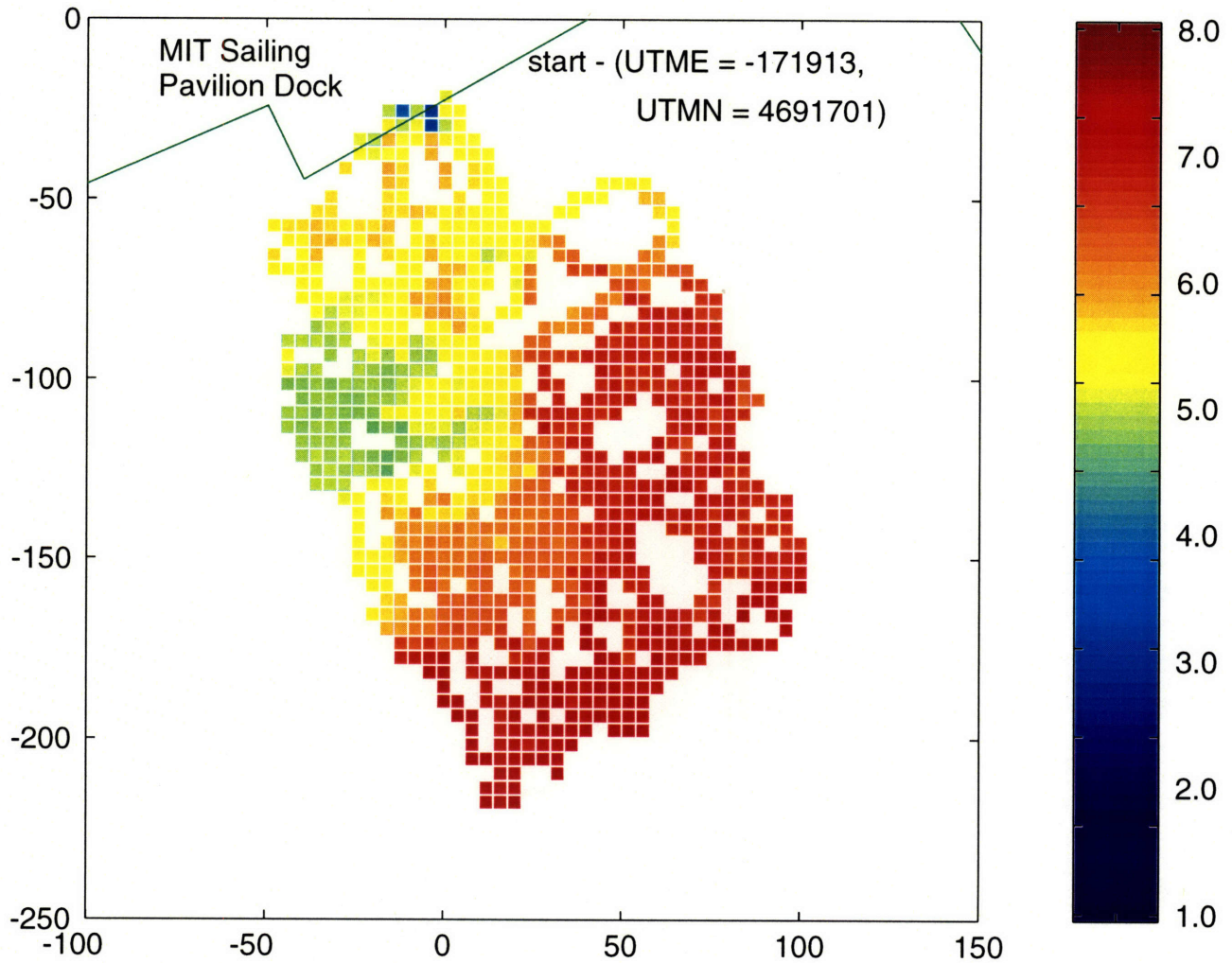


Figure 30 A bathymetry map of the Charles River in Cambridge, Massachusetts created by the Autonomous Surface Craft ARTEMIS. East and North positions shown are relative to the start point [-171913, 4691701] in the Universal Transverse Mercator (UTM) coordinate system. Each colored square represents the average depth in an area of 4x4 meters.

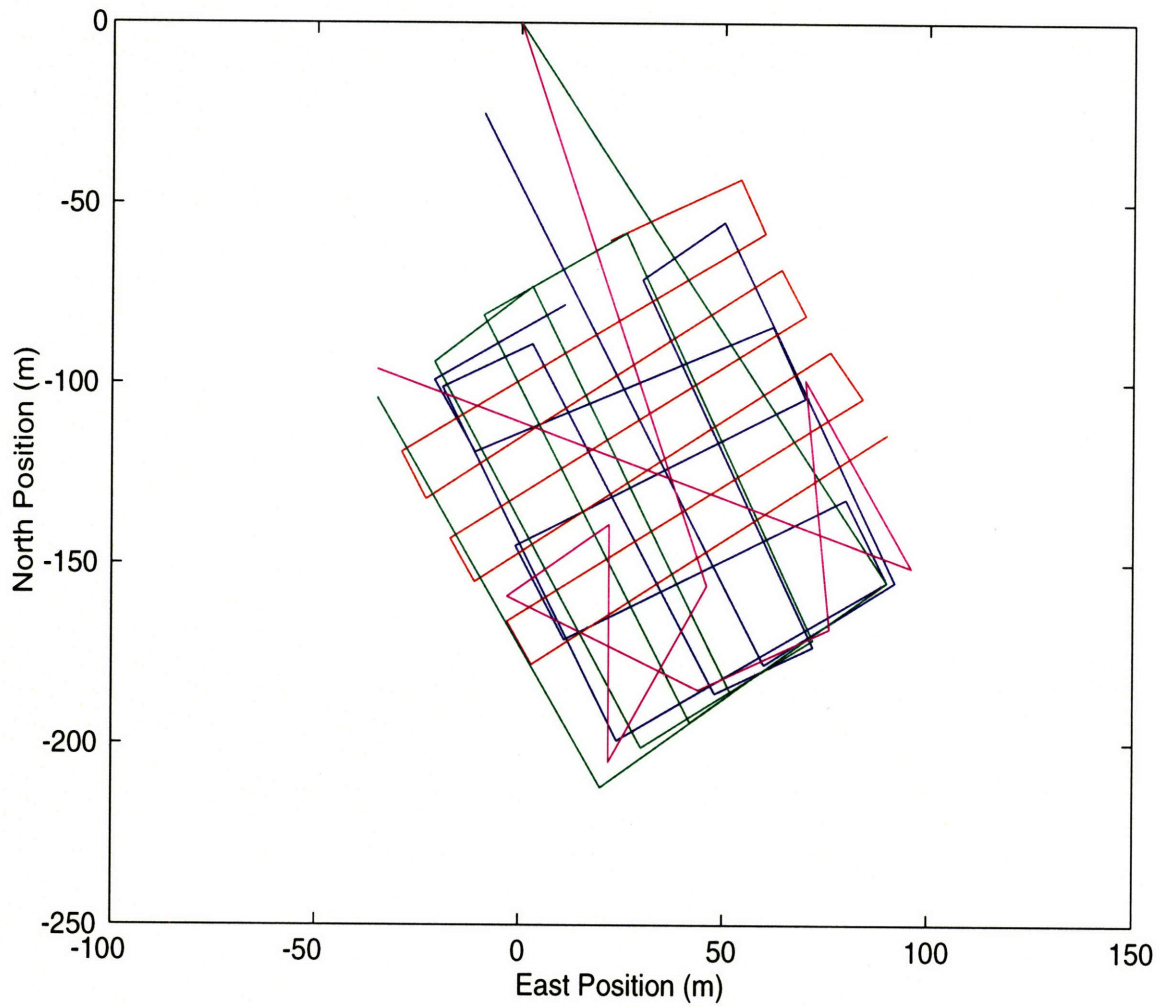


Figure 31 Survey patterns that generated the bathymetric map. Each color represents a different mission. East and North positions shown are relative to the start point [-171913, 4691701] in the Universal Transverse Mercator (UTM) coordinate system.

3.6 A Comparison of ARTEMIS with a Conventional Bathymetric Surveying Technique

The field experiments demonstrated that the ARTEMIS system can autonomously generate high-resolution bathymetric maps in real-time. In order to establish ARTEMIS as a time-efficient and economical surveying platform, it is compared to a commonly-used bathymetry surveying technique.

The ARTEMIS system is examined in relation to a typical survey performed by the Disposal Area Monitoring System (DAMOS). DAMOS, a part of the New England Division of the U.S. Army Corps of Engineers, is responsible for collecting survey data to monitor the deposition of dredged material at ten New England disposal areas. One of the primary surveys used in the DAMOS program is high-resolution bathymetry [39]. Bathymetric data incorporated with navigation data is used to detect changes in the morphology of dredged material. Below, some details of the current DAMOS technical approach for bathymetric data collection are presented (from the most recent version (1996) of DAMOS Navigation and Bathymetry Standard Operating Procedures), and compared to the ASC ARTEMIS.

An example of a bathymetry survey in Royal River in Portland, Maine is shown in Figure 32. This survey used a "ladder" survey grid, i.e., a series of parallel survey lines or transects whose spacings determine the map resolution. This survey required approximately 75 four-hundred-foot-long track-lines separated by 40 feet; it took a week to complete and cost roughly \$10,000 including a small vessel, crew, equipment and data analysis [18].

Most surveys conducted for DAMOS utilize a Del Norte Trisponder[®] microwave positioning system, and an Odom DF3200 Echotrac[®] echosounder. In microwave navigation, the distance between a master unit aboard the vessel and a minimum of two remote units at shore stations is calculated by triangulation. Setting up the shore stations consists of placing at least one remote transponder and antenna, and a power source at an accurately known location. A person monitors the shore stations during the survey unless backup transponders are available [39]. Accurate geodetic position (1-3 meters) can be obtained with this technique. The Odom Echosounder is a narrow beam (3 degrees) 208 kHz transducer, providing depth measurement accuracies of 0.01-0.05% of the overall depth. The comparison between ARTEMIS and DAMOS surveying techniques is summarized in Table 2 and Table 3.

Table 2. Comparison of Surveying Requirements for DAMOS and ARTEMIS

REQUIREMENTS	DAMOS	ARTEMIS
Ship and Crew	YES •vessel and captain	NO •shore launch and recovery
Navigation Array Setup	YES •set remote stations	NO •GPS
Shore Personnel	YES •5+ people	YES •2 people
Post-Processing	YES •after survey completion	NO •real-time •can post-process if desired

Table 3. Comparison of Surveying Capabilities of DAMOS and ARTEMIS

<u>CAPABILITIES</u>	<u>DAMOS</u>	<u>ARTEMIS</u>
Autonomous	NO •requires crew to collect data	YES •fully autonomous
Real-Time Mapping	NO	YES
Navigation Technique	BETTER •more expensive •less convenient	ADEQUATE •less expensive •more convenient
Water-Depth Accuracy	BETTER •more expensive instrument	ADEQUATE •less expensive instrument
Ease of Resurveying	DIFFICULT •unsurveyed spots identified after data processing and analysis, entire process has to be repeated	EASY •unsurveyed areas can be identified in real-time; DGPS allows repeatability of positioning (DGPS is available in Royal River)
Restricted-Visibility Operations	NOT POSSIBLE •operations are usually cancelled when visibility is poor because a human guides the vessel	POSSIBLE •ARTEMIS can still operate during nights or foggy days
Very Shallow and Restricted-Maneuverability Operations	NOT POSSIBLE •always require vessel	POSSIBLE •ARTEMIS is small and has a very low draft, permitting maneuverability in very narrow or shallow channels
Total Surveying Time	ADEQUATE •1 week to survey (setup, data collection, post-processing)	FASTER •2.3 hours to collect data, real-time display of data.
Total Operation Costs	EXPENSIVE •labor-intensive •\$10,000 (\$800/day for vessel and captain)	LESS EXPENSIVE •fast, less labor-intensive •assuming same equipment as in DAMOS operation but no captain and crewed vessel, ARTEMIS cost is \$6000

While the standard operating procedures for DAMOS survey missions have been updated to take advantage of advances in navigation and environmental sensor technologies, one expensive component during a bathymetry survey assignment – the actual data gathering – has not changed. The surveying technique remains the same, that is, a vessel collecting bathymetric data is guided by a human operator along a series of transects. Aside from the crew, personnel is required on shore, making the surveying task labor-intensive and, therefore, expensive. For instance, a small vessel guided by a captain cost approximately \$800/ day [40].

ARTEMIS has an advantage in that the surveys can be performed autonomously, i.e., without a human operator guiding a vessel. This permits 24-hour surveying even under restricted-visibility conditions (nights or foggy days). Because ARTEMIS is small and has a very low draft, operations in very shallow or narrow channels are possible. Automated bathymetry is less labor-intensive, therefore operation costs can be reduced. The equipment and the setup are less expensive with the present ARTEMIS system. Even if the same navigation technique and echosounder as DAMOS was used, the costs would still be reduced because there are no costs involving a vessel and a captain. For instance, assuming the DAMOS setup was used with an ARTEMIS vehicle, the cost of the operation would still be reduced by 40% ($\$10,000/\text{week} - 5 \text{ working days} \times \$800/\text{day} = \$6,000$). Furthermore, costs can be greatly reduced by using multiple vehicles.

Microwave navigation typically used in DAMOS surveys provides higher accuracy positioning than the GPS system in ARTEMIS. However, DGPS is less expensive and more convenient to use because it provides relatively accurate positioning (± 2.5 meters) without the need of setting remote stations. Nevertheless, DGPS is not appropriate for some areas, such as a highly-urbanized environment or dense tree-covered areas, where the

signal is subject to blocking problems [41]. If signal blockage is an issue or if a greater accuracy is required, the navigation system in ARTEMIS can be replaced by a more accurate technique, such as the one used by DAMOS.

Although the West Marine echosounder used in ARTEMIS (12-degree beam 200 kHz transducer) is not as accurate as the Odom Echotrach® echosounder, it is less expensive. Should the need for more accuracy in the depth measurements arise, the depth sounder can be easily replaced by a more accurate sensor.

Automated bathymetry mapping using ARTEMIS is significantly faster because deploying ARTEMIS does not require an elaborate setup or complex logistic and because the analysis is done in real-time. Surveys performed by DAMOS consists of four stages:

- 1) navigation set-up,
- 2) track-line configuration,
- 3) data collection, and
- 4) analysis.

An operation using ARTEMIS consists of:

- 1) ARTEMIS deployment,
- 2) waypoint configuration, and
- 3) data collection and analysis.

The same survey task using traditional survey methods can be done in considerable less time with less support equipment and personnel, both reducing the costs and allowing for

more detailed surveying if necessary. The distance covered during the Royal River survey is estimated by assuming that the 75 track lines are 400 feet long with a 40-foot separation between track lines, yielding a surveyed distance of 33,000 feet or 10,000 meters. At ARTEMIS nominal speed of 1.2 m/sec, this distance can be surveyed in 2.3 hours.

With the DAMOS system, if the need for higher map-resolution is identified after post-processing and analysis, the entire operation has to be repeated. ARTEMIS can provide a high map-resolution in less time because with real-time bathymetry mapping, faulty areas or areas of interest can be spotted and resurveyed. With automated bathymetry the same area can be surveyed repeatedly with less effort. This new approach to bathymetric surveying can increase the bathymetric-data-collection rates because it can provide high-resolution bathymetric maps economically in less time than conventional methods.

CHAPTER FOUR

Conclusions and Future Work Beyond Bathymetry

4.1 Conclusions

There is a need for real-time, low-cost bathymetry surveys. Applications include updating nautical charts and monitoring the dredging of navigation channels for the maintainance of the water transportation system. This thesis demonstrates how an ASC can be used to meet this need. During this research, all the elements necessary to perform real-time automated bathymetry were successfully integrated. First the hardware and the software were developed. The vehicle's systems were tested and verified in stages with an emphasis on the navigation and control systems. Finally, all the systems were integrated to perform bathymetry surveying autonomously.

The fuzzy-logic guidance controller used on ARTEMIS performed flawlessly. The waypoint-following approach allowed the creation of complex survey paths with little control effort. By crossing the waypoint on a specific heading, smooth trajectories were accomplished. The fuzzy control system was robust to a wide range of environmental conditions. The FLC in ARTEMIS has an additional advantage in that it can be easily tuned to new vehicle configurations.

The navigation system provided a position accuracy of 2.5 meters, which is adequate for a typical bathymetry survey. In some instances the GPS position information showed discontinuities. As shown in Section 3.1, the discontinuities coincided with a change in the number of satellites used by the GPS receiver in computing a position fix; therefore, the jumps in position presumably are associated with the fact that the GPS receiver used a

different constellation of satellites for its position computation. At the present time, this problem is not being addressed. This is an area that requires attention in the near future.

In comparing ARTEMIS with a conventional surveying technique (DAMOS) in Section 3.6, it was found that ARTEMIS can provide high-resolution bathymetric maps economically. Improved versions of ARTEMIS offer the potential of surveying large areas in less time than the conventional approaches. DAMOS surveying capabilities are superior in terms of navigation accuracy and depth measurements accuracy.

Automated bathymetry surveying offers clear advantages. An ARTEMIS mission can be carried out by only two persons, which reduces the cost associated with support personnel. The production of small, low-cost, high-performance vehicles can lead to the assemblage of multiple ASC to collect bathymetric data simultaneously. This could provide inexpensive and efficient bathymetry surveying in large areas.

Economic, real-time automated bathymetry surveying will allow a faster update of the nautical charts that are so beneficial to many enterprises, including commercial transport, which is crucial to the U.S. economy. With some enhancements, the automated-bathymetry-mapping technique developed in this research can become a valuable and profitable tool for the scientific, industry, government and military communities because all these groups are interested in obtaining high-resolution bathymetry at minimal cost.

4.2 Future Work: Near-term

Future research should focus on enhancing the individual components of the system and on expanding the capabilities of ARTEMIS. For example, the fuzzy controller can be

converted to an adaptive fuzzy controller. In an adaptive fuzzy system, the fuzzy rules do not have to be provided by a human expert, instead they are learned by feeding data into a neural system [34; 31].

Currently ARTEMIS does not have an ocean-going hull. Future generations of ARTEMIS-like vehicles should be able to perform ocean missions. The electronic configuration in the ARTEMIS system can be reproduced and placed in a hull with better seakeeping capabilities. The fuzzy controller can be tuned for the new configuration.

There are several areas in which the navigation technique can be improved. The problem concerning the jumps in position due to a change in satellite constellation used by the GPS receiver for position fixes should be studied more carefully. For example, to reduce the possibility of a change in satellite constellation the GPS receiver can be set to maintain the same three satellites.

Another limitation of GPS-based navigation systems are multipath error and building blockage. Although no clear signs of multipath were observed in the data collected by ARTEMIS in the Charles River, multipath can cause problems in more cluttered environments. Most harbor approaches, however, are located in open areas. For channel surveying in a highly urbanized area and where the accuracy requirements are stringent, an alternative form of navigation might be a better solution. For instance, DGPS can be replaced by microwave navigation. For offshore surveying, DGPS may be the best approach as long as the survey is performed within the range of the differential-correction transmitter. The use of other navigation systems (e.g., microwave navigation as used by DAMOS) should be investigated.

The depth sounder provided measurements with an accuracy adequate for typical bathymetry surveys. Should a greater accuracy be required, the depth sounder in ARTEMIS can be replaced by another more accurate sensor.

Aside from the errors inherent to the depth sounder itself, the quality of the bathymetric data is affected by the motions of the boat. These attitudinal errors need to be compensated geometrically by using an inclinometer to provide pitch and roll information. Also, a CTD can be incorporated in ARTEMIS to calculate an accurate sound speed for bathymetric data corrections.

The supervisory control can be extended so that the whole mission can be revised while the vehicle is operating. For instance, as a map is being generated in real-time, unsurveyed areas or areas that require more detail can be spotted and the surveying transects can be adjusted accordingly.

4.3 Future Work: Long-term

In a longer term, improvements in ARTEMIS should focus on increased autonomy. An interesting research avenue is adaptive sampling, where the vehicle software can adapt the survey grid according to the bottom features. With adaptive sampling behavior, the boat could survey wide areas coarsely, and once it finds an interesting feature such as a trench, it can return to survey that area more carefully. Another autonomous behavior that can be incorporated is obstacle avoidance to prevent collisions.

4.4 Beyond Bathymetry

The need for efficient and economic oceanographic data collection is not exclusively bathymetry; it applies to practically all marine data collection. There is a need to gain a better understanding of the oceans; however, the current surveying methods have not been able to meet this need. In general, advances in sensor technologies, data processing and storage, and navigation systems have enabled greater exploration of the ocean, yet it remains that the present methods do not meet the expanding needs of marine information. A continuing limitation is the platforms that carry these sensors [22].

Gaining a better understanding of the marine environment requires making a wide variety of scientific and environmental measurements. For example, it is necessary to map the bottom and sub-bottom of the ocean for exploration and exploitation of natural resources, such as petroleum. Man-made objects, such as telephone cables that cross the oceans need to be inspected periodically and oil rigs need to be checked for leakages. The quality of the water and the bottom sediments needs to be monitored. Finally, oceanographic data of the whole ocean system need to be collected in order to understand the oceanic processes and better predict global changes.

ASC can be used to collect various types of marine data other than bathymetry. Once ARTEMIS is established as a reliable surveying method, its applications extend beyond bathymetry. The system was designed focusing on bathymetric data collection, yet bearing in mind that ARTEMIS has a wide variety of applications in the future. For this reason, ARTEMIS was built to allow other environmental sensors to be integrated in the vehicle. For example, ARTEMIS can be adapted to gather marine information such as temperature of surface waters, sub-bottom profiles and water quality parameters. ARTEMIS or

ARTEMIS-like vehicles can become multipurpose or single-purpose data collection platforms depending on the application.

Autonomous surveying is advantageous because AVs can be made to withstand harsh environments (such as an area with highly-toxic pollutants) without putting a human operator at risk. An AV may be programmed to wait in a specified position for a prolonged time (i.e., loitering) until activated via satellite link when an important event occurs, such as underwater seismic activity. An ASC can potentially be coupled with an AUV to collectively gather marine information.

Another potential application for ASC could be the Autonomous Ocean Sampling Network (AOSN). AOSN, currently in the development/ experimental stage, is an approach toward four-dimensional ocean sampling [22]. It will consist of a land-based station, a fleet of AUVs, and a series of buoys and floats to provide energy to the vehicles and communication with the land-based station [22]. The AOSN concept is shown in Figure 33. The AUVs will transmit data to the bouys, and the bouys will relay these data to the land station. The communication between the bouys and the AUVs is done via acoustic modems. Underwater acoustic communication is subject to many difficulties when the path between the transmitter and the receiver is not vertically aligned [21]. The non-vertical path problem can be solved by using one or more ASC closely following the AUVs during a mission to serve as data links. At the same time, ASC could be used to provide periodic GPS position updates to the AUVs.

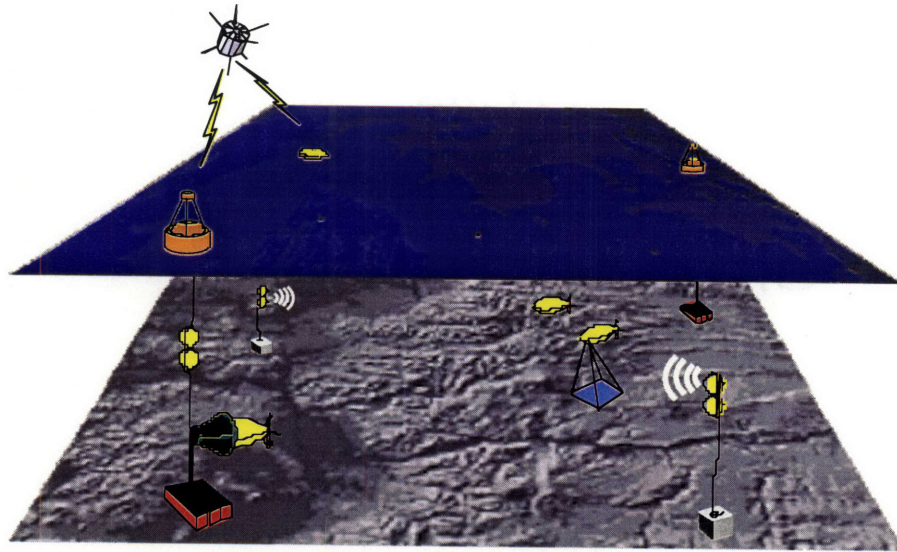


Figure 33. AOSN Concept.

ASC can prove to be a useful tool for environmental studies. Because of the rising human population, fisheries are diminishing, oil reservoirs are depleted, water quality in harbors are reaching dangerous levels, and ecosystems are being destroyed. These facts collectively demand that scientists understand and monitor the ocean for a more intelligent and responsible management of its resources in the future. With ASC environmental data can be acquired rapidly and economically, which will provide means to make more informed decisions and take corrective measures for environmental problems.

Recent technologies have enabled greater exploration of the ocean, yet the truth remains that the present methods do not meet the expanding needs for marine information. In response to this expanding need for collecting data, this research developed a mobile platform for autonomous bathymetry data collection. The long-term goal is to set the path towards a cost-effective marine data acquisition method that may complement existing technologies in a concerted effort to increase the access to the vast and varying ocean.

Appendix A

Odyssey

The Autonomous Vehicle Laboratory at MIT Sea Grant has developed a series of autonomous vehicles, including the Odyssey-class Autonomous Underwater Vehicles (AUVs). Figure 34 shows Odyssey II. For convenience, the vehicles are sometimes tested in the Charles River, off the MIT Sailing Pavilion, which is a few steps away from the lab. Some of the AUV experiments require previous knowledge of the environment. In particular, geophysical map based navigation techniques, such as the bottom following model-based approach [14; 42], rely on the availability of *a priori* maps. Although some mapping of the bathymetry of the Charles River has already been done, there is the need for high accuracy bathymetry of at least a portion of the river.

C. Goudey
4-13-94

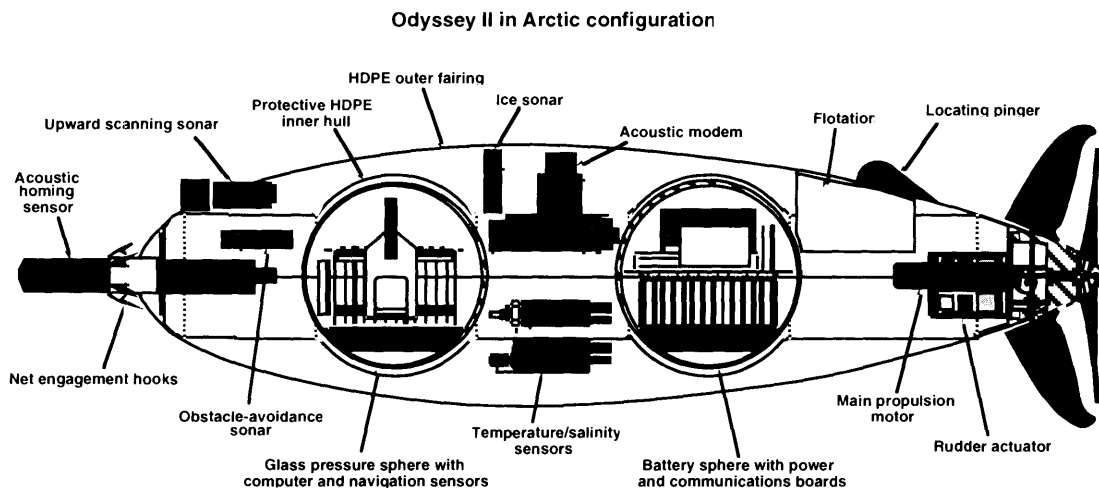


Figure 34 Autonomous Underwater Vehicle (AUV) Odyssey II.

Appendix B

Pulse Width Modulation (PWM)

In this appendix, the calculations to obtain the parameters that determine the PWM waveforms are detailed.

To define PWM, the CPU in the Tattletale[®] microcomputer (TT7) provides one parameter that indicates the period and another one that indicates the high time. The period is kept constant at 50 milliseconds, equivalent to 25,000 ticks of the TPU's internal clock. Varying the high time changes the width of the pulse in the PWM waveform. For the rudder, a 1.5 millisecond pulse width (i.e., 750 TPU ticks) indicates no offset from the center, while 500 and 1,000 TPU ticks respectively indicate the limiting angle positions (approximately -25 and +25 degrees). The motor is at full throttle forward at 1,000 TPU ticks, at full throttle reverse at 500 TPU ticks, and stopped at 750 TPU ticks. From these values found empirically and assuming that the relationships between rudder and hightime, and thrust and hightime are linear the following equations are found:

$$\text{Eq.1} \quad \text{PWM(hightime)}_{\text{rudder}} = 10.87 \times \text{commanded rudder angle} + 750$$

$$\text{Eq.2} \quad \text{PWM(hightime)}_{\text{thrust}} = 2.50 \times \% \text{ commanded thrust} + 750$$

Since the motor speed is kept constant throughout a single mission, Equation #2 is used only once at the beginning of the program. Equation #1 is used for every new rudder command.

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