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14. ABSTRACT

In this project we are integrating inexpensive, easily deployable magnetic measurement systems into small autonomous underwater vehicles (AUVs). These AUVs are being trained to work together to assess the magnetic signature of a forward deployed ship or submarine. This assessment is important to establish a vehicle's stealth condition relative to potential threats. Navy vessels, including submarines, go through a procedure where their magnetic and acoustic signature is measured and modified to reduce detection. This operation is performed in US ports. Unfortunately, no procedure is available for measuring and modifying these signatures for forward deployed vessels. Ideally, this process should be done just before the vehicle goes into an operation in a hostile environment. We are developing multiple AUVs having magnetic sensors that travel in a formation under navy ships to assess that ship's magnetic signature in forward deployed areas. All vehicle testing is being performed at the Acoustic Research Detachment of the Carderock Division of the Naval Surface Warfare Center in Bayview, Idaho.

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Magnetic Signature Assessment System using Multiple Autonomous Underwater Vehicles (AUVs)

Final Report
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ABSTRACT

This is the final report for Phase I of a three phase project. In this project we are integrating inexpensive, easily deployable magnetic measurement systems into small autonomous underwater vehicles (AUVs). These AUVs are being trained to work together to assess the magnetic signature of a forward deployed ship or submarine. This assessment is important to establish a vehicle's stealth condition relative to potential threats. Navy vessels, including submarines, go through a procedure where their magnetic and acoustic signature is measured and modified to reduce detection. This operation is performed in US ports. Unfortunately, no procedure is available for measuring and modifying these signatures for forward deployed vessels. Ideally, this process should be done just before the vehicle goes into an operation in a hostile environment. We are developing multiple AUVs having magnetic sensors that travel in a formation under navy ships to assess that ship's magnetic signature in forward deployed areas. All vehicle testing is being performed at the Acoustic Research Detachment of the Carderock Division of the Naval Surface Warfare Center in Bayview, Idaho.

LONG-TERM GOALS

The long-term goal of this project is to develop a portable assessment system to evaluate the magnetic (M) and acoustic signature of forward deployed ships and submarines. Inexpensive, easily deployable small autonomous underwater vehicles (AUVs) will be equipped with magnetic and acoustic measurement systems. These AUVs will then be trained to work together to assess the magnetic or acoustic signature of a forward deployed ship or submarine.

OBJECTIVES

The major objective of this work is to develop the preliminary system requirements and design for a portable stealth assessment system. Both magnetic and acoustic sensors will be identified and tested in this phase (i.e., year 1). These tests will include static tests where a sensor is positioned relative to a stationary barge that includes a calibrated signal, either EM or acoustic, so that the sensor can be evaluated independent of any interference from an AUV. The sensor will then be mounted on an AUV and tests similar to the static tests will be performed where the AUV will move underneath the barge. In addition to the AUV sensor tests, the passive navigation system will also be deployed on the barge and the accuracy of this system tested with multiple AUVs. From these tests and computer simulations of multiple AUVs making measurements under realistic scenarios, the preliminary requirements and a design for a portable assessment system will be developed.

APPROACH

The development of a portable system for assessing the EM and acoustic signature of a vehicle is dependent on (1) accurate measurement of the field and (2) accurate location of the measurement relative to the vehicle. For a stationary range, these two problems are decoupled because the sensors can be accurately positioned relative to a fixed coordinate system and only the ship's location relative to this coordinate system is needed. With a portable system, the sensors will be mounted on AUVs so that the AUVs can be deployed and properly positioned in order to make the measurements. Unfortunately, the AUVs used to position the sensors have their own EM and acoustic signatures that can interfere with the measurements being made to evaluate a ship's signature. This coupling of the measurement with the requirement for properly locating the sensor complicates the procedure for establishing a ship's signature.

A number of approaches will be evaluated to eliminate or minimize the influence of the AUV on its sensor measurements. We plan to mount the sensor on the outside of the AUV. This will help to reduce the noise and will make it easier to isolate the AUV's electronics from the sensors. We will also identify the source of noise problems, either EM or acoustic, and attempt to eliminate or compensate for the noise as much as possible. Because the acoustic modem is a source of both EM and acoustic noise when it operates, we plan to implement a passive navigation system where the modems do not need to ping to determine their positions while taking data. We will implement an improved Inertial Navigation System (INS) in order to provide accurate position estimates between navigational updates. Because the drive motor produces both EM and acoustic noise, one option we will evaluate is to take data when the AUVs are either in a glide mode or stationary where the drive motor is turned off temporarily. It may be possible to compensate for the EM noise by measuring the current going to the drive motor or filter the acoustic noise if the frequency is well defined. We will implement a combination of these approaches to enable accurate measurements of both the EM and acoustic signatures of ships or submarines.

The AUVs need to be able to navigate accurately underwater and to communicate with each other and an operator in order to position themselves to make the measurements needed to perform the signature assessment. The important position information needed to accurately assess the ship's signature is the position of the AUV relative to the ship when the data is logged. We plan to use a passive navigation system, as mentioned above, where transponders attached to the ship will broadcast to the AUVs. The AUVs will have clocks synchronized to the transponder clocks enabling them to triangulate their position relative to the ship. Initially, the AUVs will be deployed to a location where they will create a formation so that they can take the appropriate data for signature assessment when the ship passes over them. The logistics of deployment and recovery will also be considered in this work. The UI has extensive experience in the navigation, communication, and control of multiple vehicles that can collaborate to perform specific tasks.

WORK COMPLETED

The two problems that a portable system must solve to successfully assess the magnetic (M) and acoustic signature of a vehicle are (1) accurate measurement of the field and (2) accurate location of the measurement relative to the vehicle. The Acoustic Research Detachment (ARD) has worked with the UI and Carderock to define the acoustic and magnetic measurement requirements for the project. From these requirements we selected both a magnetic sensor and an acoustic sensor. The magnetic sensor is a TFM100G4-UWH triaxial magnetometer supplied by Billingsley Aerospace & Defense. This model measures ±100 μT with an output of ±10 V. The sensor is enclosed in a watertight casing and Billingsley custom fitted a watertight connector that directly integrates with our AUV. The hydrophone we purchased is a Reson TC 4032. We had to redesign the current AUV's nosecone to accommodate the sensor. The Reson hydrophone provides a usable frequency range of 5Hz through 120kHz and a max operating depth of 600 m. The hydrophone was mounted in the nose cone so that it is as far removed as possible from the motor and propeller. Also, mounting the hydrophone in this location prevents acoustic blind spots which would be present if it was mounted on the top or bottom of the AUV. These sensors therefore address the first problem of being able to accurately measure the magnetic or acoustic field.

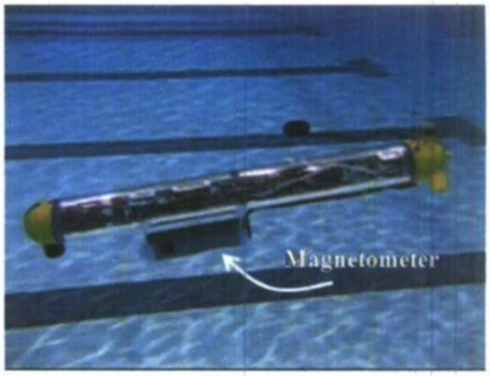

Figure 1. AUV equipped with Magnetometer.

However, an accurate sensor measurement is also dependent on the AUV's magnetic and acoustic noise. An AUV was modified in order to install a magnetometer as shown in Figure 1. These modifications included mounting the sensor as well as installing both a DSP (Digital Signal Processing) system and an IMU (Inertia Measurement Unit) in the AUV. The data acquisition system used in the AUV is manufactured by D.SignT and consists of three boards that work together to read and store data as well as interact with other AUV components. The main board is a D.Module.C6713 and implements a high performance DSP computer module to control the two daughter cards, an analog to digital converter board and an Ethernet access board. After the magnetic sensor, IMU, and DSP system were installed on the AUV, we tested the vehicle at Carderock's magnetic test facilities. These tests helped us characterize the magnetic noise of the vehicle and informed us as to how to modify the vehicle to reduce this noise. The initial magnetic measurements of the AUV were made in order to assess this background magnetic noise and the noise levels are encouraging. Acoustic characterizing of an AUV was also performed and the results were also encouraging. However, the acoustic sensing AUV system was deemed by our sponsors to have lower priority then the magnetic sensing system.

The second problem that needs to be solved for a portable system to be able to successfully assess the magnetic and acoustic signature of a vehicle is to accurately locate the measurement relative to the vehicle. The AUVs normally estimate their positions underwater using a long base-line (LBL) system. In common practice, the LBL buoys are spread hundreds of meters apart. To navigate relative to a ship, however, the buoys would most likely be attached to the ship and would be much closer together. At the start of the project, an error analysis of the current LBL navigation scheme was conducted in MatLab. The dimensions of an Arleigh-Burke class destroyer were used as positions for LBL buoys, and Monte Carlo error analysis was performed on two buoy, three buoy, and four buoy position solutions. The results showed that the two buoy solution had trouble solving for position when the AUV was within eighty meters of the ship. This is because the ship is too close to the baseline of the LBL buoys in these locations. Farther away from the ship the two buoy solution was accurate to within one meter. The three buoy solution results displayed accuracies within three meters when the AUV was within ninety meters of the ship. A four buoy solution not currently implemented was also simulated, and it displayed one meter accuracy around the ship except for areas at the corners where the error was over three meters.

We are using a Kalman-Filter to accurately determine the position of the AUV. The intent is to use a Kalman filter to improve the ability of AUVs to complete a proscribed geometrical grid, and to assign a position to magnetic signature measurements. Initial versions of a Kalman filter have been integrated into the UI fabricated AUVs, and two series of tests have been performed at ARD. The first test of a Kalman filter navigation algorithm was performed at ARD and during this test, LBL ranges were recorded every two seconds to provide a post-processed estimate of ground truth. The results show that the GPS and the post-processed ground truth (Kalman Filter) aligned very closely. Numerically, the degree of agreement between GPS and post-processed ground truth was less than 2m on average.

After analyzing the data collected from testing at ARD, several bugs in the AUV control code and Kalman filter implementation were identified. Code fixes for these problems were implemented. A second series of tests were performed at ARD. An example plot of AUV movements on the surface is shown in Figure 2. In this plot, GPS locations are shown with blue symbols, AUV location determined from LBL range updated every 30 seconds are shown in black symbols, and post-processed AUV location obtained from LBL range updated every 2 seconds are shown in green. Again, there was a high degree of agreement between GPS location and the location obtained from post-processed 2-second LBL range updates. Location determined from 30-second LBL range updates was improved over that observed in the previous tests, but several deviations were observed that exceeded expectations based upon numerical simulation. Additional trouble shooting and work on the Kalman Filter code is necessary but we are confident from these results that using LBL navigation with 2 second updates will provide the required position accuracy needed to be able to successfully assess the magnetic (M) and acoustic signature of a vehicle.

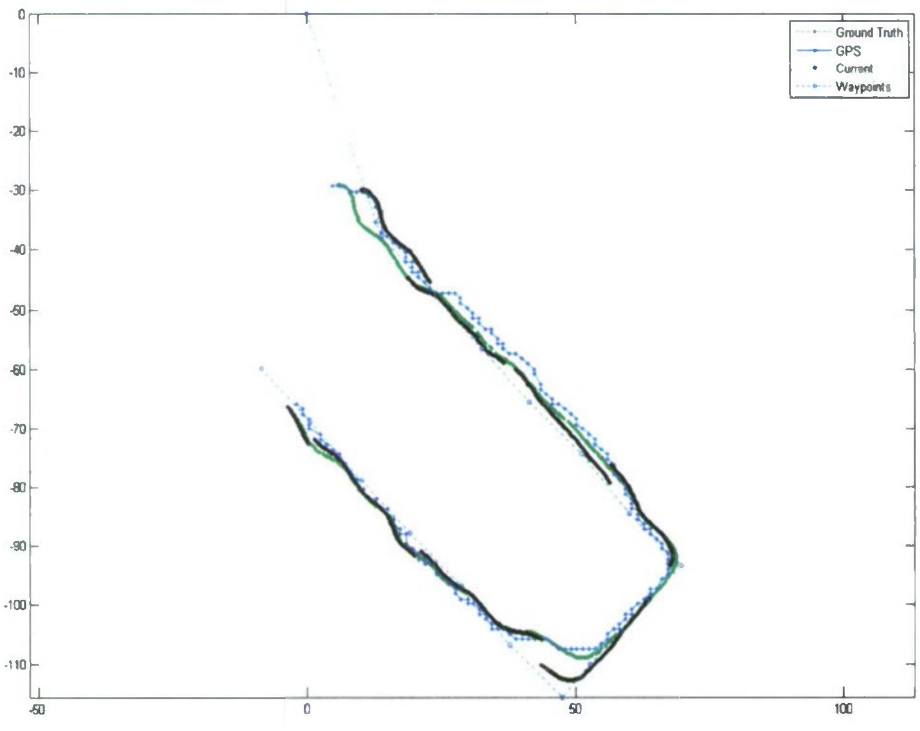

Figure 2. Kalman Filter Navigation Tests

Two AUVs were equipped with a magnetometer and six-channel data acquisition and six-axis inertial measurement units (DAU and IMU). Three channels of the data acquisition unit are dedicated to sample voltages corresponding to the three components of magnetic field provided by the magnetic sensor. Digitization of the three signals occurs at a resolution of 16 bits and at a rate of 120k Samples/channel. Each component of the magnetometer sensor is sampled at a rate of 12.5 kHz. The DAU is capable of storing 400 minutes (6.67hr) of magnetometer data at this rate. The six-axis IMU relies on solid state MEMS accelerometers and gyros. The accelerometers have a range of ±10g and an accuracy of 50μg. The gyros have a range of ±150°/sec and an accuracy of 0.0006°/sec. Experiments with AUVs having this configuration were conducted at the Acoustic Research Detachment (ARD) in Bayview, Idaho.

An extended Kalman filter (EKF) was used to improve the accuracy of on-board AUV navigation [2]. The magnetic measurements were correlated with a position relative to the surface vessel to an accuracy ~1 m. Presently, measurements available to the EKF are acoustic ranges to fixed transponders at known locations, the speed converted from propeller RPM, and the compass heading. Comprehensive tests on AUV navigation performance when using this EKF filter have been performed. Efforts have been completed to counter certain instabilities in position determination that can occur when acoustic ranging takes place with two transponders [3]. The on-board EKF has been subsequently extended to adaptively learn compass offset, and to incorporate IMU roll, pitch, and heading into the EKF estimate of AUV position. Testing of this filter was successful and took place in the Oct-Dec 2009 time-frame.

A preliminary EKF filter has been developed [2] to post-process sensor data logged by each AUV to obtain the best estimate of total magnetic field at the desired grid points relative to the surface vessel. The measurements available to the EKF are again acoustic ranges to fixed transponders at known locations; depth measured by the pressure transducer, speed converted from propeller RPM, roll, pitch, compass heading, and IMU roll rates and linear accelerations.

A shallow-water test range was developed at the Acoustic Research Detachment for experimental measurement of AUV navigation performance. A second range area is under development, at a depth of 200m. Each range is instrumented with bottom-mounted tracking nodes which are cabled to shore-based tracking systems. Each node can function as receiver, transmitter, and transponder. Each range can track multiple vehicles, each vehicle being equipped with an acoustic pinger. Tracking can be synchronous (known ping time) or asynchronous (unknown ping time). Accuracies of 0.2 m are possible for AUV tracking in the shallow-water range. The shallow-water range area is located inside the secured marina containing the docks for the base. The total area available for maneuvering within these waters measures about 130 meters in length and about 100 meters in width. The primary course is three sides of a rectangle that would represent two scans of a lawnmower search with a total length of 190 meters. The shallow-water test range is presently being used to assess AUV navigation performance; the second range will allow precision magnetic field measurements away from anomalous magnetic sources.

Acoustic characterizations of the AUVs were required in order to establish baseline references, vehicle capabilities, and limitations for future tests using the AUV as an acoustic sensor platform. Naval Surface Warfare Center Carderock Division (NSWCCD) was tasked with the responsibility of obtaining the AUV acoustic characterization data. The acoustic characteristics of the AUV were measured at the Acoustic Research Detachment (ARD) in Bayview, Idaho on October 9, 2008. Radiated, structure-borne, and platform acoustic data were acquired for one AUV in a static condition for both the individual sub-systems and the "whole ship." Radiated acoustic data were also acquired on another AUV in a free-running condition. Because of the emphasis by our sponsors on making magnetic measurements, the development of an acoustic AUV sensing system has been temporarily stopped until the magnetic AUV sensing system is functional.

RESULTS

As previously discussed, the two problems that a portable system must solve to successfully assess the magnetic (M) and acoustic signature of a vehicle are (1) accurate measurement of the field and (2) accurate location of the measurement relative to the vehicle. We have selected and purchased both a magnetic sensor and an acoustic sensor that can measure either field to the needed accuracy. We are in the process of minimizing the magnetic and acoustic noise of the AUV so that it will not negate the accuracy of the sensors. The initial results from using LBL navigation with 2 second updates with a Kalman filter shows that the required position accuracy needed to be able to successfully assess the magnetic (M) and acoustic signature of a vehicle is very feasible. Preliminary results show that a portable system for assessing the magnetic signature of a vehicle is realistic.

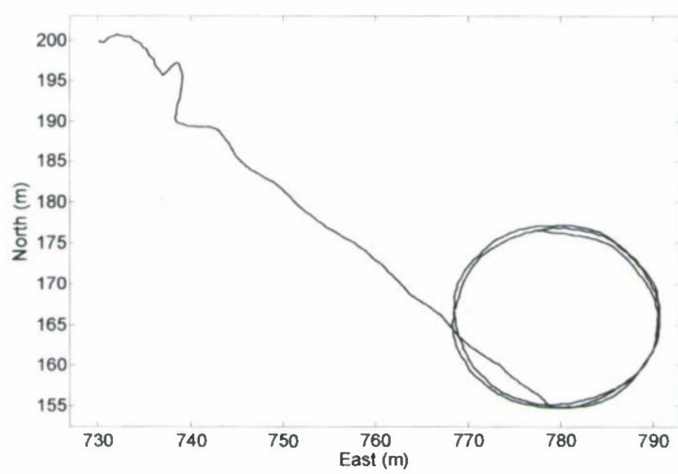

Figure 3. AUV magnetic measurement path while traveling underwater

Initial measurements with one AUV were taken in a static Earth field. Figure 3 shows the path of the AUV while operating one meter under the surface. After the dive was completed, the AUV travelled at a fairly constant heading to get away from any magnetic anomalies on the launching boat. Figure 4a shows the magnetic data recorded on the three axes and the calculated total field versus time while Figure 4b shows the heading, pitch, and roll of the AUV versus the same time scale.

Figure 5 shows a comparison of EKF position estimates used by the on-board AUV controller, the post-processed EKF position estimate, thetopside ground truth, and the intended waypoint path. The average error between the AUV controller and the topside track was 1.84m, and the average error between the post process EKF and the topside track was 0.74m. For this data the AUV controller received ranges at 30 second intervals while the post process EKF received ranges at 2 second intervals.

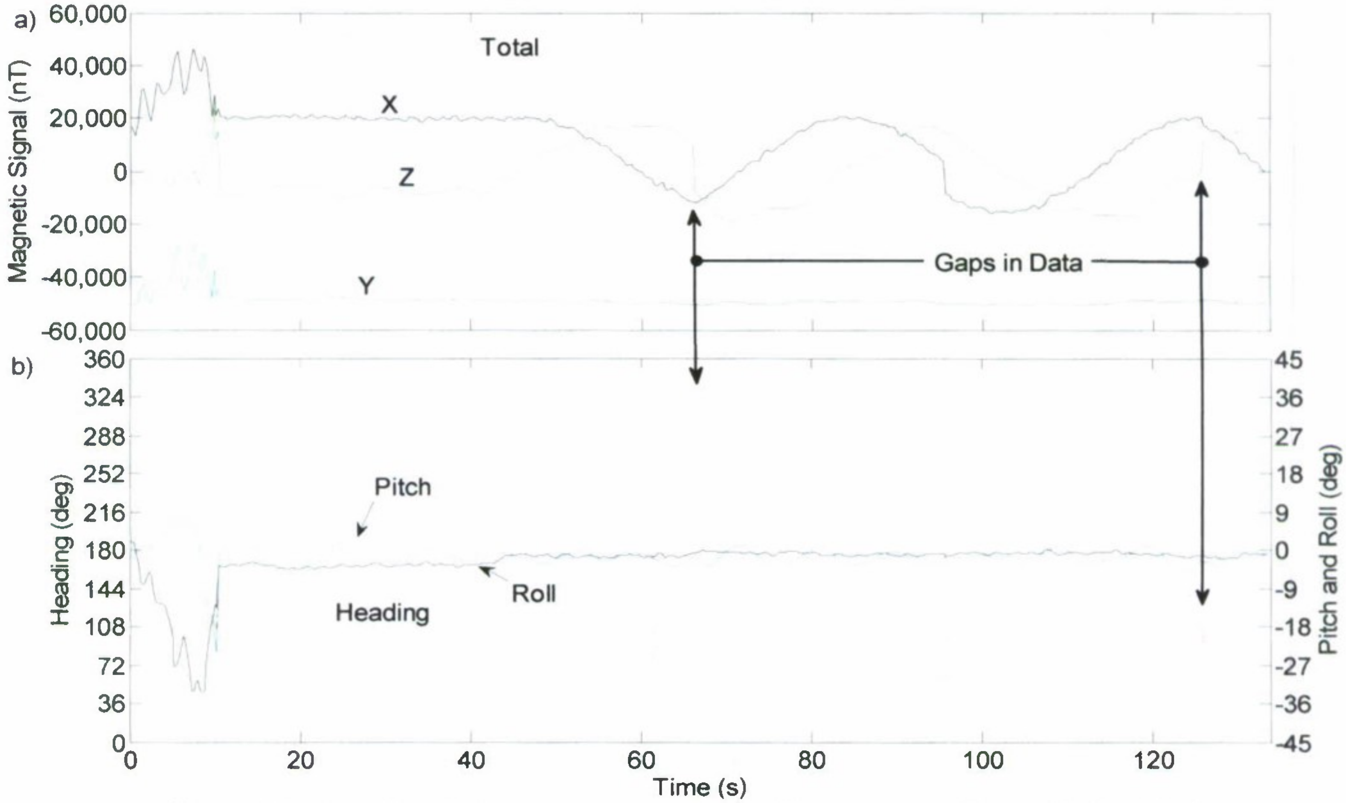

Figure 4: ***Experimental magnetometer data with corresponding vehicle attitude a)X,Y,Z components and total magnetic field magnitudes b)Heading, pitch, and roll of AUV***

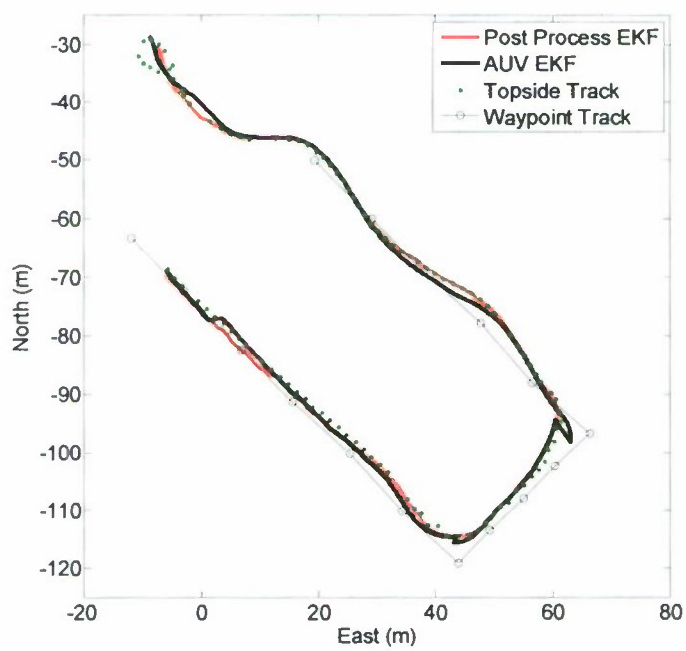

Figure 5. AUV navigation test course. Comparing on-board AUV controller, post-processed EKF, topside ground truth, and desired waypoint track

IMPACT/APPLICATIONS

Currently, ships and submarines are degaussed in a naval shipyard. While onboard systems allow the vessels to compensate for inevitable ship magnetic field changes acquired as a result of deployed transoceanic voyages, the missing piece is an accurate real-time assessment of those changes at their destinations. The portable assessment system being developed in this project would allow the magnetic signature of a ship to be determined and possibly degaussed anywhere in the world.

RELATED PROJECTS

This task leverages three previous ONR-funded projects, Decentralized Control of Multiple Autonomous Underwater Vehicles (ONR Grant N000140310634), Decentralized Control of Multiple Autonomous Crawlers and Swimmers (ONR Grant N000140310848), Communication and Control for Fleets of Autonomous Underwater Vehicles (ONR Grant N000140410506). In addition, small AUVs fabricated under another related project, Fabrication of a Fleet of Mini-AUVs (ONR Grant N000140410803), are being tested at Bayview under this project. Another related project is the Cooperative Autonomous Underwater Vehicles Used to Search Large Ocean Areas for Mines (ONR Grant N00014-08-1-0276).

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3. J. Pentzer*, B. Armstrong*, T. Bean, M. Anderson, D. Edwards, N.V. Schmehl, "Preventing Extended Kalman Filter Instabilities During Two Transponder Long Baseline Navigation with Real Time Fuzzy Logic Parameter Adjustment", *Proceedings of IEEE Oceans* 2009, 2009.

PUBLICATIONS

1. J. Pentzer*, B. Armstrong*, D. Odell*, T. Bean, J. Canning, M. Anderson, D. Edwards, "On-the-Fly Measurement of Surface Ship Acoustic and Magnetic Signature Using Multiple AUVs", *Proceedings of MSS Battlespace Acoustic and Seismic Sensing, Magnetic & Electric Field Sensorw (BAMS) Symposium*, 2009.
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