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14. ABSTRACT

We investigated approaches for designing the control and communication structure for fleets of autonomous underwater vehicles. We developed human operated surface ships to provide an inexpensive method for testing these algorithms for possible use on fleets of multiple vehicles. The testing was performed at the NSWCCD ARD in Bayview, Idaho and demonstrated a formation control algorithm that minimizes the communication needed to maintain formation. The system is a variation of a leader-follower formation where the leader periodically broadcasts its position to all the vehicles. This formation was shown to be robust and tolerant to loss of communication or the loss of any vehicle including the leader in computer simulations with a program developed at NAVSEA CSS called ALWSE-MC. The simulations show that the algorithm can be expanded to control a large number of vehicles. Preliminary measurements and analysis of the performance of a two-hydrophone sensor were performed. This sensor can be used to provide an update of the leader's location every time the leader pings for navigation or communicates in any way.

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Decentralized Control of Multiple Autonomous Underwater Vehicles

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Abstract

We investigated approaches for designing the control and communication structure for fleets of autonomous underwater vehicles. We developed human operated surface ships to provide an inexpensive method for testing these algorithms for possible use on fleets of multiple vehicles. The testing was performed at the NSWCCD ARD in Bayview, Idaho and demonstrated a formation control algorithm that minimizes the communication needed to maintain formation. The system is a variation of a leader-follower formation where the leader periodically broadcasts its position to all the vehicles. This formation was shown to be robust and tolerant to loss of communication or the loss of any vehicle including the leader in computer simulations with a program developed at NAVSEA CSS called ALWSE-MC. The simulations show that the algorithm can be expanded to control a large number of vehicles. Preliminary measurements and analysis of the performance of a two-hydrophone sensor were performed. This sensor can be used to provide an update of the leader's location every time the leader pings for navigation or communicates in any way.

INTRODUCTION

Autonomous Underwater Vehicles (AUVs) have become valuable for military, commercial and scientific purposes. For example, AUVs were used to search 3.5 million square meters of shallow water for mines in Operation Enduring Freedom in Iraq 2003. Presently, most AUVs are independently deployed and controlled. Acoustic communication bandwidth limitations on control and navigation, and the magnitude of human supervision required make it difficult to employ large numbers of independent AUVs to acquire high-resolution data from large areas in a reasonable time period.

While underwater, AUVs must rely upon inertial guidance systems or underwater acoustic triangulation using a Long Base Line (LBL) navigation system. Presently, accurate inertial guidance systems are not economically feasible for application in large numbers of inexpensive vehicles. At the same time, simultaneous operation of large numbers of AUVs navigating with an acoustic LBL is precluded because the acoustic channel will become flooded with navigation pings and other acoustic messages.

A hybrid leader-follower algorithm is introduced to overcome limitations of current underwater sensing technologies. In the hybrid leader-follower algorithm, the leader vehicle in the group broadcasts its inertial position with an acoustic modem to the other vehicles in the group so that a formation can be maintained. Although robust, this formation-flying algorithm suffers from an upper limit on the number of vehicles similar to that encountered with independent operation.

One possible way to improve the efficiency of navigation and formation-flying is to equip each vehicle with a two-hydrophone sensor. This sensor, consisting of two hydrophones separated by a distance of approximately one meter, allows the determination of the relative angular bearing to an acoustic source. By intercepting the outgoing navigation pings of the leader vehicle, follower vehicles could use the two-hydrophone sensor to determine the relative position of the leader vehicle. This practice could eliminate or at least minimize the requirement for the leader to broadcast its position.

The work performed under this grant investigated cooperative behavior between multiple vehicles used to search for mines. This work was linked to the ONR-funded project, Decentralized Control of Multiple Autonomous Crawlers and Swimmers (ONR Grant N000140310848), where the navigation and control of a fleet of small, autonomous submarines, called "swimmers," and small two-tracked vehicles called "crawlers" were investigated. These two initiatives leveraged common test equipment and extended the results from deep to shallow water.

LONG-TERM GOALS

The main long-term goal of this project was to develop a comprehensive design procedure for the communication and control algorithms of a platoon of autonomous underwater vehicles (AUVs).

OBJECTIVES

A number of short-term objectives were 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 platoon environment.

- Characterize the acoustic communication channel required for communication and control among a platoon of AUVs, including both swimmers and crawlers.
- Develop a communication network and protocol to accommodate control and data exchange among vehicles in the platoon
- Perform a multi-vehicle demonstration test with actual, or emulated, AUVs.

APPROACH

The overall approach of this project was similar to that of the related project entitled "Decentralized Control of Multiple Autonomous Crawlers and Swimmers." We conducted research in four areas. First, a system-theoretic study of the actuator-constrained distributed control problem was conducted. We believe actuator constraints will be a significant limitation in reaching our control objectives. Fundamental research in this area was conducted along the lines represented in [1]. Second, a fuzzy-logic approach to hierarchical platoon-level control was investigated. This approach was 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. Vehicle dynamics and control was embedded in ALWSE-MC using the ALWSE/MATLAB behavior module. ALWSE-MC was then used to evaluate the performance of a platoon of AUVs. Third, a "plug-and-play" communication architecture was studied to produce a scalable, robust communication network. Fourth, in-water testing was conducted at the NSWCCD ARD in Lake Pend Oreille, Idaho, to characterize underwater communication limitations with respect to platoon-based communication and control requirements. The Acoustic Tracking and Communication System (ATACS) was used for high accuracy tracking of multiple small AUVs in Lake Pend Oreille.

WORK COMPLETED

The testing was performed at the NSWCCD ARD in Bayview, Idaho on Lake Pend Oreille and demonstrated a formation control algorithm [P1] that minimizes the communication needed to maintain formation. This work is being supported by both this project and the related project entitled "Decentralized Control of Multiple Autonomous Crawlers and Swimmers."

An algorithm has been developed that controls the position of AUVs within a platoon with minimal communication among the vehicles. Algorithms accomplishing the same ends have also been developed using a robust linear-quadratic-regulator optimal control approach. These control algorithms for multiple AUVs have been simulated using ALWSE-MV. This simulation software has been very valuable in developing cooperative behaviors. The Naval Surface Warfare Center- Panama City (NSWC-PC) has collaboratively enhanced this software to incorporate features needed for simulation of cooperating vehicles. NSWC-PC workers have added vehicle position over-ride, optimization, and communications modeling features to the ALWSE-MC code. The present version of the code now being used by UI researchers is 5.3.1.

Measurements and analysis of the performance of a two-hydrophone sensor were preformed. Performance issues include the use of the sensor in the presence of propeller noise and thermal gradient, the effect of Doppler shift caused by relative motion, choice of a proper signal processing technique for extraction of difference-in-arrival time, the effect of separation distance between vehicles, and the performance of a formation-flying controller that utilizes the sensor.

RESULTS

We have investigated algorithms [P1,P2] for controlling multiple AUVs. In this section we will describe one algorithm that employs a variant of the leader-follower type strategy to maintain a fixed geometrical formation while navigating mission waypoints. A leader vehicle navigates the mission waypoints using acoustic Long Base Line (LBL) measurements of position. Each follower vehicle maintains its place in formation using acoustic LBL measurements of inertial position and knowledge of the leader vehicle position. The followers obtain the position of the leader vehicle via a parallel acoustic modem broadcast. All vehicles have knowledge of the mission inertial waypoints. One can see that the formation algorithm presented has many desirable advantages. First, it is a simple system that has low communication requirements. The system is robust enough to tolerate loss of communication or the loss of any vehicle including the leader. It can be applied to 1-dimensional,

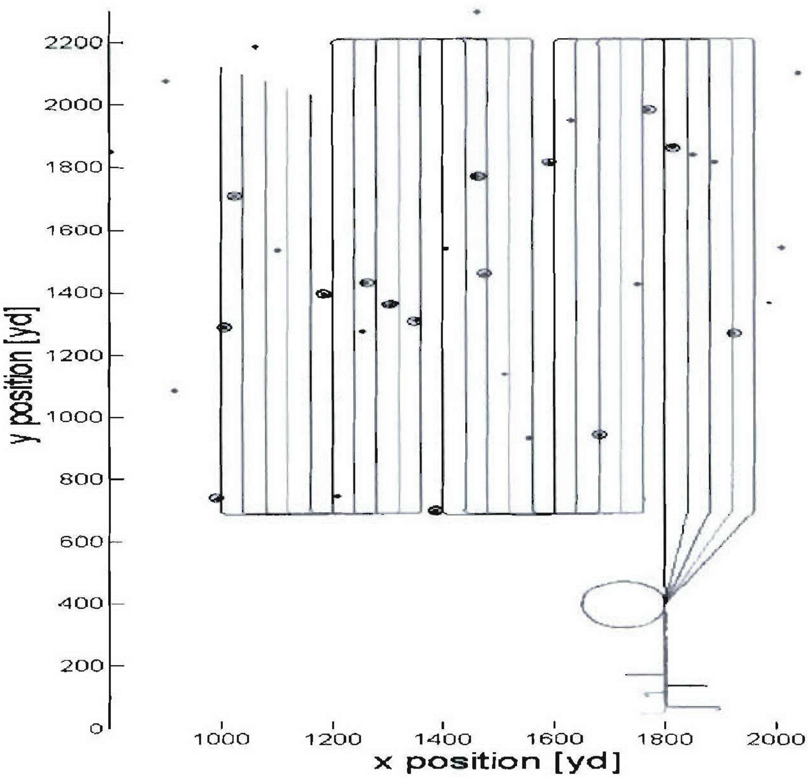

Figure 1. ALWSE simulation of 5 vehicles performing lawnmower search.

2-dimensional, and 3-dimensional formations. The algorithm can be expanded to control a large number of vehicles. Fig. 1 shows a lawnmower search pattern that illustrates how this control scheme can be implemented. When the simulation is initiated, the vehicles are placed at random near the start of the course. The vehicles form themselves into a 1-dimensional circle until all of the vehicles are in position. The vehicles then move into their 2-D positions to begin their search.

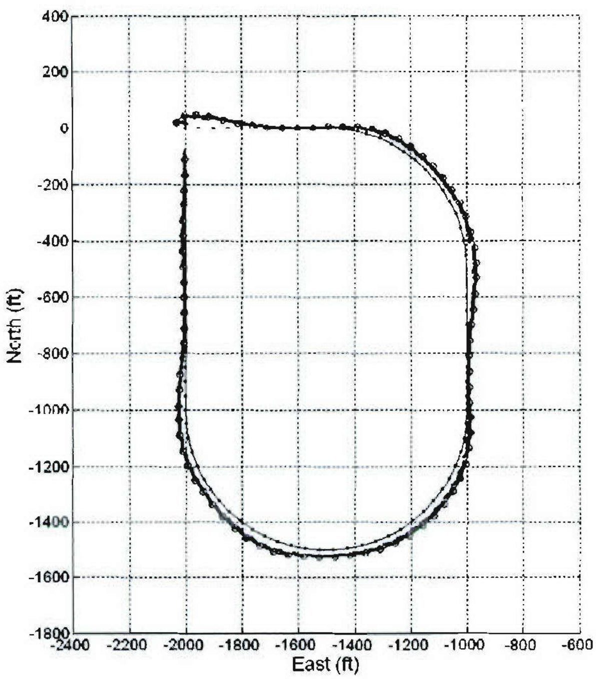

Figure 2. Experimentally measured leader-only poition.

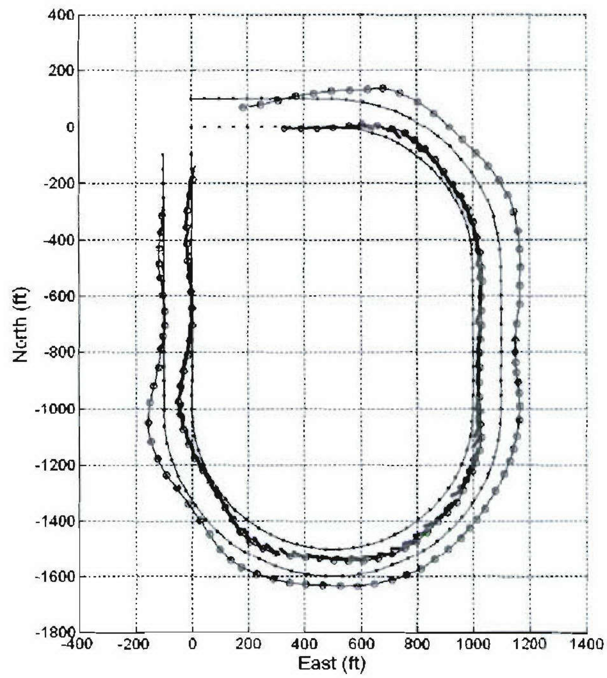

Figure 3. Experimentally measured leader-follower position.

Figures 2 and 3 show the experimental results for a single vehicle trajectory controller and the leader-follower control algorithm discussed above. These tests were performed at the NSWCCD ARD in Bayview, Idaho and demonstrate the feasibility of this formation control algorithm.

The use of a two hydrophone sensor could reduce acoustic navigation requirements by locating the leader whenever it pings or broadcasts. Tests were performed at ARD in Bayview to evaluate the accuracy of this sensor [P3,P4]. One acoustic modem, used as a source, was located in a stationary position, while a two-hydrophone sensor was mounted to a small surface craft powered by an outboard motor The surface craft intercepted LBL ranging pings from the stationary modem at distances ranging from 9-400m (30-1300ft) and speeds ranging from 1-1.8 m/s (3-6 ft/s). Cross-correlation and matched filter signal processing techniques were applied to extract the difference-in-arrival time to test the hypothesis that cross-correlation could compensate for Doppler shift.

Fig. 4 shows one example of the waveforms received by the two-hydrophone sensor, and subsequent steps in the signal processing procedure used to extract the difference in time of arrival Δt using cross-correlation. In part a of Fig. 4, the raw digitized signals from each of the hydrophones are plotted versus time on the horizontal axis. Barely visible in the two hydrophone signals is the arrival of the navigation ping at a time of approximately 1.25s. The signals were then shifted to base-band by demodulation, and low-pass filtered. After these operations, the hydrophone signals were transformed to those that are plotted in part b of Fig. 4. In part b of Fig. 4, the arrival of the navigation ping at 1.25s is clearly visible. A cross-correlation of the signals contained in part b of Fig. 4 is shown in part c. For part c, the horizontal axis is lag time in μs. A peak in correlation at a lag time of 72 μs is clearly visible. In general, our measurements showed that it was feasible to estimate relative bearing angle from the difference in arrival time Δt in the presence of propeller noise.

Experimental measurements of bearing angles are shown in Fig. 5. In part a of Fig 5, GPS coordinates of the surface craft and dock are shown for an example run. In this run, the distance from the surface craft to the dock varied from 90m to 400m, and the velocity of the surface craft was approximately constant at a value of 1.5 m/s (4.9ft/s). Note that the dock drifted back and forth during the run. In part b Fig. 5, bearing angles σ_{cc} and σ_{mf} as determined with the two-hydrophone sensor using cross-correlation and matched-filter respectively are plotted on the vertical axis versus time on the horizontal axis. The bearing angles angles σ_{cc}, and σ_{mf} are marked with open circles and a cross (×) symbol respectively. Also plotted on the vertical axis of part b Fig. 5 is the indicated bearing angle σ as determined by GPS coordinates of the dock and surface craft and a heading sensor located on the surface craft. The indicated bearing angles are denoted by a point (•) symbol.

In general, the bearing angles determined by the two-hydrophone sensor were with 9° of the indicated equivalent determined by GPS. This compared with a standard deviation error of 2° as determined in earlier static tests [11] with the same two-hydrophone sensor using cross-correlation signal processing. It was observed that the matched filter processing procedure performed better than cross-correlation for determination of relative bearing angle. The difference between indicated bearing angle and that determined with the two-hydrophone sensor using matched filter signal processing was a maximum of 4°, while when using cross-correlation, the difference was as great as 9°. This was unexpected, as it was hypothesized that cross-correlation automatically compensates for Doppler shift, while the matched filter technique requires compensation for Doppler. The reasons for this difference in performance are at the time unknown.

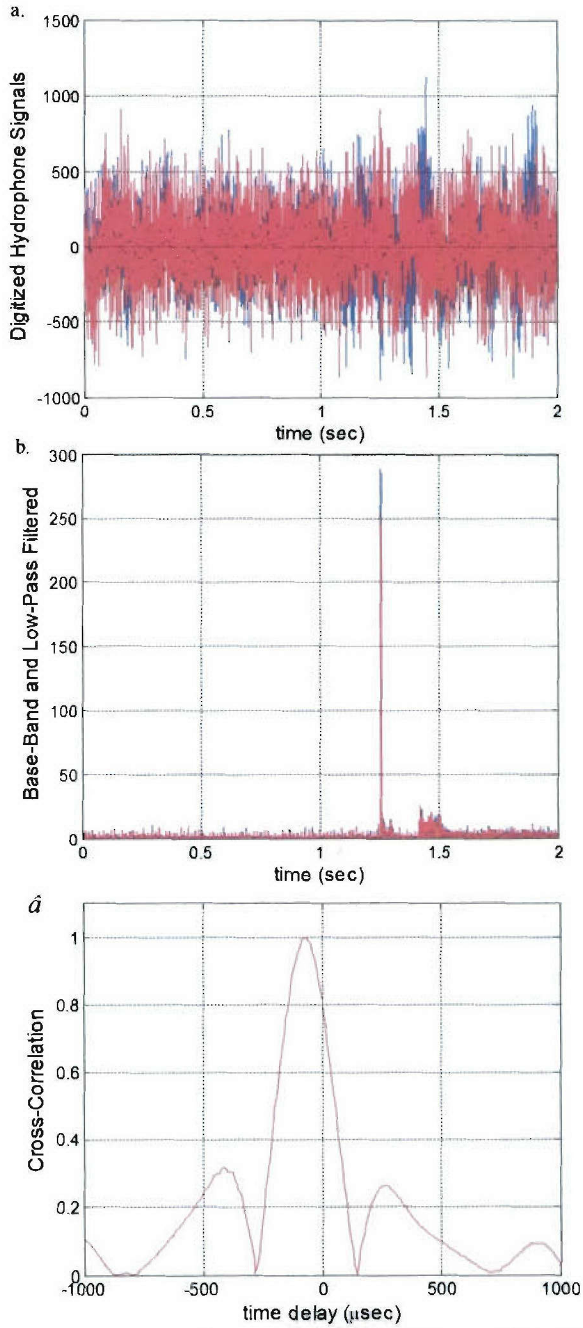

Fig. 4 Processing of hydrophone signals. a) Raw waveforms, b) waveforms after base-band demodulation and low-pass filtration, c) cross correlation of signal in part b.

IMPACT/APPLICATIONS

The results of this project are expected to have a direct impact on the ability of the Navy to conduct ocean searches. In particular, the use of multiple autonomous vehicles should significantly reduce the time required to conduct searches for mines in littoral regions. Other potential applications include deep-water ocean searches for submerged objects, missions involving data collection and measurements for scientific experimentation, and monitoring and surveillance of coastal regions and harbors.

Formation-flying as a cooperative behavior may enable large numbers of AUV's to complete tasks with comparatively little human supervision. Determination of bearing angle with a two-hydrophone sensor could lower the acoustic communication requirements to achieve formation-flying behaviors for AUV's.

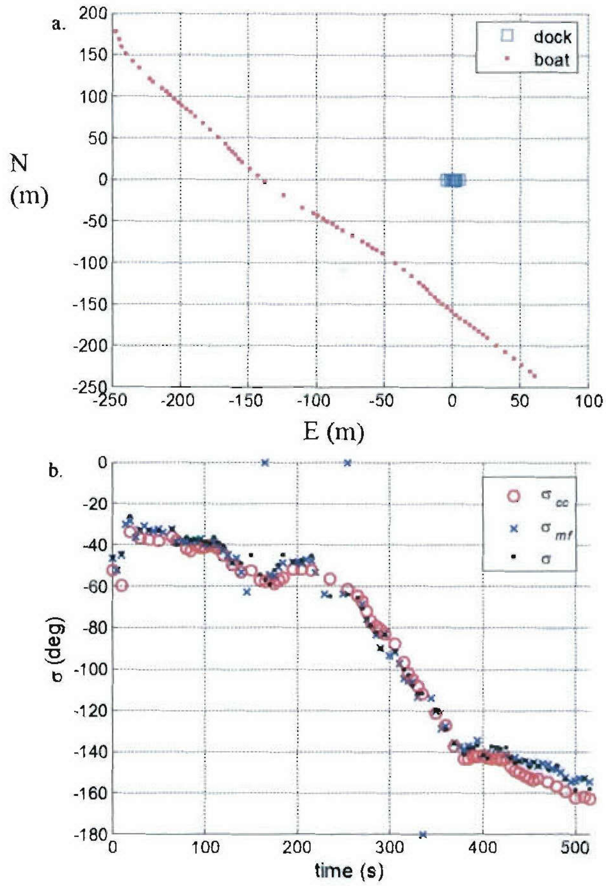

Fig. 5 GPS track positions and bearing angle determinations from relative motion test. a) GPS track positions of a surface vehicle and floating dock. b) bearing angles determined with cross correlation and matched filter signal processing.

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P2. A, Okamoto, J. Feeley, D. Edwards, and R. Wall, "Robust Control of a Platoon of Underwater Autonomous Vehicles", to appear in the IEEE Oceans 2004 Proceedings.

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.

P4. B.N. Baker, M.J. Anderson, D.L. Odell, T.A. Bean, D.B. Edwards, "Performance of a Two-Hydrophone Heading Sensor and AUV Formation Flying Controller," *Proceedings of the 14th International Symposium Of Unmanned Untethered Submersible Technology*, August 21-24, 2005.