Developing Fleets of Autonomous Underwater Vehicles

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Dean B. Edwards
Department of Mechanical Engineering
Center for Intelligent Systems Research
University of Idaho
Moscow, ID 83844
Phone: (208)-885-7229 fax: (208) 885 9031 email: dedwards@uidaho.edu
Grant Number: N000140510674
http://www.mrc.uidaho.edu/cisr/subs/

1. ABSTRACT

Autonomous underwater vehicles (AUVs) have a demonstrated capability to collect valuable data for scientific and military purposes. Historically, individual vehicles have been used. To reduce the overall time and cost of acquiring data over large areas, multiple vehicles must be used. A fleet of 5 AUVs, capable of underwater commendation, were fabricated. Languages and logics were developed to enable collaborative operations among the vehicles. Experiments with a formation of 5 AUVs operating underwater simultaneously are described. The AUVs operated autonomously, in that they enabled their operations on their own, initiated and constrained by underwater acoustic communication and navigation against a general behavioral background provided by programmed logics. The operations were not choreographed in advance and programmed into the machines, nor were they the result of intervention by an operator on the surface. The vehicles performed deployment, formation-flying, vehicle replacement, divert-to-point of interest, and leader replacement behaviors. The experiments show that autonomous collaborative behavior by 5 AUVs is possible under the constraints of underwater acoustic navigation and acoustic communication.

2. LONG-TERM GOALS

The long-term goal of this project is to develop procedures for designing the control and communication structure for fleets of autonomous underwater vehicles (AUVs). These AUVs include small submarines, referred to as “swimmers,” and small two-tracked vehicles, referred to as “crawlers.” The control and communication algorithms developed in this work will enable AUVs to use formations to search for mines and to communicate with each other in order to implement cooperative behavior.

3. OBJECTIVES

A number of objectives have been identified to support the long-term goal stated above. They include:

- Develop a stable, robust, scalable, decentralized, and constraint-tolerant control scheme for both the swimmers and crawlers that will operate in a fleet environment.

- Develop computer programs that can be used to simulate and optimize fleet behavior and performance, including both swimmers and crawlers.

- Develop an open architecture control system and a communication network with a protocol that can accommodate the control and data exchange among vehicles in the fleet.

- Perform a multi-vehicle demonstration test with actual, or emulated, AUVs.

Previous segments (see Section 8) of the research program have addressed the first three objectives. Work completed and results obtained in these efforts are document in the associated annual and final reports. This report addresses work completed and results obtained regarding the final objective.

4. APPROACH

This project is a continuation of the related projects entitled "Decentralized Control of Multiple Autonomous Underwater Vehicles" and "Decentralized Control of Multiple Autonomous Crawlers and Swimmers." We are conducting research in four areas. First, a system-theoretic study of the actuator constrained distributed control problem was conducted. Fundamental research in this area is continuing along the lines represented in [1]. Second, a fuzzy-logic approach to hierarchical platoon-level control was investigated. This approach is based on previous research conducted at the University of Idaho (UI) and Washington State University (WSU) on fuzzy logic control systems [2-4] and autonomous vehicles [5-10]. The ALWSE-MC program developed at NAVSEA CSS was used to develop mine search procedures compatible with a cooperative platoon-oriented search process. This program was used with optimization software to train AUVs to improve their performance in searching for mines. Third, an open architecture control system and a "plug-and-play" communication network were developed to produce a scalable, robust control and communication system. Fourth, in-water testing was conducted at the NSWCCD ARD in Lake Pend Oreille, Idaho to characterize underwater communication and control for multiple swimmers and tethered crawlers. The swimmers are small AUVs fabricated at UI whose design is partially based on the Virginia Polytechnic Institute vehicle.

5. WORK COMPLETED

A fleet of 5 miniature AUVs were fabricated at the University of Idaho. The submarines were used to test the cooperative control algorithms and navigation procedures. A photograph of four of the submarines is shown in Fig. 1. Each vehicle was 1 meter long and 10 cm in diameter, and was equipped with a Woods Hole Acoustic micro-modem [1] for communication and navigation.

A distributed approach for control on each vehicle was used. The five functional units communicated using an Ethernet hub. The instrumentation unit collected and configured information from all of the sensors on the AUV except those requiring underwater communications. The internal sensors included a battery monitor, a water detector, and a thermometer to monitor the internal temperature of the AUV. The external sensors consisted of a GPS unit, an electronic compass, a pressure sensor to determine the depth, and an accelerometer to determine pitch and roll. All sensors except the GPS were polled each 0.25 seconds. The mission control unit performed all of the control calculations necessary for navigation of the AUV and recorded all incoming and outgoing Ethernet packets to a 128Mb XDRAM card. The 128Mb data capacity of the log provided for approximately 30 hours of data storage. The locomotion unit controlled the speed of the propulsion motor and set the position of the control surfaces. A Woods Hole Modem was used for underwater acoustic communication and navigation. When on the surface, wireless communications were accomplished with a 900MHz MaxStream 9Xstream radio modem. A Linksys model WCF12 wireless CompactFlash 802.11b Ethernet card was used to allow configuration of the AUV from the base station.

At the University of Idaho (UI), languages, logics and algorithms were developed to enable collaborative operations among AUVs. Automatic formation control algorithms enable multiple AUVs to search cooperatively for mines in close formation [2]. Organized in a swimmer-trailer formation, with one swimmer designated the leader, and programmed to conduct coordinated searches in a lawnmower pattern, various autonomous behaviors associated with large area MCM have been modeled and simulated [3]. These behaviors include deployment, vehicle replacement, leader replacement, divert to point of interest, and map building. The behaviors are supported by a version of AUVish, an agent communication language designed for the vehicles [4].

Vehicle replacement is controlled by the leader with a 32-byte message broadcast. A flow chart describing the logic used by the leader vehicle to compose the 32-byte message for vehicle replacement is shown in Figure 2. The first step is to process the connection vectors and compute the composite connection vector. In this step, the accumulated messages received from all of the vehicles are combined with an OR logic operation. This operation determines if any vehicles are missing from the formation. The next step is to search the formation vector for duplicates to determine if multiple AUVs report the same formation position. The formation vector is then searched to locate empty slots in the formation. The first decision branch is found at this point: "is there a duplicate vehicle?". If there is a duplicate vehicle, a 32-byte message is composed to tell the duplicate vehicle to move to the first empty slot in the formation. The second decision branch is this: "is there an empty slot?". If there is an empty slot, the logic will attempt to find an available vehicle, swimmer or trailer, to fill the slot. Any vehicle assigned to a formation position of less significance is considered available for movement. For example it is more important to fill the Swimmer 2 position than to keep a vehicle in the Swimmer 3 or Trailer positions. Once a vehicle-move message is composed, it is loaded into the 32-byte package along with the leader telemetry information and broadcasted to the formation.

The leader is not a specific position in the formation; rather, leader is a role that can be assumed by any one of several vehicles, so long as it meets certain conditions. The goal for leader replacement is to ensure that the formation has one and only one leader at all times. All the information required to accomplish this goal is available in the connection and formation vectors. A flow chart of the leader replacement logic used to compose messages for broadcast is shown in Fig. 3. A vehicle must meet three conditions before assuming leadership: first, it must lose contact with the previous leader; second, all other vehicles must indicate that they have lost contact with the previous leader via their connection vectors; third, the vehicle must be in a swimmer position. After a vehicle assumes leadership it will command trailers to replace any vacant swimmer positions in subsequent 32-byte messages. The potential problem of multiple leaders is resolved by allowing the first vehicle that claims leadership to be the leader. In the case of multiple leaders, there will be multiple, overlapping 32-byte command messages which will be garbled, so all leader conflicts must be resolved with the 13-bit messages. The leader replacement logic used to process a message upon reception is shown in Fig. 4. In each communication cycle, each vehicle will broadcast one 13-bit message and receive up to four messages from other vehicles in the formation. A vehicle claims leadership by setting the leader flag in its status message to 1. As the leader, it will broadcast a 32-byte command message.

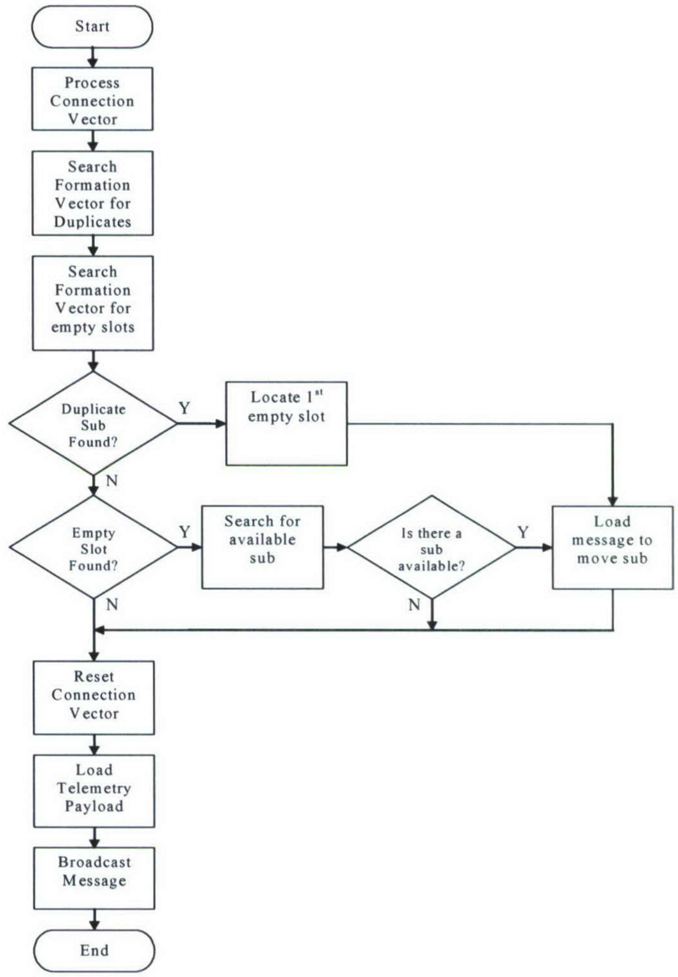

Fig. 2. Vehicle replacement logic

The AUV cooperative behavior experiments were performed at the Acoustic Research Detachment located on Lake Pend Oreille Idaho. This is a low noise, freshwater facility. The facility is equipped with a state-of-the-art acoustic tracking system [5] in deep water, a shallow water location with portable acoustic navigation beacons, underwater acoustic communication systems, and surface craft to support tests with miniature submarines. The tests were conducted in a shallow-water portion of the test facility. The depth of the water ranged from ~9-18m. The area of shallow water was limited, so the waypoint patterns used covered an area of approximately 50m×30m. Navigation transponders were used with the Woods Hole acoustic modems for LBL position measurements. Typically, three transponders were used, and they were placed outside the perimeter of the waypoint pattern.

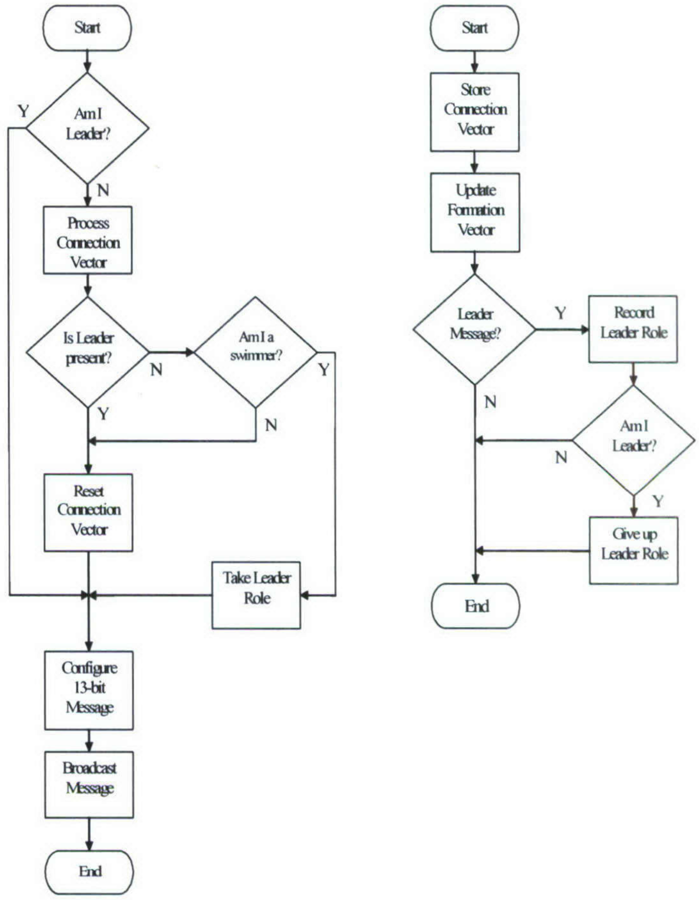

Fig. 3: Leader replacement logic, 13-bit broadcast (left), 13-bit receive (right)

6. RESULTS

6A. Deployment and Vehicle Replacement Behaviors

Results obtained from an experiment intended to test the vehicle-replacement behavior are shown in Fig. 4. A group of five vehicles participated in this experiment. Two vehicles were programmed to follow a shortened segment of the course. During the experiment, the remaining three vehicles would detect the loss of two vehicles and would re-establish the formation and proceed through the waypoint paths. After launch, there were no communications from the surface; all subsequent events were accomplished by underwater communications. The data shown in Fig. 4 were downloaded from the submarines after the experiment.

Waypoints, estimated vehicle positions, and LBL fixes are shown in Fig. 4. In Fig. 4, the waypoints describing the vehicles intended path are indicated with circles and thin lines, the estimated vehicle position by thick lines, and LBL fixes by squares. The launch position for each vehicle, obtained with GPS, is indicated with a circle/square marker. Once submerged, there was no ground-truth measurement for the absolute position of each vehicle. Rejected LBL measurements, those that differ from the estimated position by too large an amount, are indicated with dashed lines. Accepted LBL measurements are visible by discontinuities in the estimated position caused by the estimator resetting to the LBL position fix.

At the start of each experiment, a deployment behavior was initiated. The vehicles were released sequentially on the surface. They were then commanded to begin their mission by RF broadcast. After the command to commence the mission, the AUVs submerged and the deployment procedure was performed. The deployment procedure was entirely autonomous; it proceeded using underwater acoustic communications among the vehicles, without any intervention from an external controller or operator. The first underwater message for each vehicle was initialized with the communication vector indicating that each vehicle was present. This was necessary to ensure that the leader would not commence replacing vehicles simply because others had not yet had the opportunity to report their presence

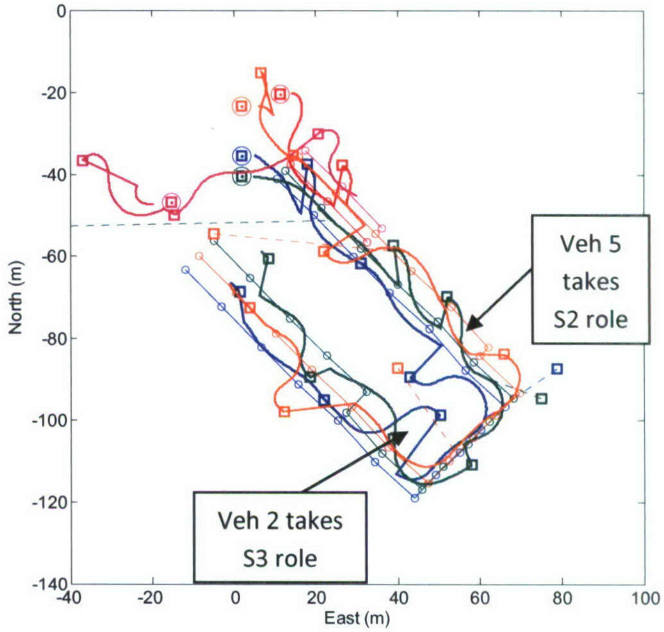

Figure 4. Vehicle position tracks for vehicle replacement behavior

The replacements are evident in the vehicle tracks contained in Fig. 4. The estimated positions for each vehicle began shortly after the GPS surface fix was obtained. By communication cycle 3, each vehicle had entered the waypoint path. After the third communication cycle, vehicles 3 and 4 had completed their assignments, and the heavy lines indicating the estimated position of vehicles 3 and 4 end. The three remaining vehicles underwent a replacement procedure, initiated in communications cycles 4 and 6. During these cycles, the intended formation waypoints for four, and then three vehicles are visible in Fig. 4 as the formation approach and round the square corners.

6B. Leader Replacement Behavior

An experiment was conducted to test the leader replacement behavior. Estimated vehicle position and communication logs are shown in Fig. 5. Again there were five vehicles involved in the experiment. Vehicles 2, 3, and 5 were pre-programmed to complete the entire waypoint pattern. Vehicles 1 and 4 were pre-programmed to abort their mission, simulating the loss of these vehicles. Vehicle 1 was initialized as the leader, so that the test would simulate the loss of a leader vehicle, and the performance of a leader replacement behavior.

From the estimated vehicle position tracks contained in Fig. 4, the vehicle replacement behaviors are evident by the change of waypoint tracks; however, the leader replacement is not visible because the leader role is decoupled from the fleet positions. To make the leader replacement more evident, the estimated position of the leader vehicle is marked with an extra thick line. As noted on the plot, the leader (vehicle 1) and vehicle 4 completed their missions and aborted just before the third waypoint. Vehicle 3 assumed the leader role, and then assigned vehicle 5 and vehicle 2 to the swimmer S1 and S3 positions respectively, as noted.

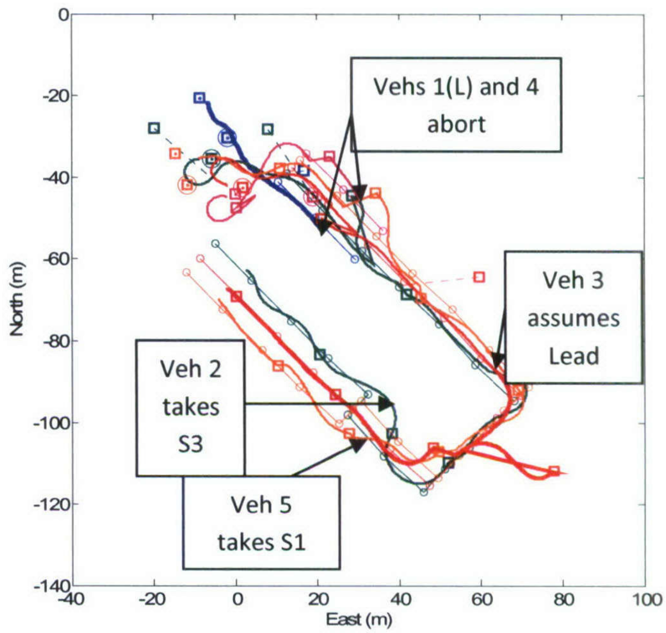

Figure 5. Vehicle tracks for leader replacement behavior.

6C. Divert to Point of Interest Behavior

This test was designed to simulate a leader vehicle finding a MLO (mine-like object) and sending a follower vehicle to inspect it. Five vehicles were used in the experiment. The leader was programmed to initiate a diversion to a point of interest in the second communication cycle of the mission.

Vehicle tracks for this experiment are shown in Fig. 6. As noted in Fig. 6, vehicle 3 left the formation to inspect a point of interest, and then returned. Vehicle 3 had only passed one waypoint by the time the leader sent the message to inspect the MLO. Immediately after receiving the leader's message, vehicle 3 headed toward the point that the leader indicated. During cycle 3, vehicle 3 reported to the leader that it was en route to the point of interest. This report indicated to the leader that no more commands were needed, and the leader removed this command from the command queue. After vehicle 3 had performed the inspection it returned to the formation by resuming formation-flying behavior at the second waypoint.

7. IMPACT/APPLICATIONS

The integrated platoon of swimmers and crawlers envisioned in this project should have a significant impact on the ability of the Navy to search for mines in very shallow water, surf zone, and beach regions. Full or even partial autonomy will produce a significant force multiplication effect on naval operations related to mines countermeasures.

8. RELATED PROJECTS

This task is a continuation of three previous ONR-funded projects, Communication and Control for Fleets of Autonomous Underwater Vehicles (ONR N00014-04-1-0506), Decentralized Control of Multiple Autonomous Underwater Vehicles (ONR Grant

N000140310634) and Decentralized Control of Multiple Autonomous Crawlers and Swimmers (ONR Grant N000140310848). These initiatives leverage common test equipment and extend the results from deep to shallow water and to a broad application of autonomous vehicles. Fabrication of a Fleet of Mini-AUVs (ONR Grant N000140410803), enabled fabrication of 5 AUVs. The tests were conducted in shallow water areas on Lake Pend Oreille that are located close to the Bayview navy facility.

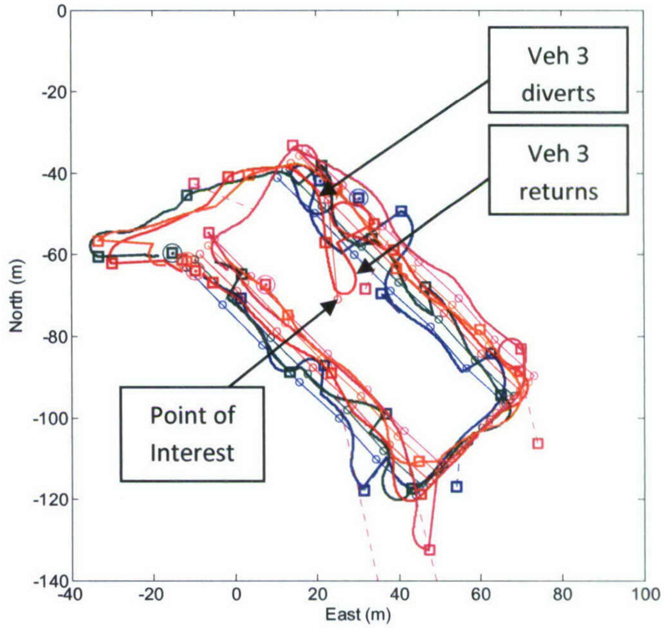

Figure 6. Vehicle tracks for divert-to-position-of-interest behavior.

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10. PUBLICATIONS

P1. T. Bean, G. Beidler, J. Canning, D. Odell, R. Wall, M. O'Rourke, M. Anderson, D. Edwards," Language and Logic to Enable Collaborative Behavior among Multiple Autonomous Underwater Vehicles", accepted for publication in the *International Journal of Intelligent Control and Systems*.

P2. T. Bean, G. Beidler, J. Canning, D. Odell, R. Wall, M. O'Rourke, D. Edwards, M. Anderson, "AUV Cooperative Operations using Acoustic Communication and Navigation", submitted to *IEEE Journal of Oceanic Engineering*, September 2007.

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University of Idaho, Office of Sponsored Programs
Morrill Hall Room 414
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14. ABSTRACT
Experiments with a formation of 5 AUVs operating underwater simultaneously are described. The AUVs operated autonomously, in that they enabled their operations on their own, initiated and constrained by underwater acoustic communication and navigation against a general behavioral background provided by programmed logics. The operations were not choreographed in advance and programmed into the machines, nor were they the result of intervention by an operator on the surface. The vehicles performed deployment, formation-flying, vehicle replacement, divert-to-point of interest, and leader replacement behaviors. The experiments show that autonomous collaborative behavior by 5 AUVs is possible under the constraints of underwater acoustic navigation and acoustic communication.

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