NMIO Technical Bulletin

National Maritime Intelligence-Integration Office

OCTOBER 2015 - VOL 10

Director NMIO View:

Rear Admiral Elizabeth L. Train, USN

As the Director of the National Maritime Intelligence-Integration Office (NMIO), I am pleased to present Volume 10 of NMIO's Technical Bulletin. This volume is primarily focused on autonomous science and technology relevant to the maritime domain. The articles provide insight into strategic assessments of autonomous systems and challenges being tackled by research and development. Unmanned Underwater Vehicles (UUVs) introduce many opportunities and threats to operations within the maritime domain.

I would like to personally thank the authors who have invested their valuable time to contribute to this edition of our Technical Bulletin. As we work together to promote global maritime security, I encourage others to become more involved in this community publication by submitting articles to help us broaden the topics and regions covered in this product.

I am equally grateful to our readers. Your insights, commitment, and feedback continue to positively affect the safety of the international maritime domain. It is my hope that through increased awareness and collaboration, our mutual efforts will strengthen maritime security overall. NMIO remains focused on identifying concerns and issues that resonate among government, academia, industry, and foreign partners to identify the most efficient and cost effective solutions to our mutual maritime challenges.

The Technical Bulletin is one of our key vehicles to promote enhanced maritime domain awareness and information sharing. We appreciate and invite your continued input, interaction, and contributions to this and other efforts that promote global maritime security. We hope you enjoy this publication, and I look forward to working with you to advance maritime security and build shared domain awareness.

NMIO Technical Bulletin **Volume 10, October 2015**

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Contributions welcome: We welcome contributions from all Global Maritime Community of Interest stakeholders, both domestic and international. In submitting your article, please highlight who you are, what you are doing, why you are doing it, and the potential impacts of your work. Please limit your article to approximately one to two pages including graphics. Articles may be edited for space or clarity.
Cover image: Rendering of the Mayflower Autonomous Research Ship (MARS). Project MARS is being developed by a partnership of Plymouth University, autonomous craft specialists MSubs, and Shuttleworth Design.

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BIO-INSPIRED AUTONOMOUS SYSTEMS

Thomas McKenna, PhD, Office of Naval Research**, Jason Geder,** Naval Research Laboratory

Daniel Parry of the Naval Research Laboratory is a contributing editor to this article.

Harbors and inland waterways can appear to be placid spaces, with the silence occasionally punctuated by the noise of powerboats and jet skis that echo off moored warships or cargo ships with unknown cargoes. Underwater, marine life moves silently, effortlessly wending their way among pilings and debris. Fish hover and glide with their flexible fins to sense obstacles in murky waters. There is not a drop of water in the harbor, not an inch of bottom or breakwater or pier that living organisms do not visit. Under the water, many niches exist where a wide range of animal propulsion systems with special bio-senses are constantly on patrol, agile and silent. These animals sense currents, eddies, electric fields, subtle mechanical events, chemical gradients, polarized light, and the motion of bodies, both large and small.

Soon, a new generation of bio-inspired underwater vehicles may be silently patrolling harbors and rivers. These new autonomous vehicles will stealthily examine each ship and dock, perhaps leaving markers, and standing guard against divers that could pose a threat. Smaller bio-inspired vehicles will closely inspect complex ship structures like propellers and swim in tanks inside of ships. These new vehicles will have propulsion and control that make them stealthy, efficient for endurance and highly agile. The Office of Naval Research's (ONR) Warfighting Performance Department supported researchers seeking to identify the principles, strategies, and mechanisms used by aquatic animals and to exploit these to achieve capabilities beyond the current engineering of undersea vehicles.[1]

The ONR bio-robotics program focuses on bio-inspired autonomous undersea vehicles (AUVs) with additional work in micro air vehicles and humanoid robots to support human-robot interaction research.

Accomplishments include:

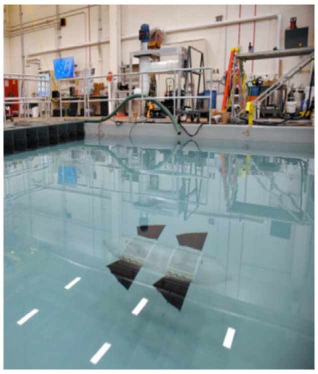
- Neuroscience research into neuromotor control circuits controlling movement patterns led to an analog nonlinear neural controller to produce precise adaptive synchronization of a 6-foil underwater vehicle.
- Analysis of the fluid dynamics of fly wings and fish fins led to new principles for high-lift propulsion due to dynamic stall mechanisms. High-lift pitching and heaving foils developed at Naval Undersea Warfare Center have been able to capture this efficient propulsion on prototype underwater vehicles. These vehicles are quiet, highly maneuverable and capable of operating for weeks with current battery technology.
- Research into bio-sonar, electrosense and lateral line sensors is leading to new search and identification capabilities.

Research challenges and opportunities include:

- Extracting principles and implementing efficient bio-propulsion and control surfaces.
- Developing adaptive controllers for high-degree-of-freedom bio-inspired locomotion.
- Integrating bio-sensing, bio-navigation, locomotion, and closed-loop control to enable agile vehicles operating in complex environments.
- Developing muscle-like actuators.
- Developing vehicles that can support high-level human autonomous system interaction, including within shared spaces.
- Developing the capabilities for micro-air vehicles to perch and grasp.

[1] "Swim like Fishes", Thomas McKenna, PhD., Innovation, Office of Naval Research Vol. 11/Winter 2014

Researchers at the U.S. Naval Research Laboratory (NRL) have taken inspiration from nature—from fish, in particular—to design and develop novel underwater propulsion, control, and sensing solutions for near-shore and littoral zone missions.



AUVs have demonstrated many successful capabilities in inspection, surveillance, exploration, and object detection in deep seas, at high speeds, and over long distances. However, operations in littoral zones requiring low-speed and high-maneuverability present mobility and sensing challenges that have not been satisfactorily resolved.

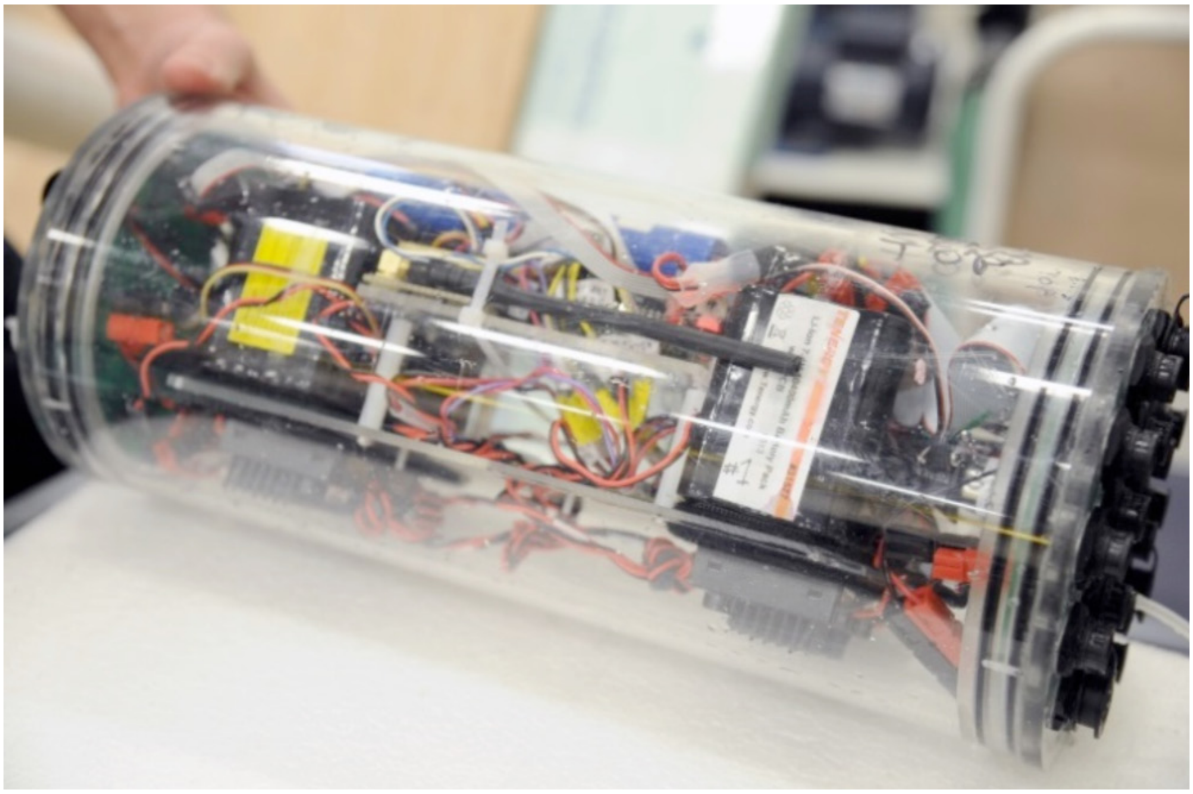
"Expeditions in near-shore environments are complex, often proving turbid, cluttered with obstacles, and plagued with dynamically changing currents," said Jason Geder, aerospace engineer, Laboratories for Computational Physics and Fluid Dynamics at NRL. "Inspired by the pectoral fins of the reef fish, bird wrasse, NRL researchers have developed an actively controlled curvature robotic fin that provides scaled down AUVs a novel low-speed propulsion system."

The artificial pectoral fin has been integrated into a man-portable, unmanned vehicle named the Wrasse-inspired Agile Near-shore Deformable-fin Automaton, or WANDA. Four side-mounted fins, two forward and two aft, provide all the propulsion and control necessary for the vehicle. A set of custom control algorithms uses information about the vehicle motion and surrounding environment to inform changes to the fin stroke kinematics or fin gaits. This kind of artificial fin technology can adapt to varying flow conditions and provide the thrust control necessary for low-speed maneuvering and precise positioning.

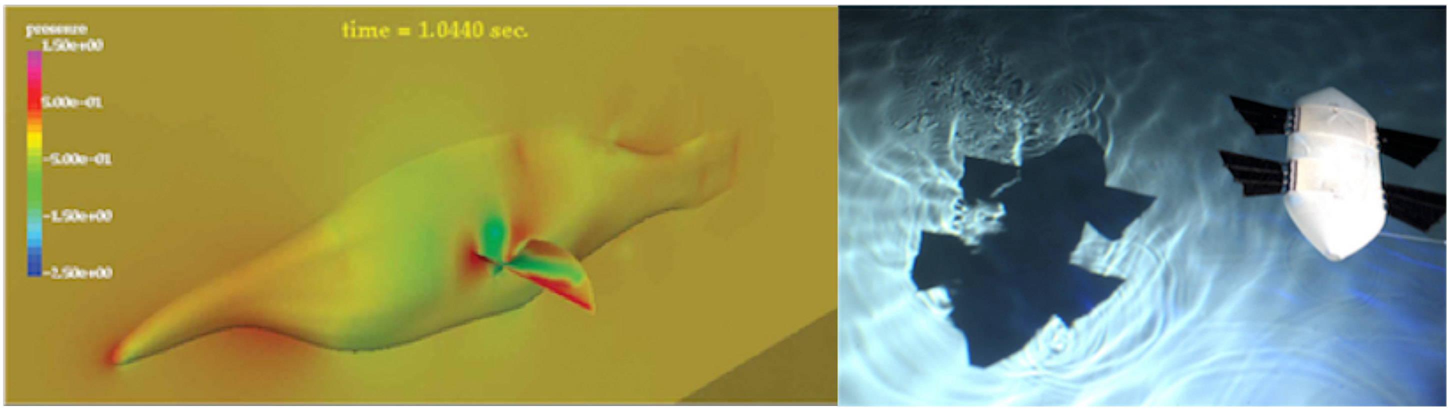
"Computational and in-water experimental results have demonstrated WANDA's capabilities," Geder says. "WANDA can perform low-speed maneuvers to include forward and vertical translation and turn-in-place rotation, and we are currently evaluating station keeping in the presence of waves."

WANDA is designed to operate at speeds in excess of two knots or hold position in the presence of two-knot currents, giving it the propulsion and control authority needed in many harbor and other near-shore operational zones. WANDA can also successfully coordinate maneuvers to achieve waypoint navigation.

As WANDA's fish-inspired technologies are perfected, the AUV is being prepared for payload testing. The vehicle's modular construction enables easy



At the heart of the WANDA AUV is the watertight onboard electronics pressure vessel that houses the power source, microcontroller unit, navigation and monitoring sensors, and communications hardware. Watertight connectors on the pressure vessel provide connectivity between the onboard hardware, fin actuators, and external sensors. A set of custom control algorithms uses information about the vehicle motion and surrounding environment to inform changes to the fin stroke kinematics, or fin gaits. (Photo: U.S. NRI/Jamie Hartman)



Researchers at the U.S. NRL, Laboratories for Computational Physics and Fluid Dynamics, digitally modeled the geometry of the bird wrasse using computational fluid dynamics simulation then validated the data against experimental results. The result was the development of artificial pectoral fins integrated into a man-portable, unmanned vehicle named the WANDA. Four side-mounted fins, two forward and two aft, provide all the propulsion and control necessary for the vehicle. (Photo: U.S. NRL/Jamie Hartman)

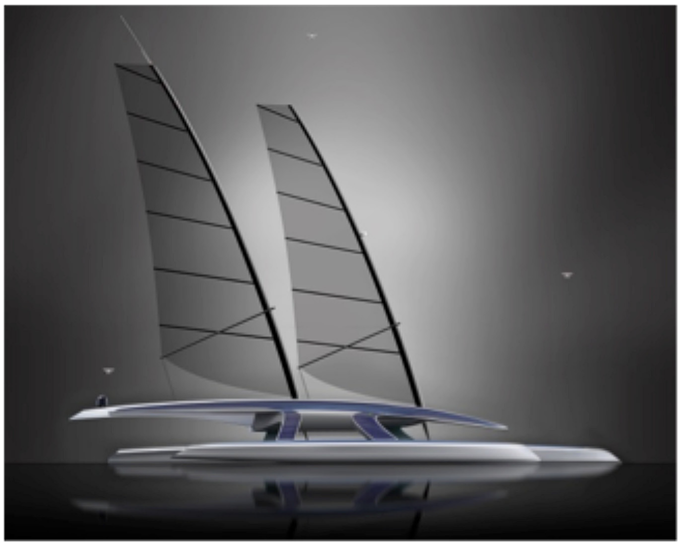
integration of different mission-specific payload packages. One such payload that will be developed and tested on WANDA starting this year is a biochemical sensing system for trace level detection of chemical signatures. This sensor system built onto a capable low-speed platform such as WANDA will enable missions in plume tracking and target localization in shallow water environments.

The WANDA program has spawned other related programs to enable Navy critical missions using AUVs. NRL's Flimmer (Flying Swimmer) program seeks to develop an unmanned platform that will be deployed from the air, glide to a water surface landing in an area of interest, and transition into a swimming AUV. NRL is leveraging its expertise in UAV technologies to design and build the Flimmer vehicle. Modifications have been made to the WANDA fins to enable them to function as aerodynamic control surfaces and to survive the impact of landing.

As the Navy's focus on autonomy and unmanned systems intensifies, NRL's bio-inspired research into capable propulsion and control technologies for low-speed operation in near-shore environments is helping to close a clear gap in AUV technology. An unmanned vehicle that can effectively operate in these areas, where traditional platforms experience stability and control problems, will improve performance for critical missions, including harbor monitoring and protection, hull inspection, covert very shallow water operations, and riverine operations.

MAYFLOWER AUTONOMOUS RESEARCH SHIP (MARS)

SHUTTLEWORTH DESIGN



A pioneering project has been launched which aims to design, build, and sail the world's first full-sized, fully autonomous unmanned ship across the Atlantic Ocean. At more than 100ft in length, the Mayflower Autonomous Research Ship, codenamed MARS, will use state-of-the-art wind and solar technology for its propulsion, enabling a potentially unlimited range. The revolutionary trimaran vessel will carry on board a variety of drones through which it will conduct experiments during its voyage. Following a year-long testing phase, the planned Atlantic crossing in 2020 will mark the 400th anniversary of the original Mayflower sailings from Plymouth, England to Plymouth, Massachusetts, USA.

Project MARS is being developed by a partnership of Plymouth University, autonomous craft specialists MSubs, and Shuttleworth Design. Detailed development of the design is underway, and Shuttleworth Design will be preparing scale models for testing in the University's Marine Building. The approach to developing the concept was to fully explore and take advantage of the opportunities that arise from not having to carry crew and to create a vessel that is capable of using only renewable energy. Working within the limitations of renewable energy sources has given a clear direction to the developing form of the vessel. The solar cell area required for effective motoring is too large for efficient sailing and safety in large waves. To overcome this obstacle, development of a folding wing system will increase the solar cell area by 40 percent in calm conditions.

A trimaran was chosen because it provides the most efficient hull form for low-speed motoring. The hull configuration developed from a requirement to reduce windage, while keeping the solar array sufficiently high above the water to reduce wave impact. Without the need for accommodation, the center hull has been kept low to the water, and the wings and deck are separated and raised above on struts. This allows waves to break through the vessel and significantly reduces roll induced by wave impact. The outer hulls are designed to skim the water reducing resistance by 8 percent. The two masted soft sail rig, which will enable a top speed of around 20 knots, is designed to work with both or either sails hoisted, giving three sail combinations for varying wind speeds. Each sail is simply controlled by a single sheet, and the sails can stow into the deck taking up minimal space. Stowing the sails while motoring reduces windage and eliminates shadows cast over the solar cells on the deck, while allowing the masts to stay standing to carry navigation lights.

Professor Kevin Jones, Executive Dean of the Faculty of Science and Engineering at the University, states:

"MARS will be a genuine world-first, and will operate as a research platform, conducting numerous scientific experiments during the course of its voyage. And it will be a test bed for new navigation software and alternative forms of power, incorporating huge advancements in solar, wave and sail technology. As the eyes of the world follow its progress, it will provide a live educational resource to students, a chance to watch, and maybe participate in history in the making."

Plymouth-based firm MSubs will be leading on the construction, using its expertise in building autonomous marine vessels for a variety of global customers. Managing Director Brett Phaneuf states: "The project will confront current regulations governing autonomous craft at

sea." He also confirms that conversations have already been initiated with bodies such as the Maritime and Coastguard Agency and DNV GL, the international certification and classification society. "While advances in technology have propelled land and air-based transport to new levels of intelligent autonomy, it has been a different story on the sea" Brett states. "The civilian maritime world has, as yet, been unable to harness the autonomous drone technology that has been used so effectively in situations considered unsuitable for humans. It begs the question, if we can put a rover on Mars and have it autonomously conduct research, why can't we sail an unmanned vessel across the Atlantic Ocean and, ultimately, around the globe? That's something we are hoping to answer with MARS."

The vessel will conduct all manner of meteorological, oceanographic, and climate data gathering and research. It is intended to house one or more modular payload bays, much like a space shuttle, into which a diverse range of mission equipment will be fitted to support the various research tasks. Equally important, we will be conducting research on renewable energy and propulsion systems for marine vessels, research on the software for automated and autonomous operations for extended duration, advanced satellite communications and co-operative behavior between nested automated and autonomous vehicles operating below, on, and above the water simultaneously. We will also be looking at data harvesting issues—how to know when something is significant enough to alert the scientists at mission control in Plymouth (UK) and Plymouth (USA) and perhaps 'goal oriented programming' to create dynamic mission plans that better serves the scientific goals of a specific mission without significant human intervention through direct operation of the MARS.

An Atlantic crossing could take as little as 7 to 10 days with optimal wind conditions but what is important is that it could take 7 to 10 months if we so choose, so that the ship could collect voluminous data for ongoing analysis by shore-based teams of scientists and not worry about refueling, reprovisioning, illness, or loneliness. It is optimized to be at sea supporting science, not racing across the Atlantic; however, speed will be useful when the MARS needs to head to remote areas of the globe. MARS will be monitored continuously so vandalism and piracy is a minor concern when compared with concerns about structural, mechanical, electrical, corrosion, and software issues. The sea can be punishing on equipment, and there will be no one present to repair the vehicle; hence, it will need to have redundant systems and be as robustly built as possible using the latest in composite materials.

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MARITIME ROBOTX CHALLENGE

Paul Shapiro, PhD, National Maritime Intelligence-Integration Office (NMIO)

The goal of the Maritime RobotX Challenge is to foster interest in autonomous robotic systems operating in the maritime domain, with an emphasis on the science and engineering of autonomy. RobotX has two primary objectives: to create a pinnacle STEM student outreach event and promotion of interest among Pacific national partners in the science and technology of autonomous systems. Jointly organized by the Association for Unmanned Vehicle Systems International (AUVSI) Foundation, the National University of Singapore Faculty of Engineering, Science Center Singapore, and supported by the Office of Naval Research (ONR), the inaugural Maritime RobotX Challenge was hosted in Singapore in October 2014. International student teams from Australia, Japan, Singapore, South Korea, and the United States competed in a variety of autonomous navigation, control, and obstacle detection and avoidance missions.

ONR provided a standard Unmanned Surface Vessel (USV) to each team, serving as the maritime platform for the various sensor suites and control systems that the teams determine necessary to complete the mission tasks. The Wave Adaptive Modular Vessel (WAM-V) was chosen by ONR and AUVSI Foundation as the sole platform. Marine Advanced Research, Inc., supplied 15 vessels to competition participants. The USVs are provided without propulsion units so that the maneuvering control of the USV must be selected by each team and integrated fully into their autonomy schema. Each team was also provided with a stipend to defray the costs of designing and assembling their own propulsion system, motor controller, and electric power source.

The competition took place at Marina Bay, Republic of Singapore, adjacent to a large floating platform that abuts a stadium on the north shore. The platform is 120 meters long and 83 meters wide with a square practice area approximately 80 meters on a side located on the east side of the platform and two competition courses laid out to the west side located inside an approximately 190 meter square area. The general RobotX Challenge event layout is shown in Figure 1.

The competition consists of five tasks to demonstrate: navigation and control, underwater search and report, identify symbol and dock, observe and report, and detect and avoid obstacles.

The Wave Adaptive Modular Vessel (WAM-V) is an innovative class of watercraft based on a patented technology by Marine Advanced Research, Inc. (http://www.wam-v.com)

Task 1: Demonstrate Navigation and Control
To demonstrate autonomous control of the USV, all teams must complete this task at the start of each of their scoring runs before continuing to other tasks. In this task, the USV must maneuver autonomously along a marked course, beginning at the start point, traversing a linear course marked by two sets of buoys ("gates"). The start point GPS position will be provided for each course, but the teams must detect and navigate through the start gate and end gate autonomously.

Task 2: Underwater Search and Report
In this task, the USV must successfully identify and locate a specific underwater device that is emitting an acoustic signal.

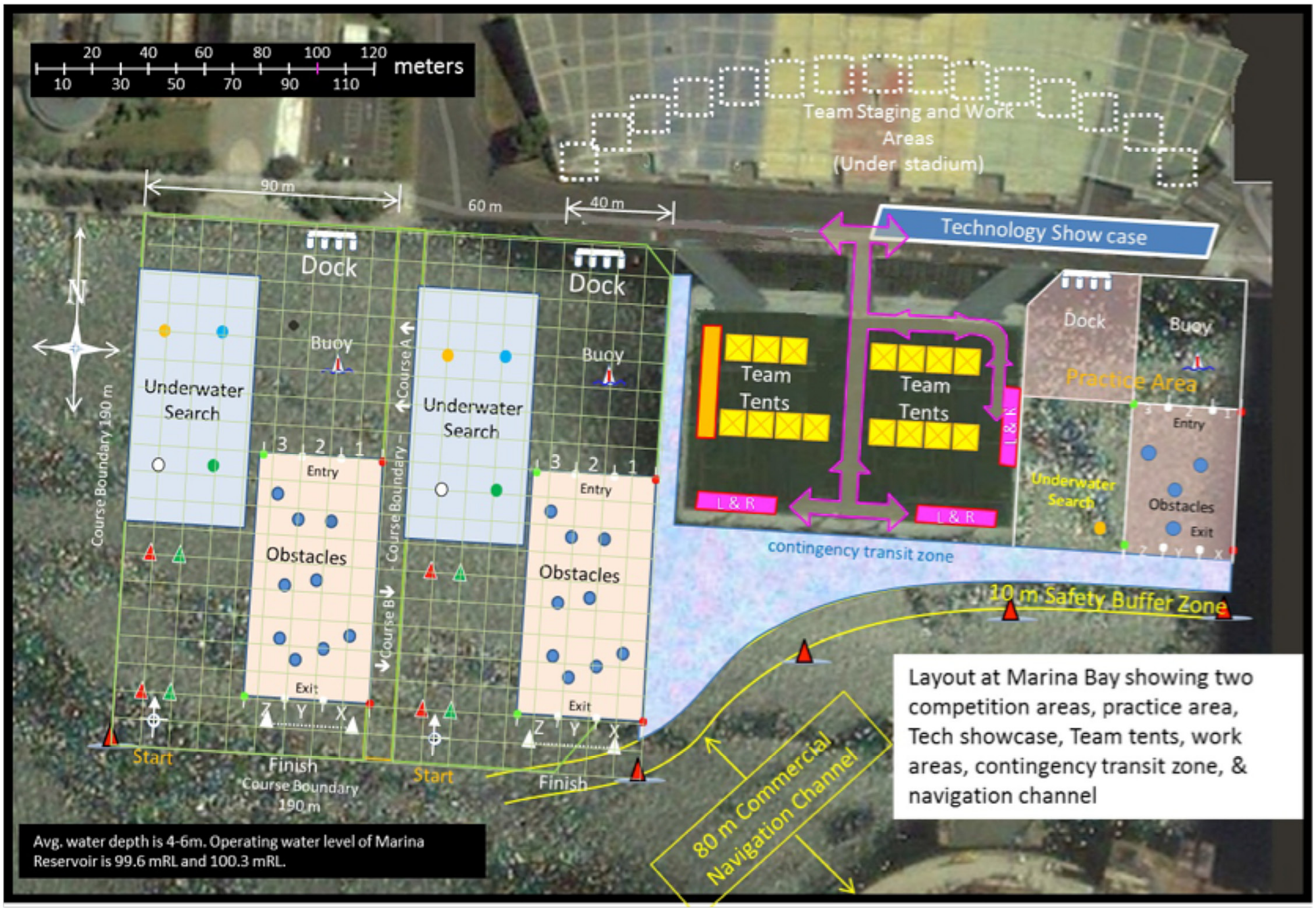

Figure 1. Overall Maritime RobotX Challenge Event Layout

Task 3: Identify Symbol and Dock
For this task the USV must successfully identify one of three marked docking bays, locate it, maneuver to enter the correct bay, stop, and then maneuver to exit the bay, subsequently moving on to the next task or terminating the run.

Task 4: Observe and Report
In this task, the USV will be required to conduct observation of a "light buoy" to determine the sequential light pattern it flashes. The USV must autonomously report the color sequence of the buoy's flashing light. The light buoy will not be activated until the USV has started its autonomous mission run on the competition course.

Task 5: Detect and Avoid Obstacles
This final task requires the USV to navigate through a designated entry gate (1, 2, or 3), travel autonomously through an arrangement (or field) of various floating, but stationary obstacles, and complete the course by passing through the designated exit gate (X, Y, or Z). The objective is to traverse the course passing the correct entry and exit gates, completely avoiding all obstacles and gates.

Next Competition
The AUVSI Foundation and ONR are proud to announce that the Maritime RobotX Challenge (RobotX) 2016, Hawaii will be held on the island of Oahu, Hawaii, in December 2016. Details about RobotX 2016 are posted on the website at www.robotx.org.

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GLOBAL ANALYSIS OF THE NEED AND GROWTH PROSPECTS FOR UNDERWATER UNMANNED VEHICLES

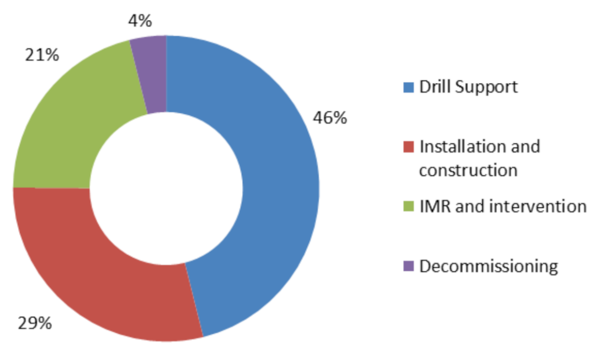
Chinmay Waikar, IndustryARC

Oil extraction activity has been carried out for more than a century, and continuous efforts have been made through the years to develop the technology to safely extract large volumes of oil in the least possible time. Oil is generally extracted from the most accessible region, as well as from the most difficult terrains to meet the ever growing energy demand. As the oil demand kept increasing and most of the potential areas on land were explored, drilling activity slowly moved to coastal waters.

Technological advances made it possible for companies to drill in shallow waters and extract oil, which started the offshore drilling and offshore oil industry. Movement to coastal waters for drilling was a gradual process, with slow commercial growth and uptake across the globe. Initially, human divers were used for setting up offshore oil rigs and constructing drilling platforms, performing maintenance and repair, and decommissioning. As shallow water drilling increased and more oil reserves were found underwater, the drilling activity started moving to greater depths beyond 300msw. These depths, however, were found to be unsafe for humans, and regulatory norms prevented divers from operating beyond this depth. As a result, the need for underwater performing machines increased, and the current line of unmanned underwater vehicles (UUV) was born after multiple technological breakthroughs in their design and construction.

Growth of UUVs was driven by high R&D investments, increased offshore exploration ventures, increased IMR (Inspection, Maintenance, and Repair) activity, higher oil demand, and safety concerns for humans. UUVs, as a replacement for divers, perform various functions underwater where the conditions are not safe for human divers in deep-waters and in applications requiring high power. They can be deployed underwater for a prolonged period of time, even weeks or months, as required. The UUVs are basically of two types: Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs). The main difference between them is that an AUV does not require continuous human interference or control and operates according to the pre-programmed instructions, while the ROV is controlled by an operator via an umbilical cord.

ROVs address emergency needs in offshore oil rigs. ROVs are tethered vehicles that are controlled from the on-board surface vessel by a human operator. The attached umbilical cord provides power and also the operating signals to the ROV. The size, weight, power source, propulsion mechanism, array of sensors, manipulator arm, and the tooling components are all derivatives of the application and function it is used for. ROVs can be mainly divided into Observation class (OROV) and Work class (WROV). The observation / inspection class ROVs are generally small, electric powered, and cost effective vehicles used for diver substitution or as a support mechanism to the divers by providing video feed. Weight of power delivery component, pressure rating of mounted components, and the need to maintain neutral buoyancy for free



Global Work Class ROVs for Commercial Market Users, By Usage/Function, 2014 (%) Source: IndustryARC Analysis,

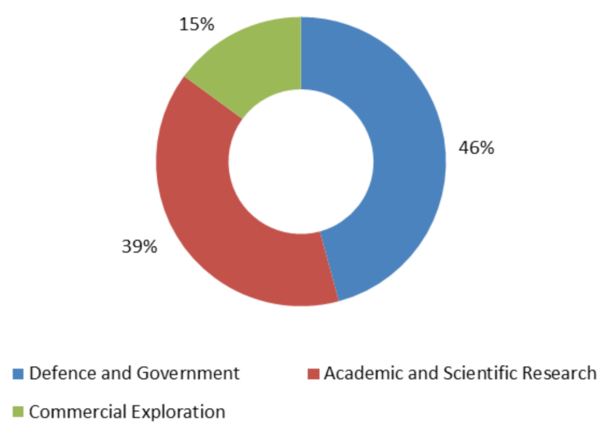
swimming are major constraint parameters for size and depth rating. The main function of these ROVs is providing visual feed for inspection, surveillance, and observation. Recently developed micro-ROVs are being used for functions such as pipeline and dam inspection.

WROVs are heavy electromechanical vehicles requiring high voltage AC and a hydraulic power system for propulsion, manipulator arm functions, and tooling activity. They are the only vehicles that are used to perform heavy underwater work activity in the oil and gas industry commercially. They are equipped with an HD camera, sensor arrays, and a multi-functional manipulator arm that can perform delicate functions and activities requiring high power. The weight and depth rating of these

ROVs makes it necessary to use a launch and recovery system (LARS) and tether management system (TMS). The major applications of WROVs are drill support, installation and construction, IMR and intervention, and decommissioning. They are extremely critical for emergency functions that arise in the underwater oil fields.

The UUV industry is highly consolidated, with fewer than ten major manufacturers occupying about 80 percent of the market size. Major ROV manufacturing companies include Oceaneering, Subsea7, FMC Shilling Robotics, Forum Energy Technologies, ISE, and many others. The WROV market is estimated to be $1.4 billion in 2014 and the OROV market to be $430 million. According to IndustryARC analysis, the WROV segment accounts for 68 percent of the total UUV market.

According to the U.S. Navy Unmanned Undersea Vehicle (UUV) Master Plan (2004 edition), a UUV is defined as a self-propelled submersible whose operation is either fully autonomous (pre-programmed or real-time adaptive mission control) or under minimal supervisory control, and is untethered except for data links such as a fiber-optic cable. Autonomous Underwater Vehicles ((AUV) are programmable, robotic vehicles that



Global AUV Market Demand, By End-User Segments, 2014 (%)

depend on their hardware and software design to drift or glide through the ocean, and no human control or interference is required on a real time basis. Using satellite signals or underwater acoustic beacons, some AUVs communicate with operators periodically or continuously so as to allow some level of control and improvisations in their activities and movement profiles. AUVs are typically equipped with a variety of oceanographic sensors or sonar systems, such as side scan sonar, Conductivity-Temperature-Depth (CTD) sensors, GPS-aided Inertial Navigation Systems (INS), Acoustic Doppler Current Profiler (ADCP), and other equipment so the AUV can be customized and equipped with the necessary instruments for performing the required function.

AUVs are extensively used in the defense and research segments for survey, surveillance, identification and mapping of submerged wrecks; commercially for exploration of the ocean floor for oil and gas; and for mapping the subsea surface. Some of the major companies manufacturing AUVs are Bluefin Corporation, Kystdesign, ECA robotics, Liquid Robotics, and many others. The market for AUVs globally was estimated to be $530 million in 2014 and is projected to grow with a compound annual growth rate of 23 percent for the next five years.

Hybrid Vehicles-The Future of underwater Exploration

Hybrid vehicles are a combination of AUVs and ROVs such that they can be tethered or untethered. The tether is usually in the form of a fiber optic cable that can be as small as 1mm in diameter. The small diameter of the optic fiber tether cable offers a great maneuverability to the hybrid ROV. They can carry around 40 km of the tether in their canisters that can play out as the vehicle descends to greater depths. These vehicles can be switched to autonomous free swim mode that does not require any interference from human operators. It can be switched back to the ROV mode to conduct specific tasks related to the survey or experiments that are to be carried out at particular locations such as collecting samples of the sediments or the marine life. They are still in the development stage and are expected to be the future of UUVs.

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AUTONOMY TECHNICAL ASSESSMENT EXECUTIVE SUMMARY

U.S. Department of Defense Office of Technical Intelligence (DOD OTI)

U.S. and foreign technology and capability development is pushing existing human-machine systems to the edge of their abilities by introducing extreme timescales, high levels of complexity, severe risk to warfighters, and increasing costs. While these trends and the challenges they pose to the U.S. Department of Defense (DoD) do not appear likely to abate, autonomy has the potential to enable U.S. forces to break out of current limitations by allowing systems to understand the environment, to make decisions, and to act more effectively and with greater independence from humans. In doing so, autonomy can augment or replace humans to enhance performance, to reduce risk to warfighters, and to decrease costs.

This assessment identifies research and development (R&D) and policy opportunities to position DoD to more effectively leverage autonomy. Based on an analysis of the security environment, opportunities presented by autonomy, and private sector investment, there are four major gaps in DoD efforts to date:

1. There is no unified analytic framework to examine needs and opportunities for autonomy across DoD tasks and missions.

2. Few DoD efforts are conducting R&D, carrying out experimentation, or developing approaches to testing for systems to operate against intelligent adversaries.

3. While there is substantial interest in autonomy to enhance capabilities and to decrease risk to warfighters, there is relatively little focus on leveraging autonomy explicitly to decrease costs.

4. There is insufficient R&D, experimentation, and policy for developing architectures, concepts of operations, and test, evaluation, verification, and validation approaches to ensure future systems are affordable and can operate effectively as a joint force.

The assessment addresses these gaps by providing a capability-focused analytic framework that applies across mission spaces and by making recommendations in the key technology and policy areas that are critical to ensure that the U.S. maintains a superior and affordable force:

Technology: Autonomy relies on three multidisciplinary technical fields: perception, cognition, and action, which cover areas from sensors to artificial intelligence and robotics. There are opportunities to leverage private sector investment where applications overlap and in technology for more permissive environments, but DoD has unique, critical needs for technologies to enable operations in complex, adversarial environments.

Recommendation: Leverage private sector activity in low-cost aerial systems, data analytics, cyber defense, human-machine interaction, and efficiency-related technologies, and focus DoD perception, artificial intelligence, and robotics R&D on developing autonomy for platforms intended to operate in complex environments with special consideration for adversarial behaviors.

Modularity & Interoperability: Enabling the reuse and reconfiguration of both hardware and software from different systems in a modular fashion will play an important role in determining R&D costs of new platforms. This will also affect the flexibility of U.S. forces to tailor hardware and software to mission needs. Likewise, interoperability standards for communication can play an important role in enabling synergistic effects across platforms and domains. These needs are not unique to autonomous systems, but they will be critical to maximizing the effectiveness of their widespread implementation.

Recommendation: Fund research to develop a forward-looking open architecture and interoperability standards for autonomous systems and mandate cross-Service compliance.

Resiliency: The fact that autonomous systems ‘think’ differently than humans will open up new vulnerabilities, as the U.S. and adversaries can take advantage of the shortcomings of machine perception and cognition. These systems will not necessarily be more vulnerable than human-controlled systems, but they will be vulnerable in different ways. This is particularly challenging because widespread adoption of a large number of autonomous systems with similar or identical perception and cognition systems raises the potential for one or a small number of weaknesses to endanger a large proportion of the force, as with agricultural monocultures and disease susceptibility.

Recommendation: Study the unique vulnerabilities of autonomous systems, and intentionally design heterogeneity into classes of U.S. systems to mitigate system-wide vulnerabilities.

Concepts of Operations Development & Experimentation: Autonomy will enable and benefit from new concepts of operations (CONOPS) by making it possible for systems to operate in environments, at levels of performance, and in new configurations which have not been possible to date. Autonomy will also impact the behavior of humans and raise new ethical and legal challenges. As with other technologies, the most effective CONOPS will not be immediately evident and will require experimentation to identify. At the same time, almost all DoD efforts are focused on enhancing capabilities and warfighter protection, but autonomy also presents major cost-saving opportunities in areas such as logistics, maintenance, and data analysis.

Recommendation: Fund intensive, adversarial experimentation in realistic environments to inform CONOPS development, paying special attention to artificial intelligence’s propensity towards unconventional approaches to problems; opportunities to employ larger numbers of lower-cost systems; the interaction between humans and autonomous systems; and ethical-legal considerations. Compliment these efforts with programs to experiment with and implement autonomy explicitly to reduce costs.

Test, Evaluation, Verification, & Validation (TEV&V): Because of the complexity of autonomous systems, especially those that can learn, there will also be major challenges to carrying out effective TEV&V. Complex systems will render current approaches that rely on holistic testing infeasible because it will be impossible to test all possible circumstances, especially in laboratories where the environment cannot sufficiently replicate the real world. As a result, there are open needs for metrics, standards, methodologies, and appropriate environments to conduct TEV&V for autonomous systems.

Recommendation: Fund research into metrics, standards, methodologies, and approaches for TEV&V, including modeling, simulation, and licensing, and establish a dedicated air-land-sea autonomy range to ensure a realistic environment for TEV&V, which can also support experimentation.

Further Information: The full report by OTI is available on the Defense Innovation Marketplace website.
http://www.defenseinnovationmarketplace.mil/resources/OTI_TechnicalAssessment-AutonomyPublicRelease_vF.pdf

AUTONOMOUS UNDERWATER VEHICLE (AUV) SURVEY AND INSPECTION

C&C Technologies, Inc.

C&C Technologies was the first company to offer commercial Autonomous Underwater Vehicle (AUV) survey services to the offshore oil and gas industry. In 2000, C&C's clients requested help to reduce deep water survey and inspection costs. C&C combined its extensive operational experience with lessons learned from its U.S. Navy unmanned research programs to introduce C-Surveyor I, the world's first commercial AUV designed for surveys for the oil and gas industry.

As the result of C&C's expertise and vision for the survey and mapping market, cost-effective AUV surveys are now being performed routinely in a variety of worldwide offshore applications. C&C has put this AUV technology to work for more than 74 different clients in 14 countries to date.

As the energy industry has expanded its use of AUVs for subsea survey efforts, C&C has remained committed to leading AUV technology advancements. As oil and gas operators have moved into deeper waters, the need for high quality and reliable pipeline and flow-line inspection methods to verify the integrity of subsea structure has become more essential. C&C Technologies has helped change deep water survey methods by ushering in the use of AUV inspection technology for pipeline surveys. AUV technology offers higher quality data in pipeline inspections while being faster and more cost-effective than previous survey methods.

Continuing to advance AUV technology for pipeline inspection and geohazard surveys, C&C has unveiled the fastest and most accurate pipeline inspection tool in the industry, with field results from the AUV pipeline inspection innovation that captures high-resolution images, a laser-producing 1,400 soundings per profile, and collecting 29 profiles per second. C&C's newest AUV survey technology, C-Surveyor VI, incorporates an innovative payload that offers unique capabilities for the inspection of pipelines and subsea infrastructure. In addition to a side scan sonar, multibeam echosounder, and sub-bottom profiler, the C-Surveyor VI is integrated with a 3D bathymetric laser, a camera photo mosaic system, a hydrocarbon detector, and a magnetometer. The C-Surveyor VI captures 3D "point cloud" renderings at 5mm resolution of pipelines, subsea infrastructure, and surrounding geomorphology. Combined with high-resolution photo mosaics, this innovative capability is used to inspect and document the survey life-cycles of pipelines and peripheral seafloor assets.

C&C has performed a wide variety of specialized AUV surveys, including downed aircraft searches, deep water coral mapping, and high-resolution micro seismic at 4m line spacing. AUV survey services include:

Geohazard Surveys
These surveys identify any conditions at the seabed or in the foundation zone where hazardous subsurface features or unstable soil conditions exist. C&C's customized sensor suite provides unmatched data quality to identify potential geohazards, including submarine landslides, debris flows, shallow gas accumulation, faults, mud volcanoes, and methane hydrates.

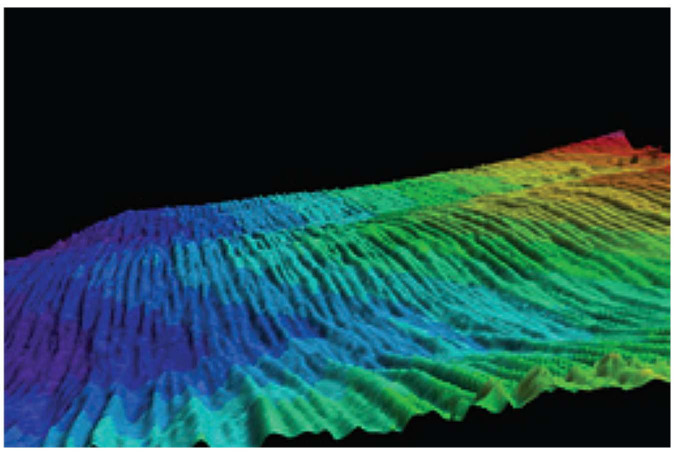
Pipeline Surveys
Pipeline surveys are performed to assess the seafloor and subsurface for geologic features and to identify any man-made hazards and obstructions that may impact potential archaeological resources or have an adverse effect on the proposed pipeline

activities. AUVs are ideal for pipeline route surveys due to their agility and efficiency. AUV survey data is developed into reports and alignment sheets for pipeline, flowline, and umbilical routing.

As-Built Surveys
As-built surveys verify the condition of the pipeline shortly after its construction. Periodic inspection surveys reduce risk by providing documented evidence of the existence or absence of spans, cathode erosion, leaks, movement, and damage. C&C provides cost-effective deep water AUV pipeline inspection surveys with engineering quality 3D bathymetric laser data and high-resolution photo mosaics.

Block Studies
AUV surveys are conducted in the deep water Gulf of Mexico prior to any operations involving oil and gas exploration and production. This data is used for archaeological assessments and to identify seafloor and subsurface features that may have an adverse effect on drilling operations. Potential geological surface hazards may include faults, gas vents, surface channels, furrows, sinkholes, hydrate mounds, unstable slopes, and reefs. Subsurface geologic hazards may include gas-charged sediments, faults shallow-water flow, and buried channels.

Archaeological Assessment and Site Surveys
Historic Marine Archaeological Assessments are required in the Gulf of Mexico where proposed bottom-disturbing activities may impact submerged archaeological resources, including pipeline, flowline, umbilical, anchor, and platform placement. C&C's AUVs meet or exceed archaeological assessment data requirements and offer advanced onboard sensor options should further investigation be warranted. Unique sensors complement C&C's standard AUV payload suite. These include a bathymetric 3D laser, a camera photo mosaic system, and a magnetometer. The bathymetric laser collects high-density 3D point cloud data at a resolution of 5 mm. The camera photo mosaicking system delivers photomosaics with rapid view, zoom, and search capabilities. A magnetometer detects ferrous objects, which is beneficial data for marine archaeological assessments. Correlating these complementary data sets provides accurate identification and verification of site artifacts, debris field mapping, and precise target measurements.



Deepwater Gulf of Mexico AUV data showing furrows fronting the Sigsbee Escarpment. Furrows are 3 to 10 feet in depth and 15 to 3 feet in width (data courtesy of BP).

Government and Academic Surveys
C&C's AUVs have been employed for a variety of government and academic survey projects. These include scientific expeditions for the National Oceanic and Atmospheric Administration (NOAA) Office of Ocean Exploration to perform deep water coral mapping, historic shipwreck surveys, and geotechnical investigations. Notable AUV projects include detailed mapping of the German Submarine U-166 in the Gulf of Mexico, locating the historic HMS Ark Royal near Gibraltar, and finding two missing aircraft lost off the archipelago of Los Roques, Venezuela, one of which was carrying Italian fashion design CEO Vittoio Missoni and his wife Maurizia Castiglioni.

Deepwater Benthic Community Surveys
AUV camera assessments provide ground-truthing of deep water benthic communities to identify and localize, or disprove, their presence. Deepwater benthic communities may include clams, mussels, tubeworms, and other organisms that thrive in the absence of sunlight. C&C's AUVs provide documented assessments of deep water benthic communities, which meet or exceed regulatory requirements to maximize leaseholders' development options. C&C Technologies, Inc., is the worldwide leader in land and offshore surveying services in the oil and gas industry.

Further information regarding C&C Technologies, Inc., technology and services is available at http://www.cctechnol.com/.

FUTURES FORUM ON UNMANNED UNDERWATER VEHICLES (UUVS)

Richard Bunting, National Maritime Intelligence-Integration Office (NMIO)

The National Maritime Intelligence-Integration Office (NMIO), in collaboration with the Johns Hopkins University Applied Physics Lab (JHU/APL), recently hosted a forum that explored the future of commercial and military Unmanned Underwater Vehicles (UUVs) out to the year 2025. Participants from academia, industry, and government addressed the current state of UUV technologies, capabilities, and missions as a foundation for postulating potential future missions. They identified strategic considerations and headlines that indicate the materialization of technology trends.

Current developments in UUV technology

At the outset, the forum endeavored to lay out a baseline of the current state of UUV technologies to frame discussions of future uses of UUV technology within the commercial and government sectors. Recent historical trends in subsystem technologies and missions, including autonomous undersea vehicles (AUVs) and remotely operated vehicles (ROVs), were explored including energy and propulsion, autonomy and navigation, reliability and sensors, and communications.

Energy and Endurance

Lithium ion (Li-ion) batteries are the current state of the art for untethered vehicles. In 10 years energy density increases are expected to be ~2-3 times that of Li-ion for battery and fuel cells with UUV size constraints. Small diesels that snorkel and charge batteries may also be possible, extending ranges by a factor of 100 beyond current Li-ion capabilities. Forward-deployed energy storage and generation outposts may act like gas stations. For ROVs, tethers can provide virtually unlimited power, but are limited in range and require a host platform.

Propulsion

Propellers are still the most efficient means of propulsion for vehicles that need to hover and move horizontally and vertically on demand. Gliders take advantage of buoyancy changes, move vertically, and their lifting surfaces use that vertical movement to create horizontal translation; however, horizontal translation without vertical translation is not possible.

Autonomy and Navigation

Current systems are programmed to deal with what they expect to encounter, however, dealing with unknowns is not currently possible for UUVs. Despite advances in artificial intelligence, these advances are not yet capable of supporting true autonomous activity, though multi-sensor fusion and pattern identification may help in this area. As such, UUV obstacle avoidance is currently not possible. Current efforts to develop self-driving cars that are able to deal with severe ambiguity and the unknown will be an indicator of what can be done.

Navigation

There is currently no global positioning system (GPS) underwater, though long range, relatively precise navigation is possible with long range gliders. Precision navigation needs either updates from GPS that require periodically surfacing an antenna, or internal navigation systems that involve a double integration - such as accelerometers - to determine distance traveled, combined with bottom lock using transponders. Other navigation options include the placement of buoys with GPS antennas that acoustically transmit their location to a UUV and pre-planted submerged navigation nodes that acoustically transmit their locations.

Reliability and Sensors

Reliability of UUVs is currently not an issue, as vehicles operate for days and weeks at a time; however, it is unknown if longer periods would pose a problem for users. Although, the question that needs to be asked is whether the loss of a vehicle(s) is affordable.

Sensors

Current side-scan sonar resolution is on the order of 1 x 1 inch at 1000 feet; this is not expected to change much over the next ten years. Electrooptical systems such as cameras are range-dependent on water quality. For instance, clear water can image at ~10-100 feet, while murky water may prohibit imaging at all.

Communications

Communication capabilities are currently limited to tens of feet for lasers and are dependent on water quality. Acoustic (sound) systems offer more range but, in the case of military applications, are detectable unless mimicking naturally occurring organic sounds. High frequency (HF) carries more information and requires less power, but is attenuated quickly. Low frequency (LF) carries less information and has longer range, but requires more power; again, both are detectable. The alternative is to surface an antenna and conduct radio frequency (RF) burst transmissions via satellite communications or line-of-sight to an aircraft. Neutrally buoyant fiber optic tethers provide for much longer communication ranges, i.e., on the order of 100 nm without repeaters, but could get cut by, or tangled in, fishing nets and tow cables.

Future Missions

Once the current state of UUV technology was addressed, participants postulated potential future missions by considering plausible technology development within the next 10 years based upon the current state of technology. The forum postulated eight potential future missions for the commercial and industrial sectors, including: Infrastructure Monitoring and Repair, Open Ocean Marine Sanctuary and Exclusive Economic Zone (EEZ) Monitoring, Deep Sea Prospecting and Mining, Seabed Mapping and Monitoring, Remote Oil Platform Surveillance and Servicing, Mapping Efforts on an Ocean Basin Scale, Autonomous and Remote Infrastructure Manipulation, and Support to Subsea Oil and Gas Industry. For the government sector, the forum postulated ten missions, including: Global Posturing and EEZ Claim Enforcement, Persistent ISR (Intelligence, surveillance and reconnaissance), Straits and Harbor Monitoring, Projection of Power (weaponized UUVs), Under Ice ISR and Territorial Claims, 200+ Mile ROV for standoff capability, Persistent Payload Delivery, Collaborative In-Stride Mine Countermeasures (MCM), Autonomous Offensive Mining, and Submarine/Ship Self Defense. This article will focus on Open Ocean Marine Sanctuary and EEZ Monitoring, Remote Oil Platform Surveillance, servicing for future commercial missions, Persistent ISR, and Autonomous Offensive Mining for future military missions.

Mission: Open Ocean Marine Sanctuary and EEZ Monitoring

The capability to monitor for illicit presence or activities, like illegal fishing, poaching, and even unauthorized scientific activity in marine sanctuaries, together with the ability to monitor EEZ infringement for maritime law enforcement, poses significant challenges, especially for approaches that rely heavily on the use of surface vessels. UUVs, particularly AUVs, would be less costly and logistically less challenging and are weather independent. Furthermore, AUVs provide the ability to maintain an unobtrusive presence to marine life, as well as to illicit actors, when monitoring.

Required Technology Advances and Headlines

To achieve the above capabilities, UUVs need to achieve greater autonomous capability, including navigation in congested areas, obstacle awareness and avoidance, improved reliability, and vehicle prognostic health monitoring and status. Off-shore docking and sustainment, UUV recharging services for deployed sensors and charging, and replenishment for Forward Deployed Energy and Communications Outposts (FDECO) will be essential to supporting the use of UUVs in sustained monitoring operations. The community should look toward developments in UUV-sized diesel capability, use of surface buoys for offshore FDECO development, and announcements of significant advances in obstacle avoidance as trend trajectories leading toward realization of this mission capability.

Mission: Remote Oil Platform Surveillance and Servicing

The ability to conduct Remote Oil Platform Surveillance (inspection) and Servicing includes manipulation for maintenance with multiple UUVs, with charging stations, thus precluding the need for surface support ships. This greatly reduces the resources and costs associated with remote oil platform surveillance, inspection, and servicing.

Required Technology Advances and Headlines

Significant advances in autonomy are required for a group of UUVs to conduct remote inspection and servicing of oil platforms without the need for large surface support ships. This, in turn, illustrates a need for reliable wireless acoustic, optical communications, including the potential need for high bandwidth for remote manipulation. The development of charging stations and remotely operated manipulator development will indicate the imminence of remote platform surveillance and servicing.

Mission: Persistent ISR

The use of UUVs for persistent ISR, especially in support of anti-surface warfare operations, requires the ability to stay on station for long periods of time, both collecting data and avoiding detection. Persistent ISR extends Over-the-Horizon (OTH) targeting to the Anti-Access/Area Denial (A2/AD) envelope, adding robustness to an adversary's A2/AD kill chain, as the undersea component provides far-forward stealthy sensing and presence. Therefore, it is difficult to counter UUVs with inherently quiet signatures. Additionally, persistent ISR using UUVs provides an asymmetric cost imposing strategy, i.e., the adversary deploys low cost UUVs against expensive capital ships.

Required Technology Advances and Headlines

To make persistent ISR with UUVs a reality requires significant advances in artificial intelligence to autonomously conduct the various mission sets associated with persistent ISR, including undersea navigation in congested areas, with an emphasis upon clandestine, open ocean operations, improved reliability, and vehicle prognostic health monitoring. Additionally, providing fire-control quality data requires the ability to conduct autonomous detection, classification, localization, and tracking. Marked improvements to long-range undersea navigation and positioning are also required, as well as improved powering for sustained endurance, e.g., snorkeling diesels, nuclear, at-sea replenishment, e.g., FDECO, or surface ships. This requires long-range, reliable, robust, jam-resistant, OTH communications. Look for developments in robust long-haul data exfiltration capabilities (to provide targeting support) and efforts in collaborative sensing, ad hoc networking, and UUV autonomy and open ocean operations as indications leading to the realization of persistent ISR.

Mission: Autonomous Offensive Mining

The ability to conduct autonomous offensive mining would be an important capability for use against critical undersea infrastructure in denied areas or against adversary ship and submarine platforms off coastal areas. The strategic implications of this cannot be overstated, as the ability to conduct timely and effective offensive mining can be a "show-stopper" for an adversary and provides for potential disruption to critical undersea infrastructure operations and loss of expensive ship or submarine platforms.

Required Technology Advances and Headlines

Several technological issues and considerations need to be addressed to realize this capability. First, energy density needs to be cost-effective and sufficient for increased range and large payloads. Second, as shown with previous mission sets, autonomy is an imperative to allow for mining in very shallow, confined, and congested areas. Third, the ability to accurately navigate is a key component to ensure maximum damage to certain types of critical undersea infrastructure while minimizing collateral damage to non-belligerents. Fourth, stealth will be essential for the vehicle(s) to ensure an adversary does not detect and compromise the mission before its completion. Developments in mine technology and new methods for deployment, together with advances in autonomy, especially advances in unmanned automobiles, testing of obstacle avoidance, and navigation (ocean floor mapping efforts), are key indicators that autonomous mining is imminent.