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Edwards, Dean B.

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University of Idaho, Office of Sponsored Programs
Morrill Hall Room 414
PO Box 443020
Moscow, ID 83844-3020

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Attn: ONR 00CC
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14. ABSTRACT
The communication and control performance of autonomous underwater vehicles (AUVs) relates directly to the tactical warfighting capability for force multiplication and improved effectiveness. The project objective is to develop a comprehensive design procedure for communication among, and decentralized control of, a fleet of AUVs. The AUVs consist of small submarines, called “swimmers,” and small tracked vehicles called “crawlers.” The vehicles are capable of organizing themselves in specified geometric patterns and navigating between predetermined points and around obstacles. Communication and distributed control concepts for a fleet of cooperating AUVs were investigated theoretically, by computer simulation, and through prototype testing in a controlled in-water environment. The testing was performed at the NSWCCD facilities at Bayview, Idaho. We investigated both fuzzy logic and system theoretic approaches to the control problem. We investigated and developed communication strategies appropriate for the fleet-wide control problem.

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Communication and Control for Fleets of Autonomous Underwater Vehicles

Final Report
10/30/2006

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: N000140410506
http://www.mrc.uidaho.edu/cisr/subs/

ABSTRACT

The communication and control performance of autonomous underwater vehicles (AUVs) relates directly to the tactical warfighting capability for force multiplication and improved effectiveness. The objective of this project is to develop a comprehensive design procedure for communication among, and decentralized control of, a fleet of AUVs. The AUVs will consist of small submarines, called "swimmers," and small tracked vehicles called "crawlers." The vehicles will be capable of organizing themselves in specified geometric patterns and navigating between predetermined points and around obstacles. Communication and distributed control concepts for a fleet of cooperating AUVs will be investigated theoretically, by computer simulation, and through prototype testing in a controlled in-water environment. The in-water testing will be performed at the Naval Surface Warfare Center Carderock Division facilities at Bayview, Idaho.

We intend to leverage our experience in the development of autonomous vehicles for land-based applications to facilitate this water-based application. We will investigate both fuzzy logic and system theoretic approaches to the control problem and seek to find appropriate synergies between them. Recognizing that communication among cooperating vehicles is an integral part of this combined communication and control problem. We will investigate, adapt, and develop communication strategies appropriate to the fleet-wide control problem. The resulting communication and control system design procedures will be available to the Navy for use in developing communication and control systems for multi-vehicle fleets of AUVs. This work is a continuation of work previously funded by the Office of Naval Research (ONR) entitled "Decentralized Control of Multiple Autonomous Underwater Vehicles" and "Decentralized Control of Multiple Autonomous Crawlers and Swimmers."

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.

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.

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. The UI vehicle is shown being tested in Buttonhook Bay on Lake Pend Oreille near Bayview, Idaho in Figure 1. The vehicle was fabricated under a related project entitled "Fabrication of a Fleet of Mini-AUVs."

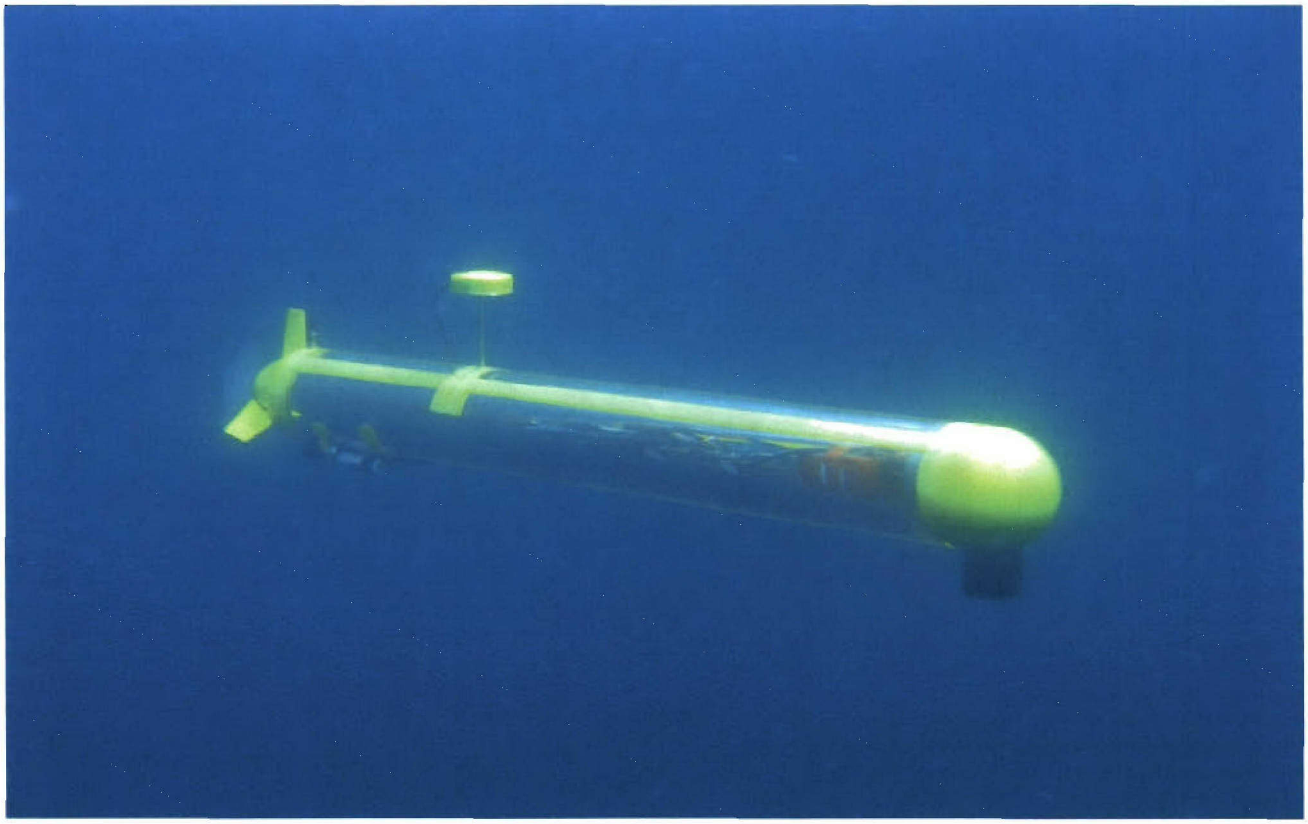

Figure 1: UI's AUV being tested in Lake Pend Oreille

WORK COMPLETED

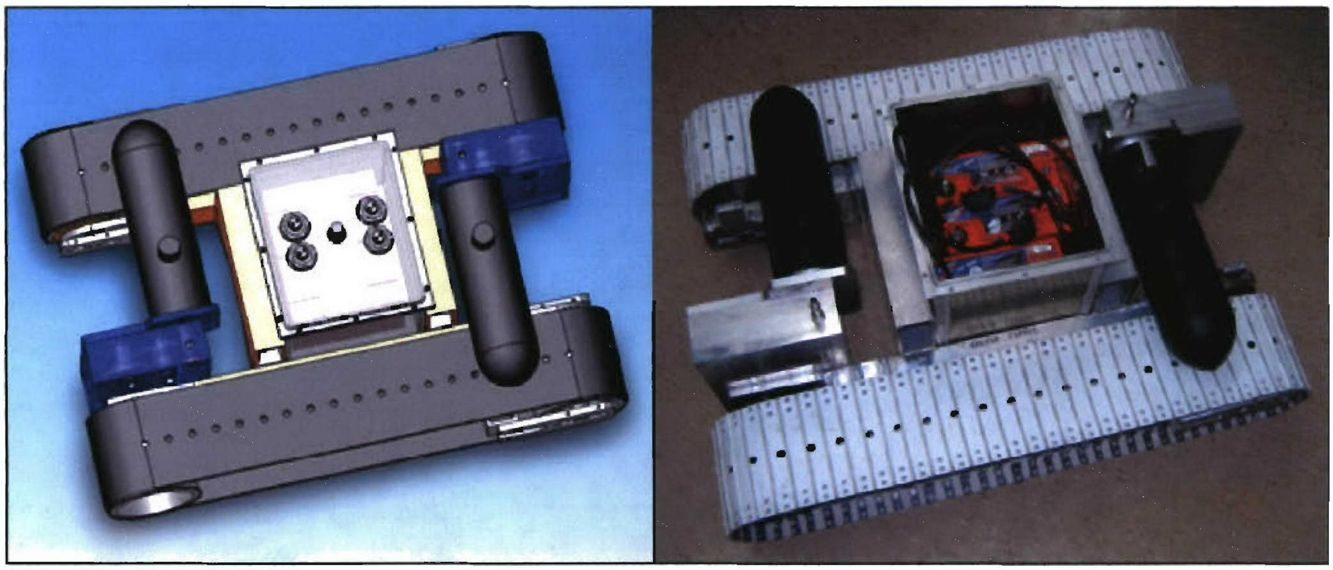

Figure 2: UI's Crawler (Solid Works Model and Picture)

UI and the Naval Surface Warfare Center- Panama City (NSWC-PC) have collaboratively enhanced the ALWSE-MC software package to incorporate features needed for simulation of cooperating vehicles. We have used ALWSE-MC to help develop a hierarchical, fuzzy logic control system for an individual crawler. This system is adapted from previous work on autonomous, two-tracked vehicles used in forests for timber harvesting operations, [5-10]. We are investigating the use of rotating head sonar on crawlers as an additional sensor for navigation. We have previously investigated the use of video cameras on autonomous vehicles for navigation purposes [11-13] and are using some of these methods for an underwater crawler using sonar. A picture of the tethered crawler is shown in Figure 2. In addition, we have shown that a leader-follower platoon formation is inherently stable where the leader continuously broadcasts its position and each individual AUV is stable relative to its planned trajectory. A vehicle replacement strategy that relies on communication between AUVs was also demonstrated for this leader-follower platoon formation.

RESULTS

We changed a formation control problem into a formation regulation problem and developed a simple and robust decentralized control algorithm for a fleet of vehicles. Stability of the system was shown in terms of the non-existence of unstable fixed modes. It was also shown that the stability of the *n*-vehicle leader-follower system was achieved by stabilizing each vehicle separately. This property allows control engineers to design advanced, high performance controllers for individual AUVs that will also make the fleet stable. As an example, a hybrid leader-follower system was designed and simulation results showed that the design and analysis methods were valid and useful.
We used a realistic, nonlinear, six-degree-of-freedom model and investigated the stability of a fleet having a leader-follower control algorithm. Using results from decentralized control theory, we showed that if the followers are able to measure the distance to the leader, the algorithm does not have any unstable fixed modes. We also showed that the leader-follower control algorithm has fixed modes at the origin, indicating that the formation is marginally stable when the relative distance measurements are not available. We performed multi-vehicle simulations using a hybrid leader-follower control algorithm where each vehicle is given a desired trajectory to follow and adjusts its velocity to maintain a prescribed distance to the leader. Because each vehicle has a trajectory to follow, formation flying is accomplished if the followers maintain a prescribed forward distance to the leader.

Figure 3 shows an example of this formation where the vehicle trajectories are triangles and the search paths are dashed lines. The desired distance was set to 10m in the x_i-direction for this example while the trajectories were separated by 40m. Although the vehicles were initially placed at random position and orientation, they converged to their assigned search trajectory and maintained a prescribed distance to the leader. Figure 4 shows the formation errors. A positive error means a follower is behind the desired position and vise versa. The simulation result indicates that the assumptions are valid, and the controller design methodology is simple, robust, and efficient. Even if the followers lose communication with the leader, the followers would still follow the trajectory since the coupling only causes their velocity to change.

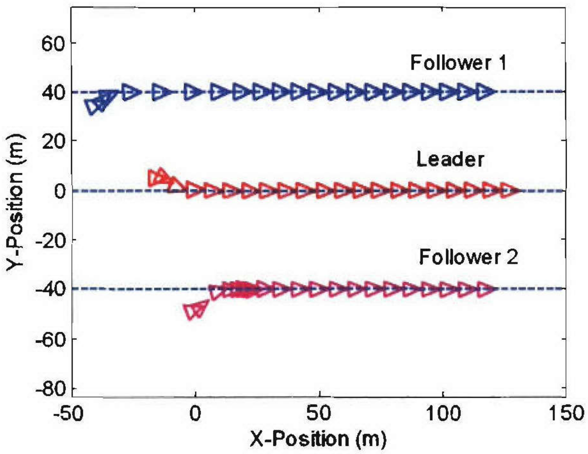

Figure 3: Vehicle Trajectories

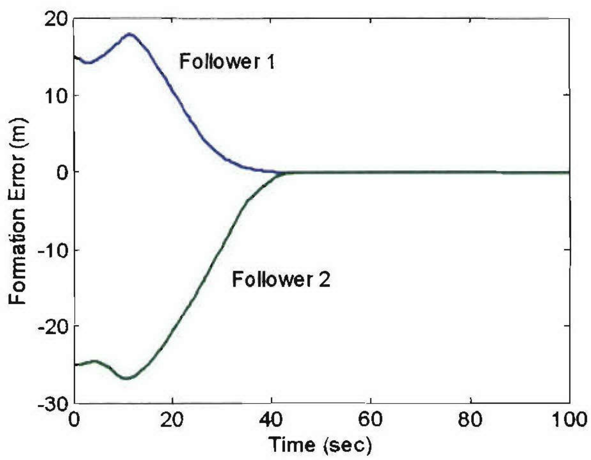

Figure 4: Formation Errors

When AUVs are moving in formation, they can be lost or stop communicating for many different reasons. Therefore, the formation (i.e. see Fig. 4 for an example) must be able to compensate for lost AUVs or else the benefits of using multiple AUVs will be decreased. To accomplish this collaborative behavior, a common language and logic structure was developed. The common language allows the AUVs to communicate and coordinate their behavior, and the logic structure allows them to process the messages, take the correct actions, and generate outgoing messages.

The language allows the leader to replace a lost swimmer with a follower or have the remaining AUVs reconfigure their search pattern and allows vehicles to communicate their mine locations during the mission. The logic developed uses the concept of vehicle number, formation number, and formation rank to change positions during the mission. The AUVs were all provided the same logic so every vehicle was capable of performing any role in the formation. In the logic, AUVs process messages by invoking different modules for different messages. The simulations demonstrate that the common language and logic are effective in maintaining coverage if any of the AUVs are lost. For example, Figure 5 shows a simulation where swimmers are replaced with followers. As can be seen, the language and logic used in the simulation does work and is a good start to solving the problem of replacing lost AUVs and adds to the robustness of using multiple AUVs.

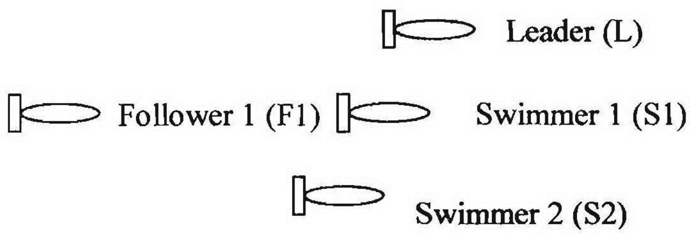

Figure 5: Vehicle Formation

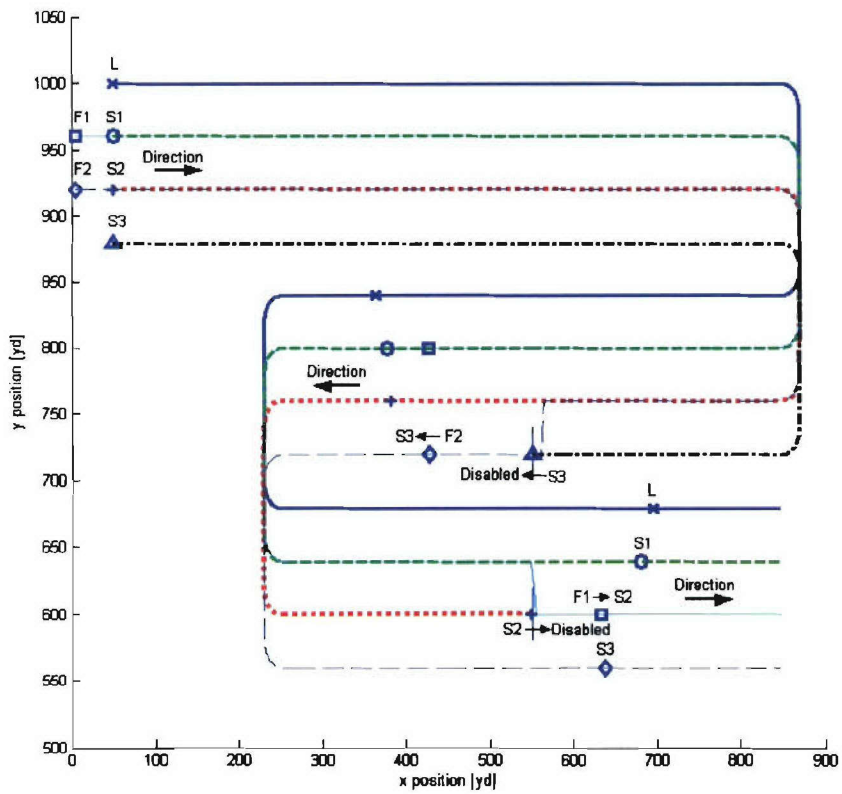

Figure 6: Disabled swimmers replaced with followers. (F2 replaces S3, F1 replaces S2)

A linear, fuzzy logic controller was developed for an autonomous underwater crawler. The controller is hierarchical in design with obstacle avoidance, a path finding, and a supervisor model. The obstacle avoidance module takes information about the nearest obstacles and outputs a recommended corrective heading. It attempts to avoid obstacles using the smallest possible deviation from the current vehicle heading, but it has no inherent path finding abilities. The path finding module takes information about the current vehicle heading and the desired vehicle path and outputs a corrective heading to attempt to stay on the path. The path finding module used without the obstacle avoidance module would make the vehicle follow a straight line between a series of predetermined point without avoiding any obstacles.

The software used for the simulation environment is the Autonomous Littoral Warfare Systems Evaluator – Monte Carlo (ALWSE-MC) developed and maintained by Naval Surface Warfare Center Panama City. ALWSE-MC simulates autonomous vehicles performing mine reconnaissance/mapping, clearance, and surveillance in a littoral region. Three simulations were preformed; one each for trajectory control, point to point control, and random walk. Each simulation consisted of 100 runs in a 200 meter by 200 meter minefield filled with 20 mines. Each run consisted of different randomly located mines and 200 randomly placed obstacles of 2 meters in diameter. Simulation runs using trajectory and point to point control were ended when the crawler finished one complete pass through a lawnmower search pattern. Random walk runs were terminated at the mean time of completion of the trajectory and point to point control searches. This was done to make a more meaningful comparison between the three strategies.

A stochastic optimization procedure was developed using ALWSE-MC simulations and a simplex method routine to help further improve the fuzzy logic using trajectory control. The optimization procedure was an iterative process in which a set of 25 simulation runs were performed, the average performance function was calculated, a simplex calculation was executed, and a new set of fuzzy logic

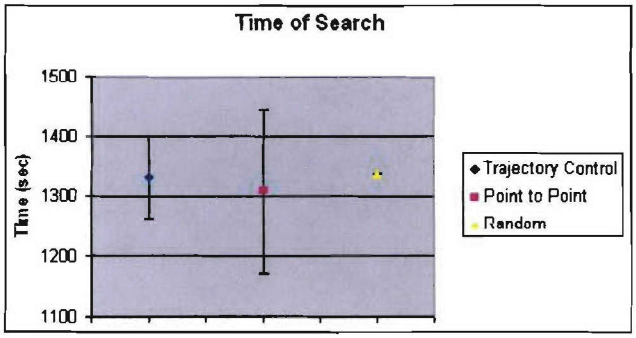

Figure 7: Time of Search

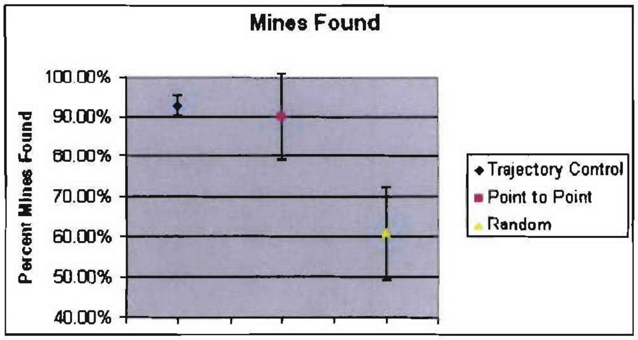

Figure 8: Mines Found

parameters were recommended. There is no statistical evidence that there is a difference in time of search between the trajectory control and the point to point control, see Figure 7. The random walk time of search was made to match the mean of the trajectory control time of search and was used as the termination condition for the random runs. This allows the random walk to be compared to the other two strategies in mine finding capability as seen in Figure 8.

Both point to point and trajectory control outperformed the random walk in finding mines. Observation of the random runs found that given the time of search, the crawler would typically not be able to get to all the corners of the search area, leaving a number of mines unfound. The error bars represent one standard deviation. There is not a statistical difference in the mean number of mines found over the 100 runs for the point to point and trajectory controls. However, the point to point control could tend to leave gaps in the pattern and miss mines.

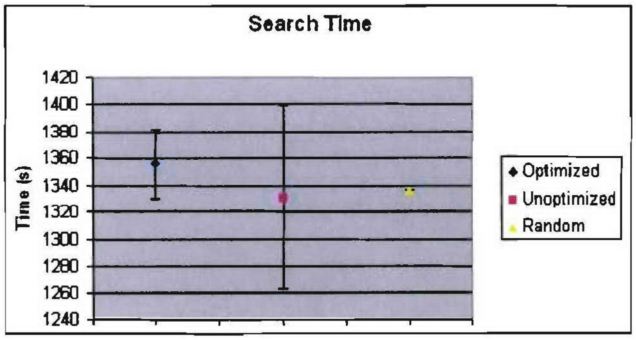

Figure 9: Search time after optimization

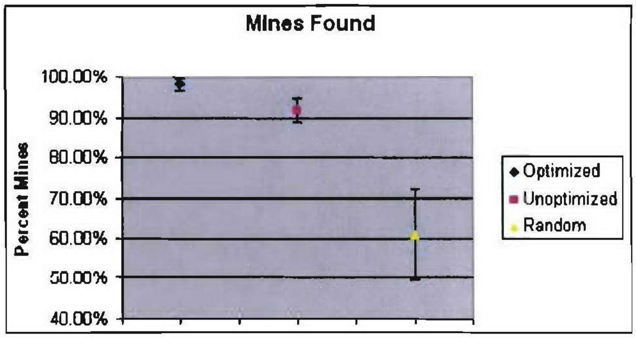

Figure 10: Mines found after optimization

After optimization the trajectory control search time became more consistent as the total distance traveled by the crawler became closer to the distance of the lawnmower search, see Figure 9. The mine finding capability of the lawnmower search pattern increased after optimization from about 92% ± 2% to about 98% ± 1%, see Figure 10. This is believed to be because of fewer gaps in the search because the optimized controller returns to the path of the search pattern quicker than the non-optimized controller.

Trajectory control and point to point control have the capability of performing equally well, but trajectory control has shown to have less variance and is therefore a better choice for MCM missions. The closer a crawler can stay to the lawnmower pattern while avoiding obstacles, the better mine finding performance will be realized. Total search time was expected to be lower using a point to point control, but it was found that there was no difference. Random walk control did not perform as well as the other two methods, but it should not be discredited as a viable option. Random walk can be performed using less communication bandwidth and may take less processing capability.

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.

RELATED PROJECTS

This task is a continuation of two previous ONR-funded projects, Decentralized Control of Multiple Autonomous Underwater Vehicles (ONR Grant N000140310634) and Decentralized Control of Multiple Autonomous Crawlers and Swimmers (ONR Grant N000140310848). These two initiatives leverage common test equipment and extend the results from deep to shallow water and to a broad application of autonomous vehicles. In addition, small AUVs being fabricated under another related project, Fabrication of a Fleet of Mini-AUVs (ONR Grant N000140410803), were tested. The tests were conducted in shallow water areas on Lake Pend Oreille that are located close to the Bayview navy facility.

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P1. Welling, D., Edwards, D. and Anderson, M., "Fuzzy Logic Control for an Autonomous Underwater Crawler", to appear in the Proceedings of the *ASME 2004 Design Engineering*

Technical Conferences and Computers and Information in Engineering Conference September 28- October 2, 2004, Salt Lake City, Utah, USA.

P2. D. B. Edwards, T. Bean, D. Odell, M.J. Anderson, "A Leader-Follower Algorithm for Multiple AUV Formations", to appear in the Proceedings of the Autonomous Underwater Vehicles 2004, A Workshop on Multiple AUV Operations, Sebasco Estates, Maine - June 17-18, 2004.

P3. C. Reeder, A, Okamoto, M. Anderson, D. Edwards, "Two-Hydrophone Heading and Range Sensor Applied to Formation-Flying for Underwater AUV's", to appear in the IEEE Oceans 2004 Proceedings.

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