AN AT-SEA, AUTONOMOUS, CLOSED-LOOP CONCEPT STUDY FOR DETECTING AND TRACKING SUBMERGED OBJECTS

James Luby, J. Mark Stevenson, Vincent Keyko McDonald, Brian J. Granger, Peter Sullivan, Ryan G. Jones, and Andrew Huizinga
Space and Naval Warfare Systems Center
San Diego, CA

William S. Hodgkiss
Scripps Institution of Oceanography
La Jolla, CA

Bruce Howe, Robert T. Miyamoto, Matthew Grund, Greg Anderson, and Megan Hazen
Applied Physics Laboratory
University of Washington
Seattle, WA

Paul Hursky and Michael B. Porter
Heat, Light & Sound Research, Inc.
La Jolla, CA 92037

Mark R. Anderson
Metron, Inc.
Solana Beach, CA 92075

(Received September 12, 2008)

A concept study of autonomous, directed mobility conducted during the October 2007 persistent littoral undersea surveillance network sea trial (PLUSNet-07 or PN-07) is described. The study integrated the following key elements of the concept under investigation: (1) field node sensing, onboard signal processing, and contact/bearing reporting; (2) sensor information collection by communications relay gliders to a central, land-based, field controller; (3) fusing of in-field target detection and localization information; (4) generation of behavior modification messages that were then transmitted back to vehicles in the field; (5) vehicle response to recommendations; and (6) successful autonomous control of multiple assets. Specifically, we undertook a pilot study of an autonomous, closed-loop prosecution of a target whereby contact (detections with bearing estimates) and track reports from the field were solicited and received by means of a polling communications protocol by Seaglider vehicles and transmitted to a centralized base station for
further processing of field-level data. Reports from the various underwater assets were collated to provide a probable target location with a track developed over time. Once developed, the track was transferred to a tactical advisor algorithm that made repositioning recommendations to in-field vehicles for continued target prosecution by using identified target information, environmental information, and the current sensing node geometry to allocate system resources.

I. INTRODUCTION AND PROBLEM STATEMENT

Protecting vital sea lanes represents a growing priority for the U.S. Navy as sea-borne trade has more than quadrupled over the last four decades and now accounts for 90 percent of all international commerce and two-thirds of global petroleum trade. Since the end of the Cold War, the changing nature of underwater surveillance requirements reflects a gradual understanding that the impact of a maritime attack on a high-value United States asset could be significant to the Navy. Reflecting this, U.S. naval forces are shifting emphasis from operating sonars in deep waters to counter fast, deep-diving, nuclear-powered Soviet submarines to an emphasis on operating sonars in littoral waters to counter smaller submarines. The area of operations of these new, threat submarines are varied and often consist of complex shallow-water environments. These environments are characterized by complex acoustic propagation conditions and high levels of anisotropic noise due to commercial shipping, fishing, biological activity, and weather. Additionally, threat submarines may deploy from a variety of locations that are often in far forward areas not easily accessible by fleet assets. To deal with this threat, a sensing system must be capable of covert deployment in days from initial order, and operate for months to provide detection capability against threat submarines as they deploy, transit, and operate in their patrol areas. Sensors, systems, and concepts of operation (CONOP) must change to meet the challenges of these submarine threats.

Legacy Navy systems depended on fixed surveillance systems to cue tactical platforms that would then re-acquire, classify, localize, and prosecute threat submarines. This sequence often took hours to days to complete, was platform-intensive, and put the manned platforms at risk. In December 2004, the U.S. Navy approved a new antisubmarine warfare (ASW) CONOP. This concept shifts the Navy away from the traditional approach of operating large numbers of organic ASW platforms (aircraft, surface ships, and submarines) and toward a new approach that uses a smaller number of these ASW platforms in cooperation with unmanned vehicles and distributed sensor networks.

Through long-term Navy investment in technologies such as autonomous underwater vehicles (AUVs), in-node signal processing, compact sensors, environmentally adaptive sensor field approaches, and robust underwater connectivity, a capability is being developed to enable a change in the ASW approach. It is envisioned that AUVs will be able to deploy and operate as a distributed sensor field that can be controlled adaptively through an autonomous command, control, and communications (AC) architecture. This change in approach can reduce the prosecution time of threat submarines from days to hours and put them at risk while reducing the risk to friendly manned platforms.

To help address a small part of this problem, we sought to test one of the scientific principles underlying this change in approach to ASW. Specifically, while examining autonomous mobility in the detection of submerged objects, we sought to test the feasibility of an autonomous sensor platform to work under closed-loop control with an autonomous decision-making asset. This article describes the findings and observations that resulted from this test. The approach undertaken was built on seminal work by a number of innovative researchers to exploit the interesting capabilities that AUVs provide when applied in a passive undersea sensing role.

The outline of this article is as follows: Section II describes the experimental approach we undertook to conduct a closed-loop test of autonomous detection, decision-making, and redirection. Section III details the conduct of the
persistent littoral undersea surveillance (PLUSNet-07 or PN-07) event C-30, which was conducted in Dabob Bay, Washington, in October 2008, describing what events transpired while relying on a companion article in this issue of JUA(USN) to fill in technical details about how the data acquisition stage of the process was accomplished. Finally, section IV discusses the overall findings, observations, and lessons learned.

II. APPROACH

Figure 1 shows the general approach taken to demonstrate the concept of interest. The guiding idea was to conduct an experiment that consisted of eight sequential events that figuratively closed a loop. These events were:

1. Data acquisition by a submerged sensor platform;
2. Onboard data processing of raw acoustic data to provide messages of interest in the surveillance context;
3. Transmission of these messages from the submerged sensor platform to a submerged communications relay node;
4. Solicitation and reception of the messages by the submerged communications relay node using a polling communications protocol – also referred to as message “harvesting;”
5. Retransmission of the messages to a decision maker;
6. Decision making based on increased situational awareness provided by the messages’ content;
7. Communication of a decision back to the sensor platform to modify its behavior; and
8. Redirection of the sensor platform in a relevant way given the evolving ASW situation.

Submerged ASW sensing platforms (e.g., glider towed array system (GTAS)) patrolled a specified region of the operational area (OPAREA), attempting to detect targets. The target of interest was an Oasis mobile acoustic source (OMAS) transmitting narrowband tones at three frequencies (roughly 800, 900, and 1000 kHz) at output sound pressure levels of 120 to 140 dB re 1 µPa at 1 meter (m). At nominal separation distances between source and receiver (roughly 2 kilometers (km)), the estimated acoustic transmission loss in Dabob Bay varied from 55-70 dB for the frequency band of interest at representative depths of operation. Towed array hydrophone data were acquired in midwater column while the submerged sensor platform conducted patrol missions. These data were processed in the real-time signal processing system aboard GTAS using a digital signal processor (DSP) running detection and bearing estimation algorithms. Bearing to target was computed every 30 seconds (sec). The output of the signal processing pipeline was status, contact, and bearing information. The GTAS onboard the real-time signal processing suite did not calculate target depth or develop a target track.

Upon successful detection and bearing estimation, the ASW sensing platform summarized the relevant information (e.g., estimated contact, heading, and signature information) in a 32-byte PLUSNet compact control language (CCL) contact report. This report was then transmitted via the acoustic modem to one or more nearby Seaglider communications relay vehicles. The Seagliders stored the contact reports until they returned to the surface. At this time, they transmitted the reports to the command and control (C2) center via an Iridium satellite communications (SATCOM) link.

The system’s field control portion processed the data received from the sensing platforms via the Seagliders, determined how the sensing platforms should respond, and formulated 32-byte deploy or prosecute commands for transfer back to the ASW sensing platforms via the Seagliders. The Seaglider started its next dive and, upon reaching an appropriate depth, transmitted appropriate CCL-based deploy or prosecute commands to the sensing vehicles via acoustic communications.

The next section describes the event chronology as it transpired on 11 October 2007, when the culminating event of the PN-07 experiment, event C-30, demonstrated an autonomous, closed-loop prosecution of a target. In
In this event, contact reports from the field were harvested (i.e., solicited and received by means of a polling communications protocol) by nearby mobile communications assets (Seagliders) and transmitted to the network and field controller (NAFCON) and passed to Nodestar (a software program developed by Metron, Inc., that provides multitarget tracking), where the reports were fused to provide a probable target location with a track developed over time. This track report was transferred to the tactical advisor, which made vehicle movement recommendations to vector in those vehicles capable of repositioning ahead of the target for continued tracking, and recommendations to maintain sensor coverage behind the vehicle for acquisition of new targets entering the field. In completing this sequence of events, the feasibility of closed-loop cooperative behavior between mobile, unmanned surveillance assets was tested through field-level, directed-mobility for coordinating sensor platform movements to optimize prosecution of submerged targets.

III. EXPERIMENT CONDUCT

The PLUSNet-07 (PN-07) exercise was conducted from 2-12 October 2007 in Dabob Bay, Washington. A complete overview of the exercise is provided in an accompanying article in this issue of JUA(USN) by Stewart et al. One day of the exercise, 11 October 2007, showcased an autonomous, closed-loop, field-level detection, classification, and prosecution sequence of a simulated submerged target during a scripted event named, in the nomenclature of the exercise, event C-30.

Data Acquisition with the Glider Towed Array System

The apparatus used to acquire the acoustic data (Fig. 2) was the glider towed array system (GTAS). This apparatus was developed by the Unmanned Maritime Vehicles Laboratory and Advanced Research Branch within the Space and Naval Warfare Systems Center, Pacific (SSC-Pacific). It was a small, lightweight, low-power, autonomous sensing system based on sensing and telemetry technology used previously in a variety of configurations (i.e., fixed, vertical and horizontal, free-drifting, and towed) for more than two decades. GTAS was designed to incorporate

---

Fig. 1 — Overview of the concept under test
A DIRECTED MOBILITY CONCEPT STUDY

Fig. 2 — General schematic overview of the glider towed array system (GTAS)

a low-drag, low-power towed array, sensor data recording, real-time signal processing, underwater communications, and glider control into a small, low-power system integrated package with a Teledyne-Webb Research, Inc. Slocum glider (Fig. 3). A complete treatment of the system is provided in a companion paper in this issue of JUA(USN), but a brief description is provided next.¹⁵

Undersea glider locomotion departs from conventional propeller-driven unmanned underwater vehicle (UUV) propulsion by using the vehicle’s adaptively controlled buoyancy to create forward movement rather than relying on a propeller. A single-stroke piston, located in the forward hull section of a Slocum glider, uses a rolling diaphragm seal that moves 504 centimeters (cm) of water directly into and out of a 12-millimeter (mm) diameter port on the nose centerline. With the vehicle ballasted properly, this provides adequate negative buoyancy (piston pulled back and flooded with water) or positive buoyancy (piston pushed forward, expelling water and aft of piston filled with air) to cause the glider to fall or rise through the water column.

As the glider adjusts its buoyancy to ascend or dive, a pitch weight moves forward or aft, imparting the desired vehicle pitch or angle of attack. The wings convert the vertical force vector into a vector with a forward component. This allows forward translation when the glider is heavy and descending, and when light and traveling toward the surface. The buoyancy engine enables the glider to advance through the water in a sawtooth depth trajectory.

The Slocum undersea glider dead reckons to waypoints using an onboard navigation system. The glider pitch inflects at set depths based on operator-selected parameters within the mission text file and input from the glider’s depth and altitude-above-bottom sensors. Heading changes are achieved via an adjustable tail (rudder) controlled by a hydraulic steering motor. The glider periodically surfaces according to its pre-programmed instructions to communicate data and obtain a GPS location fix. Any difference in the dead-reckoned position estimate and the GPS-based reference position is attributed to water currents. Consequently, for more precise navigation, the vehicle’s intended heading for the subsequent segment is biased to account for the estimated water current vector. Additionally, while on the surface, the glider’s operators can provide a new mission program to the glider.

Reference 14 provides an excellent overview and understanding of the array technology and signal processing invoked in a prototypical system like GTAS. The array variant deployed during PLUSNet-07 consisted of 16 hydrophone sensors, 3 heading sensors, and 3 auxiliary devices. (Since then, two additional glider towed arrays (containing 16 and 32 elements) were developed for experiments off the coast of Kauai in the summer of 2008). The PLUSNet-07 array was 12-m long with an 8-m acoustic aperture. The acoustic sensors were spaced at 0.5 m for a cut frequency of 1500 Hz, with 7.5 kHz of available bandwidth. This array could theoretically provide about 12 dB of array gain with
standard planewave beamforming. The acoustic sensors implemented in the array were Benthos AQ-16 hydrophones having a sensitivity of roughly –198 dB re 1 V/μPa and response up to 10 kHz. Approximately 80 dB of dynamic range was available. There was one stage of fixed gain at the hydrophone preamplifier of about 50 dB and a subsequent 30 dB of adjustable gain that could be set in software. The array was not an oil-filled hose design. Instead, the cable was very thin (to minimize drag) and there were pods, or modules, along the length of the array containing hydrophones, floats (for distributed buoyancy), and engineering sensors. The sensor pods contained potted electronics to digitize the data and insert it into the time-division multiplexed intra-array telemetry scheme for communications via underwater electrical cable (with copper wire conductors) up to the vehicle. The pods were roughly 0.03 m in diameter at their widest point (Fig. 3). Noteworthy is the fact that – due to programmatic considerations – the array design was not initially undertaken with the PLUSNet experimental objectives in mind. It was a compromise between needing a lower frequency array for detecting a variety of submerged and surface targets and needing a higher frequency for a separate application that involved using ambient noise to map the bottom properties.
The onboard signal processing suite used an ORSYS micro-line C6713 compact board computer in the vehicle, with a 300 MHz, Texas Instruments, Inc. (TI) TMS320C6713 chip, 256 kB of internal static random access memory (SRAM), and 64 MB of external synchronous dynamic random access memory (SDRAM) residing on the ORSYS board and interfaced with the DSP chip dynamic access memory (DMA) controller. This was a nonstandard combination of processor speed and memory size specifically developed for GTAS. This board uses a floating-point DSP chip, which we opted for in favor of a lower-power fixed-point chip in the interest of initially prototyping the passive acoustic detection algorithms. An external flash drive and an external 2.5-inch (in.) (0.0635-m) hard drive (which allowed recording of all the raw data during testing) are interfaced with a micro-controller (that also communicates with the DSP chip, the array interface board, the WHOI micro-modem, and the vehicle control system).

The DSP chip communicates with a micro-processor through a high-speed, multi-channel buffered serial port (a McBSP port configured as a universal asynchronous receiver/transmitter (UART)). This gets the digitized array element data from an array interface board through another similar data port. The micro-processor is the controller of the system. It talks to a secure digital memory card (SD card) via a serial peripheral interface bus (SPI) interface, to the Woods Hole Oceanographic Institution (WHOI) micro-modem via a UART, to the vehicle science computer via a UART, and to the array interface board via a UART. The array interface board has a micro-controller and a field-programmable gate array (FPGA). The FPGA is attached to a hard disk drive (or solid state memory), which provides a completely independent data path (separate from the DSP processing) for recording the raw data. All sensor outputs are digitized locally at the sensor and, consequently, all telemetry is digital. Acoustic samples are provided over a differentially driven telemetry scheme, while all other auxiliary sensors provide data via a low-speed UART-based link (universal asynchronous receive/transmit). Each sensor has a common digital interface provided by this UART, which allows integration of different sensor types onto the array.

Beamforming is done on all frequencies, not just the frequencies detected at a single-element level. To accomplish this, a data matrix (16 elements × 5 scans) is extracted from the complex fast-Fourier transform (FFT) version of the data stored in SDRAM and passed to the beamforming algorithm resident in other allocated memory. The algorithm returns a buffer containing the power at each beam angle. The end result of the beamforming stage is a buffer in SDRAM that contains the beams (37 beams at 5-degree (deg) separation) for each frequency bin selected by the detector. A separate peak detection is performed at the output of the beamformer to provide a bearing angle for the beam that contains the highest power. The bearing angles for two contacts can be included in the contact report. Reporting consisted of frequency and bearing for the selected two contacts. In addition, a larger data set (all detected frequencies and beam data) was recorded to the SD card as well as a spectrogram and a compressed frequency vs azimuth (FRAZ) display. Once a contact report was issued, data were recorded to compact flash memory.

GTAS was deployed 9 times, for a total of 66 hours of run time during PN-07. Commandable, adaptive vehicle control with a towed array was implemented. Specifically, the glider’s control system was modified to allow vehicle navigation along a racetrack pattern and racetrack relocation through a NAFCON-generated deploy command. In the PLUSNet lexicon, this command is a specifically formatted CCL message sent via underwater modem that provides instructions to the glider’s onboard computer to undertake a particular surveillance-related behavior. GTAS demonstrated the ability to rotate its racetrack pattern for better target localization through the field of view (FOV) of the deploy command. Finally, the glider demonstrated an adaptively maximum depth excursion during its periodic dive pattern through the deploy command from NAFCON.

A newly designed interface between the Slocum glider’s navigation computer and the GTAS payload’s master controller was used in the PN-07 experiment. For example, vehicle position reporting was transferred to the GTAS master controller for inclusion in status reports. Waypoints were generated by the master controller from within fields received within the deploy command, and were conveyed to the vehicle’s navigation computer. The vehicle
then responded correctly to the new set of waypoints. Once coordinates of target conveyed to GTAS system were conveyed to GTAS through a prosecute command, GTAS demonstrated the ability to break way from its current racetrack loiter pattern and begin to close in on the target.

This PN-07 experiment saw the implementation of a detection and beamforming algorithm inside the onboard signal processing suite that generated approximately 500 status and 90 contact reports. GTAS responded to prosecute commands primarily by setting its threat frequency bands according to the target frequency field of this command. Absolute received spectral levels were computed and reported via the contact report. Analysis and feedback by the Metron analysts indicated that accurate beams to target were generated by GTAS. From 8-11 October 2007, full control of GTAS was handed over to either the Applied Physics Laboratory of the University of Washington (APL-UW) tactical advisor (on October 8 and 10) or the Pennsylvania State University (PSU) tactical advisor (on 9 and 11 October) to test different implementations of autonomy and control. At various times during this period, GTAS responded to deploy and prosecute commands, as discussed below.

**Sensor Information Collection by Seaglider Communications Relay Vehicles**

For the PN-07 experiment, five APL-UW Seagliders (Fig. 4) were deployed to support data communications between submerged ASW-capable vehicles equipped with (e.g.,) GTAS and a remote, land-based command and control (C2) center where field-level optimization and asset control functions were implemented. The Seagliders were equipped with WHOI acoustic micro-modems for sub-sea acoustic communications (ACOMMS) and Motorola Iridium modems for surface-based satellite communications (SATCOM) and thus provided an ACOMMS/SATCOM gateway between the submerged sensing vehicles and the land-based command and control center that consisted of NAFCON, Nodestar, and the tactical advisor.

Similar to the Slocum undersea gliders mentioned above, Seagliders move through the ocean in a series of ascending and descending glides. A typical descending glide begins with the Seaglider changing its volume to reduce its buoyancy and hence start sinking. Because the Seagliders have wings and are able to adjust their pitch angle, a component of the vertical buoyancy force can be transformed to a horizontal force, causing the glider to move forward. Pitch and heading angles are controlled by shifting an internal mass (battery pack) fore/aft and port/starboard, respectively. Upon reaching a pre-programmed depth, the Seaglider increases its volume to become positively buoyant and pitches up, resulting in an ascending glide back to the surface. Once at the surface, the glider takes a GPS position and logs into a land-based computer, hereafter the “base station,” via the iridium satellite network. While connected to the base station, the Seaglider uploads data (e.g., contact, track, and status reports) and, optionally, receives new operating instructions (e.g., new deployment waypoints or dive depth). When transmitting/receiving data to/from the base station is complete, the glider begins another dive.

Using this basic behavior, a glider can move from waypoint to waypoint or remain at a given waypoint (i.e., station-keep) while diving to a programmed depth. Human intervention is not required in this basic operation. However, if desired, a person (e.g., ASW command authority), or a piece of software (e.g., automated field controller) running on the base station or on another computer connected to the base station, can monitor and control the glider and thus exercise control of the entire surveillance system.

During PN-07 (in particular, during the scripted event labeled in the exercise nomenclature as event C-30), the PLUSNet system operated as follows: submerged ASW sensing platforms (e.g., GTAS) patrolled a specified region of the OPAREA, attempting to detect targets. Initially, GTAS was deployed in an operational state programmed to continuously provide detection. The OMAS target commenced a pre-programmed, submerged transit through the OPAREA. When the target was successfully detected, GTAS summarized the relevant sensing information (e.g.,
estimated contact heading and signature information) into a 32-byte PLUSNet CCL contact report and transmitted it via the acoustic modem to the nearby Seagliders. The Seagliders stored the detection/tracking packets until they returned to the surface, at which time they transmitted the packets to the C² center via the Iridium SATCOM link.

The PLUSNet field control portion of the system processed the data received from the GTAS sensing platforms via the Seagliders, determined how the sensing platforms should respond, and formulated 32-byte CCL PLUSNet deploy or prosecute packets for transfer to GTAS via the Seagliders. The Seaglider started its next dive. When the appropriate depth was reached, it transmitted the deploy or prosecute CCL packets to the sensing vehicle via ACOMMS.

During event C-30, the five deployed Seagliders handled all network communications (i.e., the bottom-moored ACOMMS-to-RF gateway buoys that had been used for other PN-07 tests were not used for this event). At the outset of event C-30, Seaglider SG116 was commanded to sit on the seafloor at a depth of approximately 170 m and conduct ACOMMS polling of other PLUSNet assets operating in the southern portion of the OPAREA. At the same time, the target began moving northward through the OPAREA.

During event C-30, the target initially approached from the south as Seaglider SG118 rested on the bottom of Dabob Bay and polled each of the ASW-sensing assets approximately once per minute. Seagliders SG117 and SG118 were in alternating 50-m dives near the middle of the OPAREA. Seagliders SG106 and SG107 were commanded to form a cluster in the northern portion of the OPAREA. The GTAS sensing node detected the target as it entered the southern part of the OPAREA. As the target moved northward, GTAS generated nine CCL contact reports. Six of those contact reports had valid headings, the others presumably were false targets. Seaglider SG106 picked up
three contact reports and relayed them to the base station about 12 minutes (min.) later. Seaglider SG117 picked one contact report and reported it approximately 1/2 hour (hr) after the initial series of contact reports generated by GTAS. These contact reports were fused by Nodestar into a track that was declared moments after reception of the Seaglider SG117 contact report. That report was sent to the DCL recommendation portion of the system in the C^2 command center.

**Initial Placement of Assets and Generation of Behavior Modification Messages**

Within the PLUSnet command and control architecture, algorithms were developed and implemented to automatically deploy nodes for area search and to automatically control nodes in response to confirmed tracks from Nodestar. The deployment of nodes for a target search used a system that calculates clusters of areas that have not been previously searched and also develops a coordinated deployment plan. The optimization metric is the probability of a target present that is adjusted by the sensor performance prediction and target diffusion to allow targets to re-enter an area once it is searched. If a track is received from Nodestar, then a coordinated deployment and/or prosecution plan is generated that takes into account the vehicle capability and the overall search plan, and minimizes the interception time by a mobile platform. Figure 5 provides the general message flow architecture and shows the software architecture of the detection, classification, and localization (DCL) field node recommendation.

Status and contact reports from the sensing nodes are relayed through the Seagliders to NAFCON and are necessary to adjust the probability of a target being present in an area. The probability of a target being present is reduced by the probability of detection in an area, given the position of the node and its sensor configuration. The general search planning would iterate over time, accumulating the change in probability of target presence, and readjust the search plan to maximize detection of a target. As tracks are provided by Nodestar, the plans are adjusted to determine which node is best positioned to intercept. The resulting plan is automatically provided to NAFCON as a recommendation to move a node to deploy and search an area, or to move directly to intercept (prosecute) a potential target.

The algorithm to conduct areas search for target detection first divided the overall area into smaller possible area of responsibilities (AOR) for vehicle deployment. A k-means algorithm has been adapted to cluster objects, based on geographic location and probability of target presence, into k partitions. The k-means algorithm attempts to find the centers of natural clusters in the data by minimizing total intracluster variance. The technique divides the search area into discrete pixels. Each pixel is currently assigned a value of 0 if it has < 25% probability of target presence, 1 otherwise. During clustering, only the nonzero pixels are joined using a Euclidian distance metric. This created compact regions that could be assigned to a mobile node. Within a contiguous cluster, a spatial probability density function (PDF) is used to fuse target probability of detections from all of the sensors into an overall probability of target present map. Regions with low probability of a target being present were not considered during clustering. Fokker-Plank equation models target drift and diffusion into areas where target probability is low and increases the probability over time of a target being present if no node returns to the area. An algorithm then assigns the vehicles to cluster geographical centroids by starting with the cluster with the highest mean probability of target and then assigns vehicles to each of the other areas without attempting to optimize the entire search area (also known as a “greedy” algorithm). Although this can result in suboptimum search efficiency, it is computationally much more efficient than attempting to perform a full multi-parameter optimization. Experience has shown that it provides nearly optimum search for the number of sensors that are available for the search space.

For PN-07, APL-UW implemented a terminal homing guidance algorithm to analytically solve intercept equations under a nonmaneuvering target assumption. Using exact nonlinear equations of motion in a plane, this guidance law’s objective is to minimize the interception time. It is assumed that a precise knowledge of the target’s motion is available. Unlike conventional guidance laws in which the commanded lateral acceleration is used, this technique
analytically solves for the trajectory to intercept a target by using vehicle heading as the control variable. For certain terminal missile guidance problems, the technique has been found to be superior, in terms of intercept time and miss distance, to two different proportional navigation laws, and it has been shown to require the least control energy expenditure among the three schemes. It worked very well for underwater vehicles during PN-07. Terminal guidance laws typically do not consider the pursuer to have a constrained area of operation (e.g., a geographic constraint) beyond which they are not allowed to travel. For PN-07, the guidance law was augmented with arbitrarily shaped, linear boundary constraints, guaranteeing that the computed target intercept location would always fall within the vehicle’s AOR. Even considering these constraints, the algorithm is fast enough to explore every possible assignment of $M$ assets to $N$ target tracks, where $M$ is greater than, less than, or equal to $N$. All combinations of intercepts are enumerated, and an exhaustive consideration of all rendezvous assignments are made for a sum of the time-to-rendezvous objective function. For PN-07, the result was the assignment of intercept solutions among the assets and target tracks, under the target maneuvering assumptions and cost functions described.

During approximately 6 hrs of event C-30, the APL-UW field recommendation software made 175 unique recommendations for area search, 47 track prosecution recommendations including 27 intercept solutions based on Nodestar tracks, of which NAFCON sent 19 to the field. During event C-30, GTAS was directed into position for interception of a target moving up from the south. During this event, three Seagliders were used as acoustic communications to satellite relays.

Multi-Level Data Fusion of In-Field Target Detection and Localization Information

The PLUSNet data fusion architecture can be most readily described in terms of the Joint Directors of Laboratories (JDL) data fusion lexicon. The JDL model identifies common processes, functions, and techniques that can be used for a wide range of data fusion applications.

The PN-07 experiment encompassed a diverse array of networked data sources. The primary data sources were mobile sensors that collect acoustic and environmental data within the operating area. Additional fixed nodes were used to collect radio-frequency (RF) signal and radar information. Environmental source information also came from a priori models and existing databases.

Nearly all of the PLUSNet source node platforms are equipped with embedded processors. These processors are used to pre-screen the incoming information and convert all data into engineering units. For the tactical acoustic platforms, this pre-screening process included thresholding the data to reduce clutter. Data were then formatted to
the compact control language (CCL) specification and communicated to a central shore-side control station through multi-hop RF and acoustic links.\textsuperscript{17}

Level 1 and level 2 processing are completed using the NodestarPlus\textsuperscript{TM} software program developed by Metron, Inc. NodestarPlus integrates and implements Nodestar and extended maximum a posteriori (XMAP) algorithms.\textsuperscript{31} Nodestar provides the level 1 tracking function and XMAP is used to perform level 2 track-to-track association.

Nodestar is a Bayesian nonlinear multiple-target tracker that has been deployed on several U.S. submarines. Nodestar represents target object position and velocity estimates in terms of probability distributions and uncertainty regions. For multi-target scenarios, Nodestar uses a soft association algorithm based on the probabilistic data association (PDA) method developed by Bar-Shalom and Fortmann.\textsuperscript{32} A map-based land avoidance feature was also implemented for PLUSNet. This feature was added to improve the tracking accuracy of submerged targets in littoral waters.

The track-to-track association problem solved by XMAP involves comparing track reports from two separate sensing systems to determine which tracks actually represent the same target. For this application, the track-to-track association method compares tracks developed from the PLUSNet acoustic sensors to tracks reported by surface vessel tracking systems.

Level 3 processing determines threat intent by isolating surface targets from subsurface targets. Acoustic target tracks that do not associate with any surface vessel tracks are most likely submerged target objects. PLUSNet is intended to focus on underwater targets, and it assumes that surface targets are tracked by other naval systems. As a result, submerged targets are considered more threatening and will receive a higher priority in the tactical response.

Formulating the appropriate tactical response is part of level 4 processing. This processing step was handled in PLUSNet by the APL-UW tactical advisor. The tactical advisor uses identified target information, environmental information, and the current sensing node geometry to allocate system resources.

The NAFCON program was designed and maintained by the Applied Research Laboratory at Pennsylvania State University. NAFCON was the primary interface between the underwater platforms and the shore-side data fusion processing components. NAFCON also served as the central data archive by collecting and storing test range and ground truth data.

NAFCON also served as the primary PLUSNet system display and human-computer interface. The NAFCON display contained the position and health information for each PLUSNet node as well as a graphical representation of the current tactical situation. Specialized human operator displays were also developed to monitor individual data fusion process components.

**Vehicle Response to Recommendations**

On 11 October 2007, a culminating event of the PN-07 experiment demonstrated an autonomous, closed-loop prosecution of a target. Contact and track reports from the field were harvested by nearby mobile communications assets (Seagliders) and transmitted to NAFCON and passed to Nodestar, where the reports were fused to provide a probable target location with a track developed over time. This track report was transferred to the tactical advisor, which made vehicle movement recommendations to vector in those vehicles capable of repositioning ahead of the target for continued tracking, and recommendations to maintain sensor coverage behind the vehicle for acquisition of new targets entering the field. Subsequently, GTAS received, acknowledged, and executed a deploy command that resulted in the glider conducting a turn to tighten the track solution on the target of interest.
IV. DISCUSSION AND LESSONS LEARNED

Legacy Navy system approaches have centered around the integrated undersea surveillance system’s (IUSS) cueing tactical platforms that then reacquire, classify, localize, and prosecute threat submarines. This sequence often took hours to days to complete, was platform-intensive, and put manned platforms at risk.

A proposed alternative for passive shallow-water ASW in forward areas using autonomous offboard sensors is embodied in the PLUS (persistent littoral undersea surveillance) concept. Through long-term Navy investments in technologies such as autonomous underwater vehicles (AUVs), in-node signal processing, low-power and compact sensors, and environmentally adaptive sensor fields, it is envisioned that a useful force multiplier can be provided to future ASW forces. AUVs that deploy and operate as a distributed sensor field will be controlled through an autonomous command, control, and communication (AC³) capability. This change in approach may reduce the prosecution time of threat submarines and put them at risk while reducing the risk to ownforce manned platforms and the overall manning requirement for friendly forces.

Although it is our vision that a field of lightweight, low-power, passive acoustic surveillance systems with long endurance will work in concert with mobile systems providing queuing and target signature sharing to provide important components in a complete ASW capability, experience suggests that lessons will be learned in association with the successful realization of this vision. Next, we elaborate on a few such lessons learned from this test.

During PN-07, vehicles were assigned areas for maneuvering that provided overall water space management to minimize collisions. This geographical constraint, implemented within the vehicle, limited the overall field control’s ability to task nodes to most effectively search for and prosecute targets. Nodes would only accept commands if the target were within the vehicle’s AOR at the time the message was received. With the field tracking working properly, a prosecute command could be issued with the target outside the AOR but with a target track that would take it into the node’s AOR. The other limitation was the latency of the messages arriving from the sensor nodes. When the Seagliders were the main communication pathway, many messages from sensor nodes arrived at the same time with many redundant messages. Without up-to-date information about sensor node status, an accurate estimate of probability of target presence could not be made.

Another intriguing point of discussion when considering potential end uses suggested by this concept study is whether it might be preferable to use a propeller-driven autonomous underwater vehicle rather than an undersea glider. Like many engineering studies, tradeoffs are involved. Reference 33 notes that undersea gliders, unlike propeller-driven autonomous underwater vehicles, use buoyancy change and wings to produce forward motion with minimal use of onboard battery power, i.e., about 1 W. By operating at slow speed (< 0.5 m/sec), long endurance can be achieved (i.e., over six months or over 3000 km). Undersea glider missions covering distances more than 3000 km and crossing major current regimes, e.g., the Gulf Stream, have been documented. For missions requiring extreme persistence, undersea gliders can hover using buoyancy changes alone. We know of no published data on the absolute acoustic radiated noise of an undersea glider, but the lack of propellers, gear motors, and associated machinery suggests that these instruments could be quieter than some propeller-driven undersea vehicles.

For gliders to be effective in the communications gateway role described here, there are additional questions and issues of interest. For example: how should a finite set of communication gateway gliders be distributed across a surveillance field to guarantee that one or more gliders will be within acoustic communications range and hence able to relay a high-priority contact packet to the C² command center via the glider network? Given that gliders take a depth-dependent amount of time to get to the surface, how can the latency of information flow from the sensing platforms to the ASW C² center be minimized? If a relatively long latency can be tolerated, which ultimately will
depend on the overall system operational concept, it may be reasonable to let the gliders continue to fly their pre-programmed dive paths, accepting the fact that the latency will be dependent on the depth the glider is programmed to descend to, and the glider ascent rate. If shorter latency is required, it may be better for the glider to change behavior when a high-priority target contact report is received and head to the surface at its maximum ascent rate. Or, if even shorter latency is required, it may make sense to deploy more than one glider at a given latitude/longitude and use coordinated control techniques to keep the Seagliders separated in depth. This is so that when one receives a high-priority contact, it can relay via acoustic communications the contact information to whatever Seaglider is nearest, or on, the surface.

During PN-07, we started to work on reducing glider-based communications latency. During event C-30, the Seagliders were deployed in two clusters, one having two gliders and one having three gliders. Glider pilots operating the Seagliders remotely from APL-UW developed control scripts designed to maintain depth separation between gliders operating in the clusters. The goal was to reduce ASW sensor report delivery latency. While reasonably successful, this approach involved humans studying the evolving scene and making changes to the glider’s control scripts. Ultimately, the goal is to have glider spatial separation, in both depth and horizontally, be controlled by an automated system that attempts to optimize data throughput, and to minimize data latency as the scenario evolves.

For practical considerations during the conduct of this study, the Seaglider communications vehicles were deployed in two clusters, one having two gliders and one having three gliders. These undersea vehicles were assigned areas for maneuvering that provided overall water space management to minimize collisions. This geographical constraint, implemented within the vehicle, limited the overall field control’s ability to task nodes to most effectively search for and prosecute targets for reasons discussed above. This, coupled with the fact that gliders SG-106 and SG-107 were programmed for 30-min. dive cycles, also had a mildly deleterious effect on message latency. For example, during event C-30, about 26 min. elapsed from the initial time that the target of interest entered the OPAREA before the first contact report was transmitted to NAFCON via the communications gliders. Then, another 41 min. elapsed before the formation of a target track by the Metron analysts was transmitted via underwater modem to GTAS, which was directed, by means of a deploy command, to close geographically with the target. Then, another 28 min. elapsed from the time GTAS updated the track solution and could be directed to intercept the target. Hence, for this particular event, the observed latency provided a general understanding of the time required for a representative sequence of actions and reactions, but the conduct of this particular experiment contained some practical artifacts and constraints based on safety of navigation and dive sequencing that might not be representative of, or warranted in, other field exercises.

V. CONCLUSIONS

The PN-07 experiment tested a heterogeneous, distributed, networked underwater sensor system that provided automated detection, localization, and interception using mobile nodes. The network implemented new, mobile, underwater-to-over-the-horizon communication relay. The field of sensors was controlled semi-automatically, including search placement, tracking of contacts (including association with surface contacts), and interception of targets.

The implementation of a common communication interface using off-the-shelf hardware allowed a variety of fixed and mobile nodes to operate together. Any platform could have joined the network automatically if it conformed to the defined network interface and was provided a unique modem identification. The networked system operated cooperatively. Targets could be localized using multi-node sensor fusion and then a mobile node assigned to intercept targets based on another node’s sensor data. Finally, most of the systems were launched from small vessels but yet could operate for an extended length of time.
VI. ACKNOWLEDGMENTS

The authors express their appreciation to the two reviewers whose observations and analyses improved the contents of this article. The authors are grateful to the many people who contributed to the successful conduct of the experiments, including the captain and crew of the Scripps Institution of Oceanography’s R/V New Horizon, shipboard resident technician Drew Cole, Marc Stewart, and Mitch Shipley. We acknowledge the hard work of Neil Bogue, Trina Litchendorf, Mike Boyd, Angela Wood, and Bill Felton who helped assemble, pilot, and recover the Seagliders. Special thanks are conveyed to Dr. Tom Curtin for his vision and support of the various endeavors that enabled a successful PN-07 concept study. Administrative and editing support was provided by Melanie Jones. Support with illustrations and graphics was provided by Virginia Wallace and Norman Tancioco from SSC Pacific, Code 85300. This work was supported by the Office of Naval Research, Code 32.

Next, the roles, responsibilities, and contributions of each author are described.

The team from the Applied Physics Laboratory at the University of Washington was led by Robert T. Miyamoto. The project manager for the Seagliders was Bruce Howe. James Luby provided the technical lead for the Seagliders, with assistance from Matt Grund who wrote the software for the Seaglider acoustic communications and modifications to the shore station for the networking. Greg Anderson and Megan Hazen provided the algorithms and interfaces for the asset allocation and response to target tracks from the tracking algorithms provided by Mark R. Anderson of Metron, Inc.

The team from Heat, Light, and Sound Research, Inc., was led by Michael B. Porter, who directed the research, development, and implementation of passive acoustic detection software used in this study. Paul Hursky invented, programmed, debugged, and implemented the detection algorithm and, together with William S. Hodgkiss and the MPL engineering staff, ported the software onto the digital signal processing chip and associated hardware used in the experiment. During and after the experiment, these authors were responsible for the signal analysis and documentation of observations and findings in the manuscript.

The team from the Space and Naval Warfare Systems Center, Pacific, was led by Vincent Keyko McDonald, who directed and conducted the experiment. The design team of Ryan G. Jones, Peter Sullivan, and Andrew Huizinga developed, produced, tested, and deployed the sensing, signal processing, and underwater communications hardware used in the experiment. During and after the experiment, these authors were responsible for the data acquisition, data analysis, and documentation. Brian J. Granger was responsible for the undersea glider development, modifications, deployment, data analysis, and documentation. J. Mark Stevenson prepared this manuscript and the preliminary analyses, with the help of all.

VII. REFERENCES


2. R. O’Rourke, Congressional testimony before the House Armed Services Committee Subcommittee on Projection Forces Hearing on Evolving Missions of the U.S. Navy and Surface and Subsurface Assets, 15 March 2006.

3. S. Schorer, Testimony before the United States Senate Subcommittee on Surface Transportation and Merchant Marine Commerce, Science, and Transportation Committee, 1 July 2002.


James Luby is a principal engineer and affiliate assistant professor of Electrical Engineering in the Electronic Systems Department of the Applied Physics Laboratory of the University of Washington (APL/UW). He received the B.S.E.E. degree in 1976 from the University of Connecticut, the M.S.E.E. degree in 1976 from Colorado State University, and the Ph.D.E.E. degree in 1984 from the University of Washington. His primary research is underwater acoustic signal processing including detection, estimation, adaptive array processing, and signal subspace methods. Secondary interests include automatic control systems, real-time systems, antennas, and telecommunications. Dr. Luby has been with APL-UW since 1979.

J. Mark Stevenson graduated from the U.S. Naval Academy and Scripps Institution of Oceanography. His doctoral work was on submarine gravimetry and included the first absolute gravity measurements aboard a submarine. While a member of the Acoustic Branch of the Space and Naval Warfare Systems Center, San Diego, his research included design and deployment of low-power acoustic measurement arrays for use under the Arctic icecap and in shallow-water coastal environments. He served at the NATO Undersea Research Centre from 2002 to 2007.

Vincent Keyko McDonald received his B.S. degree in mathematics and M.S. degree in electrical engineering from San Diego State University in 1988 and 2004, respectively. Since 1988 he has worked at the Space and Naval Warfare Systems Center in San Diego, CA, where he has been designing and managing the development of underwater surveillance systems. More recently, he has been conducting research in underwater acoustic communications.

Brian J. Granger received his B.A. in combined physics/mathematics from Whitman College, a B.S. in Mechanical Engineering from Columbia University, and an M.S. in Information Systems Management from Webster University. Following his undergraduate work, he was commissioned in the U.S. Navy and served seven years in the Submarine Service. In 2001, he began his career as an engineer and project manager for the unmanned maritime vehicle laboratory at SPAWAR Systems Center, San Diego, where he specializes in sensor integration onto autonomous underwater vehicles. He is currently the commanding officer for Navy Reserve Deep Submergence Unit, Detachment San Diego.

Peter Sullivan holds an M.S. degree in Electrical Engineering, with emphasis on embedded systems. He joined the Advanced Research Branch of SSC-Pacific in 2004. His contributions to the development of lightweight sensing systems include analog design, digital interface design, array manufacturing techniques, and support of sea testing.

Ryan G. Jones served 4 years as an avionics technician in the U.S. Navy before receiving his B.S in Electrical Engineering from San Diego State University. Currently he works at SPAWAR Systems Center Pacific in the Advanced Research Branch. As a lead design engineer he has focused on real-time signal processing applications, low power sensor interfacing, embedded systems, and PC software development.

Andrew Huizinga has worked with the Advanced Research Branch at SPAWAR Systems Center Pacific for five years. He has an M.S degree in Electrical Engineering from Michigan State University and has developed several low-power array data recording systems for fixed and mobile platforms during his time at SSC. He is also one of the chief designers of SSC’s lightweight, low-power array technology.

William S. Hodgkiss received the B.S.E.E. degree from Bucknell University, Lewisburg, PA, in 1972, and the M.S. and Ph.D. degrees in electrical engineering from Duke University, Durham, NC, in 1973 and 1975, respectively. From 1975 to 1977, he worked at the Naval Ocean Systems Center, San Diego, CA. From 1977 to 1978, he was a faculty member in the Electrical Engineering Department at Bucknell University. Since 1978, he has been a member of the faculty of the Scripps Institution of Oceanography and on the staff of the Marine Physical Laboratory, where he is currently the deputy director. His present research interests are in adaptive array processing, propagation modeling, and environmental inversions with applications to those in underwater acoustics and electromagnetic wave propagation.

Bruce Howe received the B.Sc. degree in Mechanical Engineering in 1978 from Stanford University, the M.Sc. degree in Engineering Science in 1978 from Stanford University, and the Ph.D. degree in Oceanography in 1986 from University of California, San Diego. Dr. Howe’s expertise is in ocean acoustic tomography. Recent research includes the Acoustic Thermometry of Ocean Climate (ATOC) and North Pacific Acoustic Laboratory (NPAL) projects, studying large-scale ocean variability, acoustic propagation over long ranges, and ocean ambient sound. Dr. Howe has also participated in the development of ionospheric observing systems using GPS signals in a tomography mode. In summer 2008, Dr. Howe became a professor in the Ocean and Resources Engineering Department at the University of Hawaii at Manoa.
Robert T. Miyamoto is the associate director and affiliate associate professor of Electrical Engineering at the Applied Physics Laboratory of the University of Washington (APL/UW). He received the B.A. degree in Mathematics and Physics in 1973 from the University of California, Irvine. His present research interests are ocean acoustics, physical oceanography, and signal processing. As associate director for applied research and technology at APL/UW, he is responsible for finding new investigative opportunities, bringing together scientists and engineers across departments and forging communities of applied research to solve problems primarily for the U.S. Navy. He joined APL/UW in 1979; from 1993-2002 he served as the head of the Environmental and Information Systems department.

Matthew Grund was previously a research engineer in the Applied Ocean Physics and Engineering Department of the Woods Hole Oceanographic Institution. He received the B.S. degree from the University of Lowell in 1992 in Electrical Engineering and the M.S. degree from the University of Massachusetts in 1996 in Electrical and Computer Engineering. His research interests include: underwater acoustic communications, acoustic navigation, marine mammal acoustics, embedded signal processing, embedded data acquisition, and distributed multiprocessing. He is presently an engineer in the Electronic Systems Department at the Applied Physics Laboratory of the University of Washington.

Greg Anderson is a senior engineer in the Environmental & Information Systems (EIS) Department of the Applied Physics Laboratory of the University of Washington (APL/UW). He received the B.S. degree in Agriculture in 1974 from the University of Idaho, a B.S. degree in Applied Mathematics in 1975 from the University of Idaho, and the M.S.E.E. degree in 1980 from the University of Idaho. He has experience in systems engineering, digital simulation, statistics, optimization, expert systems, and object-oriented programming. His current work includes estimating parameters for ocean environmental models from acoustic reverberation measurements, constructing a data storage and analysis system for environmental parameters, and developing a CD-ROM-based system for training firefighters in the handling of hazardous materials.

Megan Hazen is an Engineer in the Environmental & Information Systems (EIS) Department of the Applied Physics Laboratory of the University of Washington (APL/UW). She received the Ph.D. degree in Electrical Engineering in 2008 from the University of Washington, an M.S.E.E. degree in 2004 from the University of Washington, an M.S.M.E. degree in Computational Design in 1999 from Carnegie Mellon University, and the B.S.M.E. degree in 1997 from Carnegie Mellon University. Dr. Hazen specializes in intelligent systems such as neural networks, fuzzy logic, and optimization. Her recent research been to develop global optimization techniques for intelligent design and control. Since joining APL/UW in 2000, Dr. Hazen has worked on numerous projects for simulation of ocean sensor behavior and optimal control and deployment of those sensors.

Paul Hursky is the chief engineer at Heat, Light and Sound Research, Inc. (HLS Research). He received the B.S. and M.S. degrees in Physics from the University of Pennsylvania. He received the Ph.D. degree in Electrical Engineering in 2001 from the University of California, San Diego. His present research interests include physics-based signal processing, propagation modeling, inverse problems, and acoustic communications. Dr. Hursky is a physicist/electrical engineer working on research problems in underwater acoustics. At Lockheed-Martin from 1980 to 1999, Dr. Hursky worked on ASW applications on P3/S3 platforms. While at Lockheed, and later SAIC (1999 on), he obtained a doctorate in electrical engineering from UCSD. At SAIC, he worked on a number of ONR-funded research initiatives, including adjoint models, acoustic communications, biologically inspired sonar, marine mammal tracking, and high-frequency tracking.

Michael B. Porter is the president of Heat, Light and Sound Research, Inc. He received the B.S. degree in Applied Mathematics in 1979 from the California Institute of Technology and the Ph.D. degree in Engineering Sciences and Applied Mathematics in 1984 from Northwestern University. His present research interests include underwater acoustics, communications, acoustical oceanography, signal processing, marine mammal acoustics, scattering, and inverse problems. In 1991, he was awarded the A.B. Wood Medal and Prize (Institute of Acoustics). His previous experience includes teaching, research, and administrative positions at Science Applications International Corp., San Diego, CA; the New Jersey Institute of Technology, Newark, NJ; SACLANT Undersea Research Centre, La Spezia, Italy; the Naval Research Laboratory, Washington, DC; and the Naval Ocean Systems Center San Diego, CA.

Mark R. Anderson received a B.S.M.E. from Purdue University in 1983. He later earned M.S.E. and Ph.D. degrees from the School of Aeronautics and Astronautics at Purdue University in 1984 and 1988, respectively. Dr. Anderson has served on the AIAA Guidance, Navigation, and Control Technical Committee, the SAE Guidance and Control Technical Committee, and as a Director of the American Automatic Control Council. Over the last 20 years, Dr. Anderson has published nine journal articles, more than 30 conference papers, and numerous technical reports in navigation and control engineering.