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Lightweight Autonomous Underwater Vehicles (AUVs) performing coastal survey operations in REP 10A

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Abstract Lightweight Autonomous Underwater Vehicles (AUVs) were developed for Naval Special Warfare (NSW) Group 4 search and survey missions from a commercial AUV baseline (Iver 2) through integration of commercial off-the-shelf (COTS) hardware components, and through software development for enhanced on-board Command and Control functions. The development period was 1 year under a project sponsored by the Office of Naval Research TechSolutions Program Office. Hardware integration was completed by the commercial AUV vendor, OceanServer Technology, Inc., and software development was conducted by the Naval Undersea Warfare Center, Naval Oceanographic Office, and U MASS Dartmouth, with support from hardware and software application providers (YSI, Inc., Imagenex Technology Corp., and CARIS). At the conclusion of the integration and development period, an at-sea performance evaluation was scheduled for the Lightweight NSW AUVs with NSWG-4 personnel. The venue for this evaluation was the NATO exercise Recognized Environmental Picture 10A (REP 10A), hosted by Marinha Portuguesa, and coordinated by the Faculdade de Engenharia–Universidade do Porto. REP 10A offered an opportunity to evaluate the performance of the new AUVs and to explore the Concept of Operations (CONOPS) for employing them in military survey operations in shallow coastal waters. Shore- and ship-launched scenarios with launch/recovery by a single operator in a one-to-many coordinated survey, on-scene data product generation and visualization, data push to Reach Back Cells for product integration and enhancement, and survey optimization to streamline survey effort and timelines were included in the CONOPS review. Opportunities to explore employment of hybrid AUV fleets in Combined Force scenarios were also utilized. The Naval Undersea Warfare Center, Marinha Portuguesa, the Faculdade de Engenharia–Universidade do Porto, and OceanServer Technology, Inc., were the primary participants bringing in-water resources to REP 10A. Technical support and products were provided by the Naval Research Laboratory–Stennis Space Center, Naval Oceanographic Office, NATO Undersea Research Centre, University of Massachusetts–Dartmouth, and YSI, Inc. REP 10A proved to be a very effective exercise in meeting each of the critical goals. Results of the performance evaluation guided final development and Independent Verification and Validation (IV&V) for the Lightweight NSW AUV, leading to on-time, successful Factory Acceptance Testing and delivery of the three contracted vehicles to NSWG-4 in September, 2010.

Keywords Lightweight autonomous underwater vehicles · Environmental surveys · Naval Special Warfare · Recognized Environmental Picture 10

1 Introduction

In 2007, Naval Special Warfare Group 4 (NSWG 4) arranged for the procurement of four Iver 2 Autonomous Underwater Vehicle (AUV) for evaluation in an operational setting (Anderson et al. 2007). The AUVs were purchased as a commercial "off-the-shelf" product with no modifications of software or hardware to address unique military requirements. After a brief familiarization period, the Iver 2

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AUVs were deployed with Special Boat Team (SBT) 22 in the SW Asia theater and utilized in local search and survey missions. Operations and maintenance on the AUVs were performed by an Aerographer's Mate embedded in SBT 22. Personnel from the Riverine Squadrons and SEAL Team 5 were trained locally on Iver 2 operations, and they utilized these assets in their independent operations.

Over the next year of Iver 2 AUV operations and field evaluation, NSW Group 4 assembled a list of capabilities and system improvements required to realize full benefit of the Iver 2 AUVs in tactical applications and to support consideration as a future acquisition item. This list included additional sensors for integration, as well as changes to existing software. Specifically, the list comprised:

(a) Integration of the Imagenex Delta T multibeam sonar currently utilized in the US Navy Expeditionary Multibeam Kit (EMK)
(b) Integration of Iridium communications hardware with provision for two-way Short Burst Data (SBD) communication
(c) Integration of a DVL/ADCP system for navigation accuracy and current profiling
(d) Integration of a lightweight temperature/conductivity sensor
(e) Development of on-board Command and Control (C2) software to promote survey optimization and enhance vehicle safety
(f) The ability to develop on-scene products using software applications already familiar to the user community (FalconView, CARIS, and OceanServer Technology, Inc. VectorMap)

The integration of these components would complement the existing suite of sensors and capabilities already provided in the baseline Iver 2 AUVs, such as the dual-frequency side-scan sonar, and the navigation and communication systems.

The Office of Naval Research (ONR) TechSolutions Program Office reviewed a proposal from NSWG 4 to have OceanServer Technology, Inc. perform the integration of existing commercial components on the baseline Iver 2 AUV, and to task the Naval Undersea Warfare Center Division, Newport with project oversight, C2 software development and integration, and implementation of Iridium communications. The ONR TechSolutions Program Office awarded funding to the project in late fourth quarter FY09 and FY10. Preliminary evaluation of the Lightweight NSW AUVs was completed during the mid-project demonstration in March 2010, and a full operational evaluation of the three Lightweight NSW AUVs was conducted in association with the NATO Undersea Research Centre (NURC) exercise Recognized Environmental Picture 2010 (REP 10). Results from the Recognized Environmental Picture 2010A (REP 10A) exercise were used to drive final development and Independent Verification and Validation (IV&V) design, and led to successful Factory Acceptance Test (FAT). The delivery of three Lightweight NSW AUVs in SEP 2010 with training and documentation completed the project tasking.

1.1 Recognized Environmental Picture 2010

REP 10 was organized and scheduled under NURC leadership to sequentially address operational and tactical oceanographic objectives in two locations: 1. the Gulf of Cadiz near the western entrance to the Gibraltar Strait (REP 10A) and 2. the western Alboran Sea (REP 10B). The Gulf of Cadiz would support operational evaluation of low-powered AUVs in shallow water or near shore operations, augmenting the deep water assets for environmental characterization and providing a Rapid Environmental Assessment (REA) capability for shallow water and amphibious operations. The operational test of the Lightweight NSW AUVs was planned to be embedded in REP 10A scenarios and mission design. Rescheduling and relocation of REP 10A due to changes in ship schedules led to a hosting of the exercise by Marinha Portuguesa near Sesimbra, PO. Faculdade de Engenharia–Universidade do Porto provided the liaison for international participants, and NURC maintained endorsement. The Naval Special Warfare Group 4, Naval Undersea Warfare Center Division-Newport, OceanServer Technology, Inc., and YSI, Inc. had personnel and equipment on site, and UMASS Dartmouth and the Naval Research Laboratory (NRL) supported the exercise with data processing, management, review, and modeling.

REP 10 A was conducted primarily from the Marinha Portuguesa ship NRP Bacamarte (Fig. 1a,b) during 8 days in roughly 50 m water depth west of Troia, PO. The ship provided underway opportunities and anchored for a portion of the time to support launch and recovery of some of the larger AUVs and USVs participating from the Marinha Portuguesa AUV squadron and the Faculdade de Engenharia–Universidade do Porto research group. Approximately one dozen mine shapes and decoys were seeded in the OPAREA as targets for AUV and USV sonar missions. Rigid Hull Inflatable Boats (RHIBs) and a Marinha Portuguesa Dive Squadron were assigned to NRP Bacamarte during the exercise to support evolutions. Two opportunities were provided for shore launch of the Lightweight NSW AUVs, with personnel and AUVs delivered to the beach for deployment (Fig. 1c). Missions preloaded on the AUVs were enabled with a delayed start, and rapid launch sequences (<2 min) were completed for multiple AUVs. The AUVs completed the missions in assigned coastal areas and maintained designated stations offshore until recovery.

Fig. 1 **a**–**c** The NRP Bacamarte of Marinha Portuguesa provided services and served as a transport and launch platform for AUVs during REP 10A. The Lightweight NSW AUVs were launched sequentially while underway at 5 kt from the vessel quarter using a canvas sling. Approximately 2 min were available between launch points to prepare and deploy the AUVs. Shore launch of multiple vehicles was easily accomplished in <0.5 m of water depth using a delayed launch, with a total launch sequence of <2 min for multiple AUVs

Operational evaluation of the Lightweight NSW AUVs in REP 10A is characterized in four areas: Capability, Operability, Reliability, and On-Scene Products.

1.2 Capability

Capability was evaluated for both component and system performance. In every case, individual sensor components demonstrated good function and met the performance metrics. However, some design improvements were highlighted during the course of the exercise. Integrity of the mounts under shock loads during shipping was problematic for both a card and sensor in one of the three AUVs, and this led to a more robust solution for delivery. Additionally, electronic noise from a faulty sonar module wiring bracket affected communication and navigation component performance, leading to redesign by the manufacturer for increased reliability. Platform characteristics were assessed to ensure that control surface algorithms and responses supported maneuvering requirements and thresholds established by NSWG-4 in the performance specification. Particular attention was given to characteristics affecting navigation, vehicle safety (e.g., overshoot associated with depth changes, or excessive roll during turns) and sensor performance (e.g., excessive vehicle motion while line- and depth-keeping). Log files for each mission store some 40 parameters recorded at 1 Hz for post-mission evaluation, and individual sensor logs host detailed instrument-level data for analysis. Figure 2a–j illustrates a subset of the complete platform and sensor performance analysis completed for each mission of the individual AUVs. This subset illustrates the effects of control algorithms, which effect platform efficiency, endurance, and sensor performance.

Depth management, roll, and pitch control were consistently within the objectives for every mission. Heading variability was excessive and had potential to compromise sonar performance and products at extended ranges even with algorithmic cancellation of platform motion. Post-REP10 improvements to control algorithms for yaw fin correction during line tracking reduced heading variability to within 6° maximum (3° mean) either side of the Next Heading value, correcting for the hydrodynamic changes to the baseline OceanServer AUV introduced in the development of the Lightweight NSW AUV (Fig. 2j).

Navigation precision and accuracy were also evaluated for 2 km submerged transits with DVL lock and determined to meet the 5% threshold required for combined range and bearing error. Iridium integration was not completed for this operational test, and this was the sole component of the project specification not evaluated with REP 10A data. This capability was effectively implemented and successfully tested following REP 10A. The Iridium communications protocols were established on the secondary CPU utilizing the Mission Oriented Operating Suite (MOOS) architecture (Newman 2002). SBD transmission was adopted to provide a status and position update each time the AUV surfaced for a GPS fix as an initial implementation. Two-way SBD communication will be utilized for mission control in future releases, and automated routines for parsed and formatted data transmission are targeted for demonstration in Talisman Sabre 11 to support Special Operations Forces missions.

Fig. 2 **a** Vehicle depth (meters) versus time (seconds) for a portion of the mission illustrates the response to changing depth commands (Next Depth). Shallow dives are selected in this example to provide a scale suitable to evaluate depth-keeping ability. Note that depth overshoot is insignificant, and variations from commanded depth are typically with 0.1 m. In dives with tens of meters of depth change and dive angles approaching 25°, depth overshoot proved to be consistently <1 m. **b** Vehicle heading (degrees T) versus time (seconds) for a portion of the mission illustrates the response to changing heading commands (Next Heading). Divergence from Next Heading with course change commands of >100° occur at the surface and illustrate the relative inefficiency of surface maneuvers. Oscillations in vehicle heading with a constant Next Heading value are indicative of noise introduced by the control algorithm. **c** Vehicle heading (degrees T) versus time (seconds) for a 125-s submerged portion of the mission while on a constant Next Heading illustrates the oscillations introduced by the control algorithm. There are 16 cycles completed in 120 s, using paired 5° monotonic heading changes to define a cycle. The oscillations are characteristically of 8-s period with a median heading change of 13°. **d** Vehicle roll angle (degrees) versus time (seconds) is charted at 1 Hz in *blue* for a 900-s portion of the mission that includes two submerged legs on opposite bearings. Vehicle depth (feet) is represented in red, and Motor Speed is charted in green. Surface intervals are characterized by large roll angles from surface waves and motor speed changes with control surfaces at minimal effect. Submerged legs represented in this graph were run without active roll control, hence the positive offset from motor torque. The median for the two submerged legs were 11° and 16°, respectively, and the averages were the same. The difference in offsets is a result of the increased motor torque on the second leg required to maintain a programmed speed over the bottom against the current. Standard deviations on both legs were <2°, with a variance of 4.0° and 3.3°. **e** Vehicle pitch angle (degrees) versus time (seconds) for a portion of the mission illustrates the feedback nature of control behaviors. Oscillations in vehicle depth while submerged are a result. **f** Vehicle pitch angles (degrees) versus time (seconds) for a 140-s submerged portion of the mission while on a constant commanded depth illustrate the oscillations introduced by the control algorithm. There are 18 cycles in this segment, using paired 2° monotonic pitch changes as a threshold in the definition of a cycle. The cycles have an approximate period of 8 s, with an SD of 1.7° and a mean of −0.8° pitch. **g** The Number of Satellites acquired for a GPS fix and the Depth From Surface versus time (seconds) for a portion of the mission indicate the very rapid and dependable acquisition of GPS satellites for navigation when resurfacing. Steady positional fixes with >8 satellites are typically supported just 3 s after the vehicle has acquired the surface. The inset scatter plot indicates positional data while surfaced with no power and drifting to the South and West over a 36-s period. The excellent GPS positional data is typical of this configuration. **h** Vehicle pitch angle (*blue*, in degrees) and pitch fin setting (*red*) versus time (seconds) for a portion of the mission are compared to tune algorithms for control surfaces. An evaluation of vehicle response supports optimization of the algorithms to provide sufficient control authority while minimizing platform motion noise. **i** Vehicle pitch angle (*blue*, in degrees) and pitch fin setting (*red*) versus time (seconds) for a 40-s portion of the mission present the details of platform motion. A 6-s cycle in pitch fin motion occurs (neutral position is 128), with a resulting average displacement of 3.7° in pitch from maximum to minimum. The average maximum up pitch is 1.1°, and the average maximum downpitch is 1.7°. Vehicles require a net downpitch during submerged runs because of the positive buoyancy of the vehicles (approximately 1% of dry weight). Pitch fins are locked to provide a 5° uppitch angle when runnning at the surface to prevent porpoising and support continuous GPS fixes and RF commnications. **j** Vehicle heading (degrees T) versus time (seconds) for a 140-s submerged portion of the mission while on a constant Next Heading illustrates the significant reduction in vehicle motion provided by improved control algorithms introduced as a result of operational evaluation in REP10A. There are 10 cycles in 140 s, using paired 2° monotonic heading changes to define a cycle. Before the new algorithm was implemented, there were 16 cycles in 120 s with a 5° cycle definition. The oscillations are characteristically of 14-s period (versus 8 s) with a median heading change of 3° (versus 13°). Note the fixed offset from Next Heading is a correction for set and drift applied by the navigation routines based on course over ground

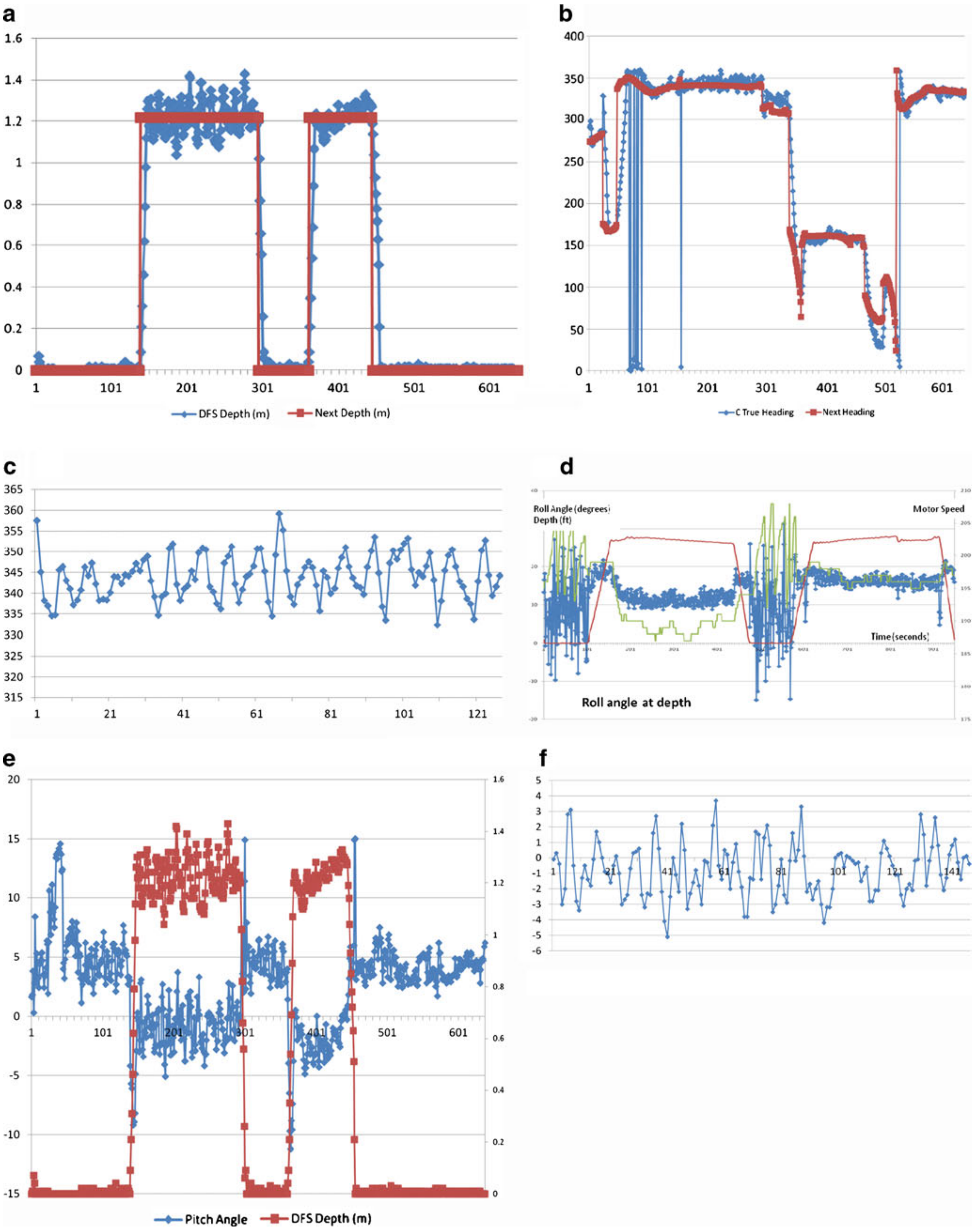
The Li ion battery chemistry and controller resulted in nearly linear discharge rates of approximately 1 Wh/min of operation at 2.5 kt with a towfloat. The discharge rates proved constant over the entire range of battery state (100% to <5%), allowing extrapolation of total endurance despite mission durations that were typically 1.5–4.0 h. With a total capacity of 570 Wh, the AUVs could operate for 8 h with the typical REP 10 mission profile (2.5 kt speed over the bottom, all sensors operating, with emergency towfloat) before impinging on the 10% power reserve.

1.3 Operability

Operability of the system proved excellent in REP 10A, and reinforced experiences from the mid-project demonstration. It was evaluated in terms of mission planning and review, AUV launch/recovery, and field maintenance/repair.

Mission planning and review were conducted using the OceanServer Technology, Inc. VectorMap software. Selection of imagery or electronic charts from a very broad choice of formats and sources provided a multilayer georeferenced backdrop for mission planning using standard Windows-based interfaces for waypoint selection and trackline design. A host of supporting tools assists the operator in automatically assigning track spacing relative to water depth, selected coverage, and many other parameters associated with the multibeam or side-scan sonar performance. A selection of standard survey/behavior profiles is available to further automate the mission design task, or to relocate, modify, and copy missions for sequential or multivehicle operations. Data logs from the AUVs were readily visualized and draped over the assigned mission tracklines for review, and selectable data popups follow cursor movement on the actual trackline to provide additional detail. Opening the ASCII log files in EXCEL or similar tools for manipulating and charting tabulated data allowed a quick evaluation of performance over the mission. Mission design and graphical review, and chart/data based log file evaluations, were essentially performed in minutes by operators with no previous training or exposure to the applications.

Lightweight NSW AUV launches were performed from the ship while underway on seven of the eight scheduled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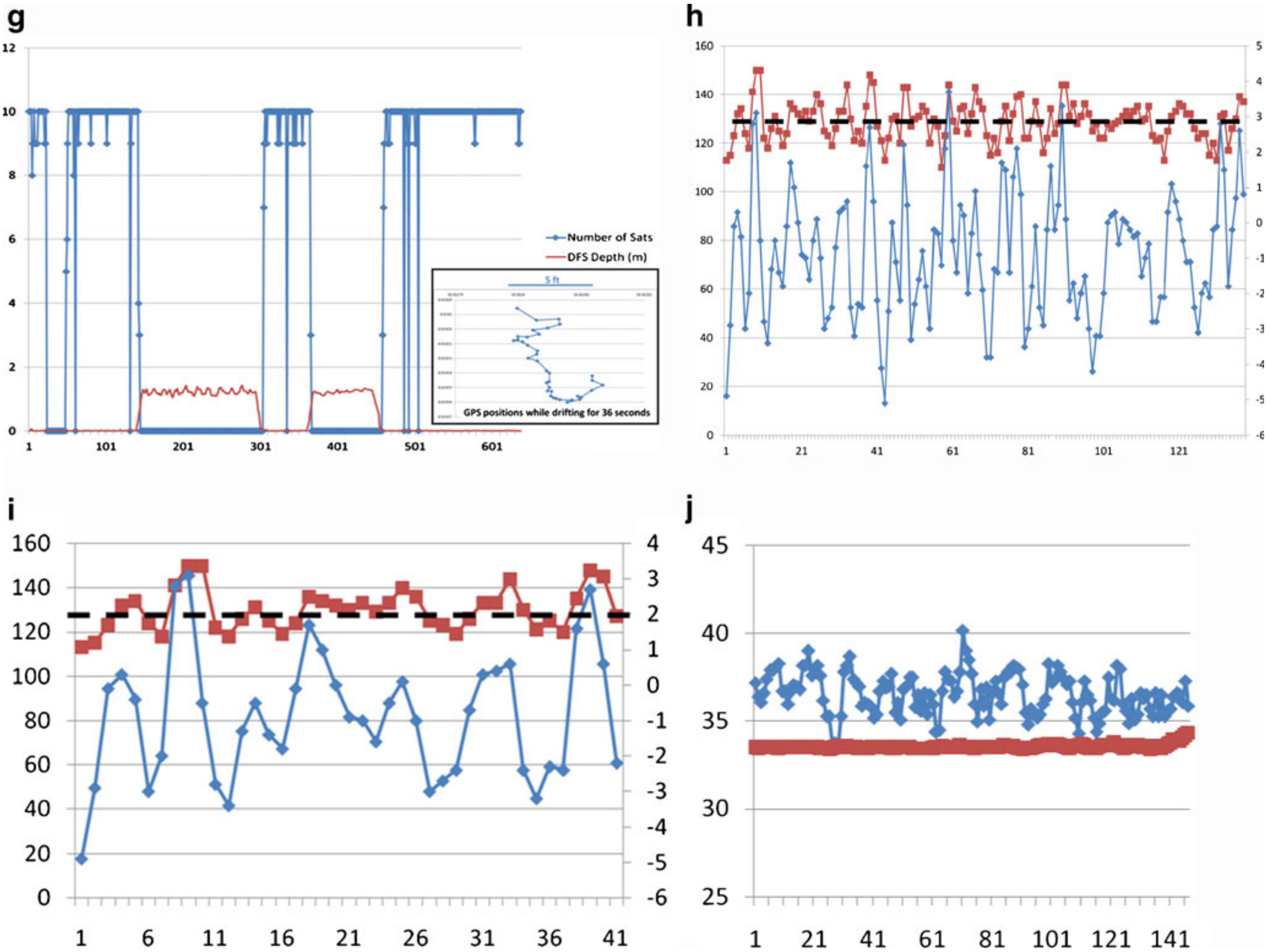


Fig. 2 (continued)

exercise days. The launches were performed at 5 kt at designated drop zones as the NRP Bacamarte steamed on a course that allowed sequential launches on the perimeter of assigned survey areas. With drop zones 300 m apart, the launch times were staggered by 2 min. A canvas sling from Brooke Ocean Technology was used to lower the AUVs for launch with approximately 2 m freeboard. The launches were easily accomplished with the <25 kg AUVs by either one or two individuals without event. The AUVs assumed station-keeping at designated coordinates at the completion of the mission. When the coordinates were within WiFi range of the ship, the AUVs were piloted using manual control and recovered via the manual sling, bow door, or alongside access. For remote stations, an RHIB was deployed for recovery. No deck machinery or auxiliary equipment other than the canvas sling was required for launch or recovery from the ship. On three of the eight exercise days, lightweight NSW AUVs were launched from the shore. Vehicles were set on a delayed launch, then carried to shallow water (0.5 m) and released to acquire the mission start point. On two of the days, the NRP Bacamarte was brought to the beach, the bow door was lowered, and the AUVs were carried ashore for launch. Total time for the launch from the time the bow door was on the beach until multiple AUVs were underway to the mission start point was approximately 2 min. All scheduled shore and ship launches over the exercise period were successfully executed without event.

Components and assemblies were replaced in the field during the exercise as a result of both external and internal causes. External causes included collision of a surface craft with a surfaced AUV and dropping the AUV on the steel deck. In the former case, the fin and bent servo shaft were replaced with a hex wrench in <10 min, and in the second case, the fin was replaced with a single hex wrench in <2 min. Other servicing of the AUV fleet during the exercise period included swap-out of a tail section, replacement of a bushing and O-ring set in a module joint, and swap-out of some suspect sensors. Each of the tasks was performed in <30 min with a screw driver and set of hex wrenches. The modularity of the system and simplicity of design support very well a Concept of Operations (CONOPS) of AUVs deployed with tactical units without special support teams or equipment. Note that shunts in the tail section are removed in <10 min to individualize battery cells and maintain the power supply at <95 Wh per unit, allowing for unrestricted commercial air shipment conforming to DOT Class 9 requirements.

1.4 Reliability

Reliability was evaluated in terms of component and system performance, and by mission completion statistics. Minor component faults associated with both software and hardware were evidenced sporadically in the first week which affected a subset of data collection and mission execution by individual units. No common faults occurred across all the AUV units, and only one repeatable fault surfaced among one of the units after servicing. In every mission throughout the exercise period, the missions were engaged correctly after launch, and in all but two of the missions across the 8-day period, the vehicles returned properly to the assigned recovery point for stationkeeping. Some of these returns were completed via a Safety Return Path designated by the operator for use in the event of a mission abort. Mission aborts were triggered properly by designated safety thresholds. One of the AUVs was apparently hit while on the surface by one of many fishing boats in the area and only recovered some days later when notified by the “finder.” A complete statistical analysis of component, system, and mission reliability was conducted through evaluation of the logs.

1.5 On-scene products

The primary objective of AUV operations for the NSW and NECC user communities is a suite of on-scene products showing the results of the local search and survey missions to support tactical planning. A secondary objective is the forwarding of the data to Reach Back Cells or other activities for model and integrated product support. To demonstrate performance that addresses these objectives, one REP 10A focus area was the simplified production of near real-time graphical products in the field without specialized personnel, support, or additional software applications. This represented a significant improvement over the challenging approach adopted in early AUV operations, where crude interpolation routines used to generate bathymetric products from sparse single-ping data provided the only graphical product in addition to the side scan sonar imagery. The on-scene environmental product suite for REP 10A comprised:

- Multibeam sonar swath bathymetry (CARIS)
- Side-scan sonar image scrolling and georeferenced mosaic products (Imagenex Technology Corp. and OceanServer Technology, Inc. VectorMap)
- Temperature and conductivity, displaying areal variability at selected depths (CARIS)
- Surface/middle/bottom ocean currents, displaying areal variability with selectable depth bins (CARIS and OceanServer Technology, Inc. VectorMap)
- Mission geometry and vehicle track made good (OceanServer Technology, Inc. VectorMap)

A simplified approach to presenting quick-look uncorrected bathymetry interpolated from single-ping data was also provided (CARIS, OceanServer Technology, Inc. VectorMap).

Figures 3, 4, 5, 6 and 7 depict some of the on-scene products available from the Lightweight NSW AUV data.

In addition to the formal graphical products, EXCEL products were used to develop intuitive views of environmental data over the mission without a graphical georeference.

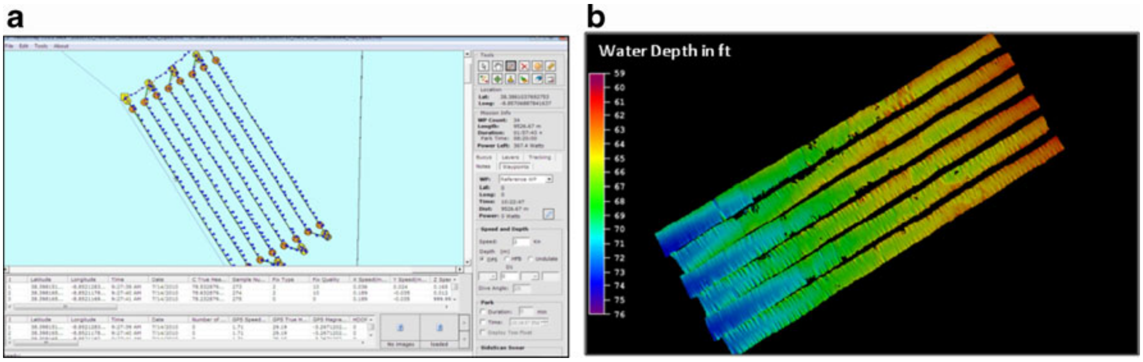


Fig. 3 a–b VectorMap software from OceanServer Technology, Inc., provides graphical window-based mission planning and review capability. In the data review mode, AUV tracklines can be superimposed on missions, and full log file review of 1 Hz data can be associated with chart locations. Data parameters, such as current vectors, can also be superimposed on the chart/image and AUV trackline for rapid evaluation of survey results. Water depth derived from multibeam sonar data (shown in part (b)) and mosaiced side-scan sonar imagery also can be displayed in VectorMap on-scene

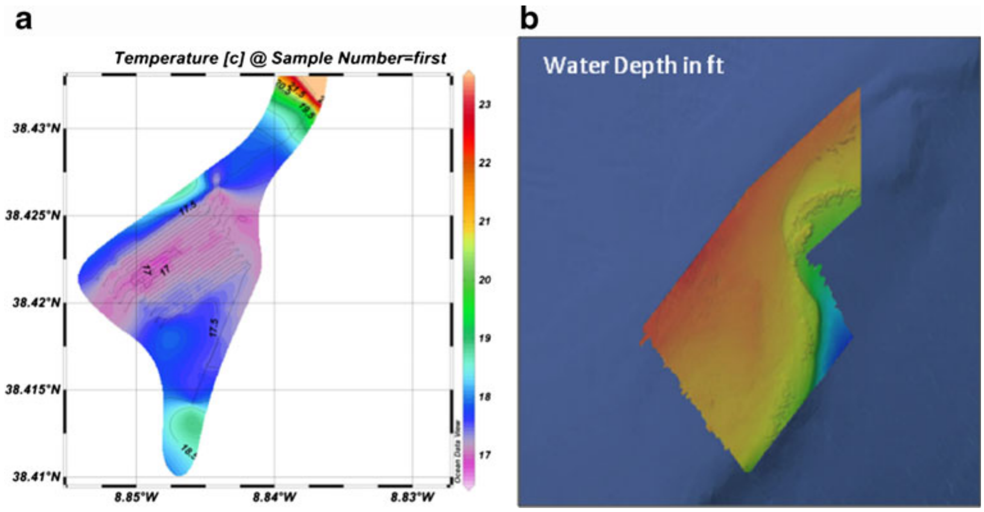


Fig. 4 a–**b** CARIS software allows for interpolation of environmental data for areal displays at selected depth planes. Conductivity and temperature plots are developed from the CT sensors on these AUVs. CARIS is also used for generating corrected multibeam sonar bathymetry products. CARIS products can be exported as GEOTIFF files for display on VectorMap

All log files containing AUV sensor and platform data were posted daily to an FTP site maintained by UMASS Dartmouth Advanced Technology and Manufacturing Center (ATMC). ATMC personnel reviewed the posted data and created daily products using the same SW applications that AUV operators in the field were using for generating on-scene products. The logs and products were available for other agencies approved for FTP site access, such as the NRL and the NURC. NRL used the temperature, conductivity, and ocean current measured locally by the AUVs to validate the regional forecast models for oceanographic conditions (RELO-NCOM, DELFT 3D), including vertical structure, areal variability, currents at selected depths (0, 10, 20 m), local wind and sea state, and sound speed. The data could also be used to evaluate methodologies to integrate AUV data directly into the standard forecast models, and to support initialization and re-baselining processes. NURC accessed the AUV data to ground truth and calibrate shallow water bathymetric products derived from remotely sensed data. Commercial satellites Quickbird and GeoEye provided high resolution images and information on atmosphere radiances in four bands (red–green–blue and near-infrared) to support product generation. This evaluation was scheduled to occur post-exercise, and not within the execution period of REP 10A.

1.6 On-board command and control

The Lightweight NSW AUVs were equipped with secondary CPUs in the form of low-power Atom processors to support additional processing and introduction of command and control functions not provided by the vendor. The MOOS architecture (Newman 2002) and Interval Programming Helm (IvP Helm) function were used to host specific functions developed for these AUVs to meet NSWG-4 needs and to manage potentially competing requirements of operational objectives and vehicle safety (Benjamin et al. 2007). Two of the four specialized C2 functions introduced to the AUV by the secondary CPU were employed in REP 10A events. Both were designed to increase survey

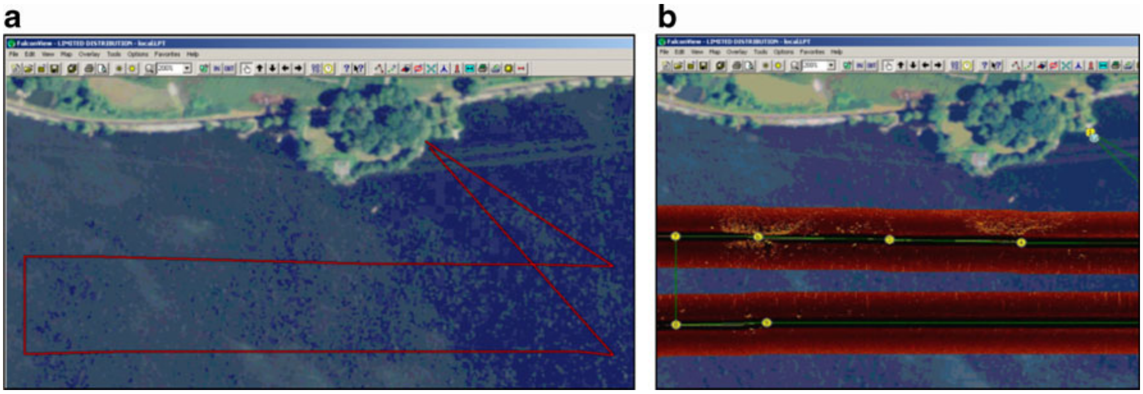
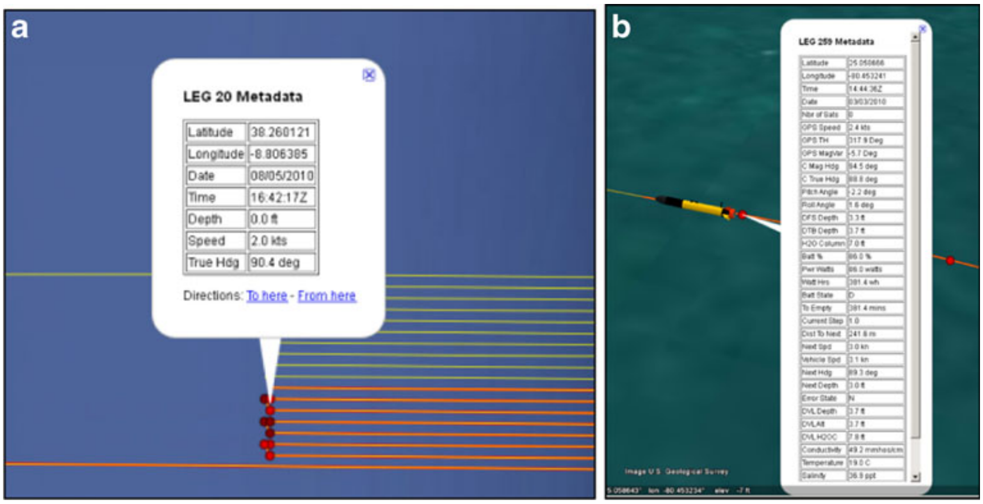


Fig. 5 a–**b** FalconView software used for mission planning and review by Naval Special Warfare personnel can host geo-rectified images from VectorMap and CARIS. Tracklines from mission design and AUV logs are displayed on the background FalconView chart, and multibeam or side scan sonar imagery can be imported to FalconView with the chart or image used in the primary application. FalconView tools function with the imported products



LEG 20 Metadata

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Longitude	-8.806385
Date	08/05/2010
Time	16:42:17Z
Depth	0.0 ft
Speed	2.0 kts
True Hdg	90.4 deg

LEG 259 Metadata

Latitude	25.050666
Longitude	-80.453241
Time	14:44:36Z
Date	03/03/2010
Nbr of Sats	0
GPS Speed	2.4 kts
GPS TH	317.9 Deg
GPS MagVar	-5.7 Deg
C Mag Hdg	94.5 deg
C True Hdg	88.8 deg
Pitch Angle	-2.2 deg
Roll Angle	1.6 deg
DFS Depth	3.3 ft
DTB Depth	3.7 ft
H2O Column	7.0 ft
Batt %	86.0 %
Pwr Watts	86.0 watts
Watt Hrs	381.4 wh
Batt State	D
To Empty	381.4 mins
Current Step	1.0
Dist To Next	241.8 m
Next Spd	3.0 kn
Vehicle Spd	3.1 kn
Next Hdg	89.3 deg
Next Depth	3.0 ft
Error State	N
DVL Depth	3.7 ft
DVL Alt	3.7 ft
DVL H2OC	7.8 ft
Conductivity	49.2 mmhos/cm
Temperature	19.0 C
Salinity	36.9 ppt

Fig. 6 **a**–**b** VectorMap and CARIS products are readily saved as .kmz files for use with the latest releases of FalconView or with Google Earth and compatible GIS applications. The saved files maintain the mission waypoint descriptions and AUV data logs to support mission evaluation

efficiency, effectively reducing requirements for vehicle endurance, survey time, and vehicle numbers in theater. One behavior was developed by the NURC, and it provided on-board path planning for area surveys (Alvarez et al. 2009). Optimal paths for surveys defined by area, vehicle numbers, vehicle speed, and time allowed are calculated on the AUV secondary CPU in a few seconds, then executed when directed by the operator. The survey effort required was just 50% that of a traditional ladder pattern survey to develop a derived survey product of equal fidelity. A second behavior demonstrated the mapping of a selected bathymetry contour from a shore launched mission. The AUV was tasked with acquiring and mapping the 10-m depth contour, using a search behavior developed at NUWC. The AUV successfully mapped the assigned contour for 5 km, then returned to the designated recovery point and held station (Fig. 8). The mapping was completed very efficiently, with just an 8% cost to the search effort, i.e., 5 km of contour was mapped with just 5,400 m of travel. Standard deviation was <0.2 m, and 95% of all measurements deviated from the 10 m contour by <0.4 m.

2 Discussion

The primary objectives of participating in REP 10A in the revised venue were: (1) operational evaluation of the Lightweight NSW AUV; (2) practical development of CONOPS for employment of this vehicle in NSWG-4 search and survey missions; (3) assessment of readiness to support hybrid fleet AUV missions in Combined Force scenarios.

REP 10A provided an excellent opportunity for operational evaluation of the Lightweight NSW AUV immediately following the hardware integration phase (about 8 months into a 12-month project timeline). The physical environment supported realistic test scenarios in open waters, while the participation of the Marinha Portuguesa and planning infrastructure from Universidade do Porto and NURC facilitated efficient operations and mitigated risk. This operational evaluation of platform and system performance was used to prepare for the FAT, and the final weeks before the SEP delivery to NSWG-4 saw 70+ in-water performance tests supporting IV&V, and some 100+ test h logged, aimed at providing design and implementation improvements identi-

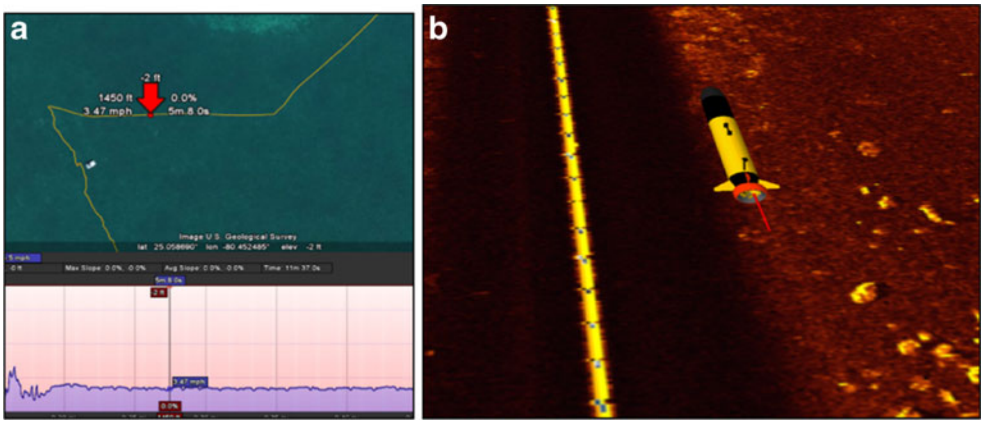

Fig. 7 **a**–**b** The .kmz files can be used with various layered analysis and animation tools to support fly-through data viewing and multidimensional evaluations

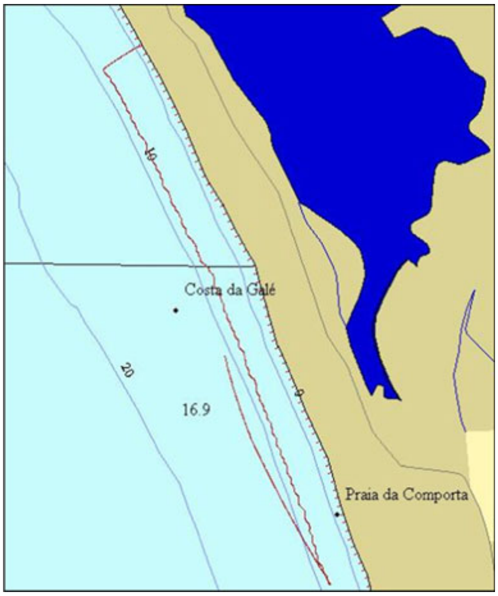

Fig. 8 The contour following algorithm executed from a shore launch effectively mapped 5 km of the 10-m bathymetric contour with just 5400 km travel, or just 8% increase over the mapped length. The trackline is represented in *red*. The vehicle returned to the recovery point after concluding the mapping mission

fied during REP 10A. Significant improvements to reliability and control algorithms addressing the hydrodynamics of the Lightweight NSW AUV relative to the commercial baseline vehicle resulted from this evaluation.

The combination of test environment, infrastructure, and participation by NSWG-personnel was ideal for evaluating the operability and CONOPS. The Lightweight NSW AUV was designed to address the requirements of forward deployed tactical units performing search and survey missions, including Intelligence Preparation of the Battlespace. Employment objectives included: ship- and shore-based operation without supporting gear, economical purchase and maintenance to mitigate risk and allow concurrent multivehicle operations, a one-to-many operating model to reduce operator load, rapid on-scene data production for tactical decision aids (TDAs), and field repair, maintenance, and modular replacement. Each of these objectives was addressed during the test period, with excellent results. Together with the demonstration of AUV performance, this provided the confidence in this development item required for NSWG-4 endorsement. Since REP 10A, work has continued in this area through continued CONUS trials by NSWG-4 and further experimentation supported by the ONR, Code 32. NSWG-4 has deployed the AUVs with sequential launches from small boats at 15 kt, for example, and shore-based operations in tidal channels with 2 kt currents have been used to validate trackline following behaviors in strong currents, as well as to tune sensor response filters in turbulent environments.

The third primary objective of the Lightweight NSW AUV operations in REP 10A was to assess force readiness to operate hybrid AUV fleets in Combined Force scenarios. The Marinha Portuguesa AUV squadron supporting this exercise with two Gavia AUVs was highly proficient, and expert in survey and mine-hunting applications. The Universidade do Porto operators and NSWG-4 personnel were equally skilled with their own crafts, though the procedures were not yet standardized to the same degree with the new platforms. The AUVs had similar sensors, duty cycles, and sensor payloads, so there was a reasonable opportunity to define a program that could demonstrate an optimal integration of their capabilities towards achieving a common goal. However, the mission planning systems were unique and stand-alone, and the navigation infrastructure and precision quite different, making true collaboration difficult. Instead, missions were run concurrently, but in a cooperative design. Each team had an assigned water space for independent operations, and they employed their multiple vehicles within these adjacent assigned areas. Communication protocols were coordinated, and water space areas were rotated during the exercise period.

Evaluation of the organic Command and Control upgrades hosted on the Lightweight NSW AUVs was very successful. Both behaviors in this open water test performed as designed, and both reduced the required survey effort significantly. The quantitative benefit to product fidelity provided by the NATO optimal path planning algorithm could not be determined in this test, as traditional survey methods were not concurrently completed for product comparison. However, the contour following algorithm demonstrated high efficiency in collecting selected bathymetric data. This concept will be carried forward in future exercises, such as Talisman Sabre 11, where approach contours will be mapped by the Lightweight NSW AUVs to support Special Operations Forces (SOF) operations, such as approach, safety of navigation, and amphibious assault planning. Tasking is in place to extend the algorithm to map multiple contours and automatically process and format the data on-board for distribution via Iridium as an Overlay (OVLY-2/3) message. This format allows for direct download and display of the tactical bathymetry data in combat systems and TDAs. Opportunities to leverage other behaviors providing survey effectiveness can be readily implemented, including proven methods which provide for real-time mission replanning based on sensed data and real-time development of 3-D characterizations (Dynamic Graphics, Inc. 1990; Incze 2008).

3 Conclusions

Economical, man-portable AUVs can be used effectively to meet mission requirements for REA by forward deployed tactical units. The benefits of this class of AUV are significant, and the CONOPS finally brings to reality the objective of a single operator managing multivehicle operations to allow timely surveys with fidelity suited to tactical decision making by NSW, NECC, and other communities. REP 10A demonstrated that half a dozen AUVs could be shore- or ship-launched under operational conditions by a single operator with a PDA, independent of special teams, equipment, or other logistical support. The straightforward field servicing and module replacement further promotes acceptance of this CONOPS.

The on-scene data production capability using accepted software applications meets the objectives for REA set by NSWG 4 and establishes a new benchmark for this capability in forward deployed units not dedicated to AUV operations.

As this class of AUVs sees increased application, the demand for component integration (e.g., IR sensors and cameras) and enhanced C2 behaviors (e.g., specialized search, avoidance, or communication responses to through-the-sensor data) will almost certainly occur. The open APIs and Back-Seat Driver supported by the second CPU with MOOS and IvP guarantee an economical and rapid pathway to introduce this capability independent of the vendor.

REP 10A provided an effective operational venue to promote the evaluation, tuning, and final test design for the Lightweight NSW AUVs delivered to NSWG 4 in September under ONR TechSolutions Program Office sponsorship.

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