NAVAL SCIENCE AND TECHNOLOGY

FUTURE FORCE™

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Robots Assemble!

Blueprint to the Autonomous Fleet

SPRING 2014

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ARTICLES

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Front Cover: *BluePrint to the Autonomous,* original artwork by Alvin Quiambao
Back Cover: Photo by Bob Brown

SPEAKING OF S&T

By Adm. Jonathan W. Greenert, USN

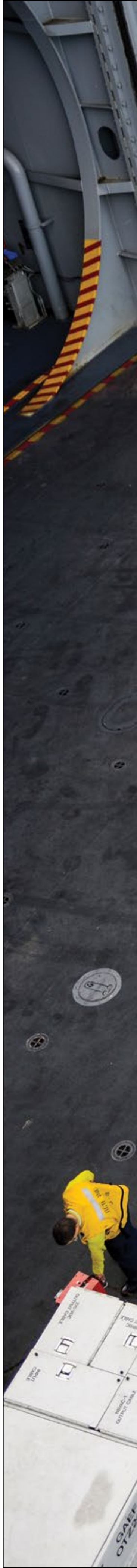
I am honored to participate in the inaugural edition of this new magazine from the naval science and technology (S&T) community. Quarterly, this magazine will highlight the innovative S&T developments and achievements of our Sailors, Marines, Government Civilians—and their partners in industry and academia—as well as the general public. *Future Force* will communicate the impressive work of our innovators and its relevance and significance to our warfighters. With your support and participation, this magazine will highlight emerging capabilities to sustain our Fleet's technological edge on, above, and under the sea and in space and the cyber domain.

This first edition of *Future Force* focuses on autonomy. Autonomous platforms, payloads, sensors, and other technologies are proliferating, particularly via unmanned vehicles, across the globe. Continued rapid advances in computing, artificial intelligence, dependable power and energy, robotics, sensors, and position-guidance technologies combine to make this an exciting and evolving area. Autonomy is a technology we can apply to current and future payloads and platforms to introduce and support new capabilities to retain our warfighting edge.

This edition describes some capabilities our S&T community is pursuing and their potential applications across the Navy and Marine Corps. As you read *Future Force*, I ask you to consider what else is possible—how we can be more effective and efficient—or suggest other areas our S&T community might consider. This magazine is one means to harness the asymmetric advantage of our Sailors, Marines, and Civilians to provide the S&T community with new ideas and concepts to sharpen our warfighting advantage. It will be your innovative ideas that instigate change and retain our advantage.

As we continue to explore and debate new technologies and creative ideas through publications such as *Future Force*, I urge you to pursue innovation, new technologies and the relentless hard work required to bring their capabilities to the Fleet.

Adm. Greenert is the 30th Chief of Naval Operations.



#autonomy

X-47B

Carrier tests of the X-47B Unmanned Combat Air System demonstrator in 2013 resulted in the first takeoffs and landings at sea of an autonomous aircraft. Autonomy in the air, on land, and on and below the sea is here to stay, and will be a vital part of the fleet and force of the future.
(Photo by MC2 Timothy Walter)

http://www.navy.mil/

►► By Colin E. Babb

A Small Tale of Autonomy and the Sea

The English fleet's use of fire ships against the Spanish Armada at Calais in 1588 wasn't the first use of an "autonomous" naval weapon, but it symbolized a desire to create weapons and vehicles without crews that could attack ships at sea. In time, that old desire would eventually be realized. (U.S. Naval Academy Museum Beverly Robinson Collection)

On 27 July 1588, after nearly a week of indecisive action in the English Channel, the ships of the Spanish Armada sought refuge at Calais on the French coast. The following evening, the thousands of Spanish, Portuguese, Italian, and other sailors of the fleet witnessed a terrifying sight: eight ships advancing toward them in line abreast under full sail, flames even then licking up the rigging and lighting the sky in unnatural orange and red hues. Small vessels soon led two of the ships away from the Armada, but the current and wind carried the other six inexorably toward the Spanish fleet. "Of all the dangers to a fleet of wooden sailing ships," wrote historian Garrett Mattingly, "fire was the gravest; their sails, their tarry cordage, their sun-dried decks and spars could catch fire in a minute, and there was almost nothing about them that would not burn." In the face of such a harrowing threat, the ships of the Armada cut their anchors and fled, breaking up their formation and making them vulnerable to the rest of the English fleet, which was in hot pursuit. It was not the last of the Armada, but it effectively ended any possibility of an invasion of England.

The English fire ships at Calais were floating, uncontrolled explosives. They were, to use a modern phrase, "unmanned" vehicles. But they also anticipated the possibility of the autonomous vehicle—capable of action not only without the presence of human beings but also without external control. The technology of the Elizabethans allowed for no sophisticated navigation mechanisms nor timing devices—the crew merely secured the rudder, set any flammables ablaze, and abandoned the ship to the mercy of wind and water. But if ambition and imagination must precede invention, the fire ship was the first crude attempt to create an autonomous naval weapon. It embodied a desire to use technology to wreak havoc and destruction on the enemy while not endangering the lives of one's own sailors. In time, technology would catch up to ambition, and the genuinely autonomous vehicle would become not only possible but an increasingly important part of naval warfare in a variety of roles and missions.

The autonomous vehicle represents the marriage of a host of ideas and technologies. The primary intent of any such vehicle is to accomplish missions too dangerous, tedious, or time-consuming to require a human crew or pilot. Throughout history there have been many unmanned vehicles possessing varying degrees of autonomy—true autonomy has come only in the past few decades—but these vehicles have shared several basic attributes. First, the vehicle must have mechanical technology that provides self-locomotion, as well as the means to carry out its mission. Second, it must have some kind of sensory input, a way of identifying its location and interacting with its environment. Third, and most important, it must have some means of control or artificial intelligence that allows it to integrate its mechanical and sensory capabilities and to act without inputs or action from human beings.

The Technology of Self-Propulsion

In the late 19th century, a series of inventions in the realm of propulsion and energy—from the internal combustion engine to electricity and batteries—made self-propulsion a possibility. In the modern era, the first naval technology to approach a reasonable level of autonomy was the Whitehead torpedo, developed by English engineer Robert Whitehead and Austrian naval officer Giovanni Luppis in 1866 while working with the Austro-Hungarian Navy. Utilizing a name that until then had only been used to describe static underwater explosive devices, the "self-propelled" torpedo was a revolutionary weapon. It also hinted at the possibility of unmanned underwater vehicles. In the United States, the first torpedo to see service was invented by Lt. Cmdr. John A. Howell in the 1870s using a different propulsion system than that of the Whitehead (the latter used compressed air, while the former used a flywheel), and it was adopted in 1889. The Whitehead would eventually win out over the Howell once a gyroscope was added to the former, which solved early issues with maintaining direction and depth.

The QH-50 DASH helicopter was the first unmanned aerial vehicle to be widely used in the U.S. Navy during the 1960s.

During World War I, inventors on both sides of the Atlantic experimented with pilotless aircraft—the first unmanned aerial vehicles. In the United Kingdom, Archibald Low tested the first wirelessly guided aircraft in early 1917. That same year, the U.S. Navy produced the Hewitt-Sperry "Automatic Airplane." Taking advantage of the Sperry gyroscope and autopilot, the Automatic Airplane was essentially a crude cruise missile that crashed into its target after reaching a predetermined distance. The first significant fully automated flight—including takeoff and landing—occurred in September 1947, when a U.S. Air Force C-54 Skymaster flew from Newfoundland to England and returned without any member of its crew touching the controls. Unmanned aircraft subsequently became early contributors to operational military forces—most notably the Gyrodyne QH-50 DASH unmanned helicopter, which served on U.S. Navy destroyers from 1963 to 1969—but autonomy has arrived only with recent aircraft such as the Global Hawk, which first flew in 1998. The first autonomous flight of a full-sized helicopter only occurred in 2010.

During World War II, both the Soviets and the Germans pioneered the use of remotely operated land vehicles—the radio-controlled "teletank" in the Soviets' case and the wire-controlled Goliath mobile mine in the Germans'. Both types of vehicles were used in combat to unremarkable effect. Land vehicle autonomy, however, long remained a significant problem that began to be solved only with the concerted efforts of the Defense Advanced Research Projects Agency (DARPA) in 2004 with the first of its "Grand Challenges," which demanded that autonomous vehicles negotiate complex race tracks more than 100 miles long.

Unmanned underwater vehicles did not receive serious effort until after World War II, but from that point they advanced quickly, building on several generations of work with torpedoes. The first autonomous underwater vehicle, SPURV (Special Underwater Research Vehicle), was built in 1957 at the University of Washington's Applied Physics Laboratory, which had been a center of torpedo-related research during the war. The longtime success of autonomous underwater vehicles—which have included such craft as REMUS and Slocum sea gliders—has been a result of an inherent quality of the ocean: wide-open spaces. Land and air autonomy have suffered from the limitation of potential human and property damage caused by errant vehicles—a problem that is now being resolved with the latest generation of autonomous craft.

Sensing New Worlds

The earliest unmanned vehicles were primarily guided by human direction either using radio control or wires or by some kind of mechanical device that cut out its propulsion at a pre-determined point (such as with the Automatic Airplane or Germany's V-1 flying bomb). Vehicles in the first half of the 20th century were able to achieve these early advances in mobility using the gyroscope and especially the gyrocompass, invented in 1904 by Sperry in the United States and Hermann Anschütz-Kaempfe in Germany. Radio control also would be the primary means of controlling early unmanned vehicles, everything from the tiny Goliath to battleships.

Marvin Minsky helped build the first artificial neural net with a $2,000 grant from the Office of Naval Research in 1951. (Photo by Steamtalks)

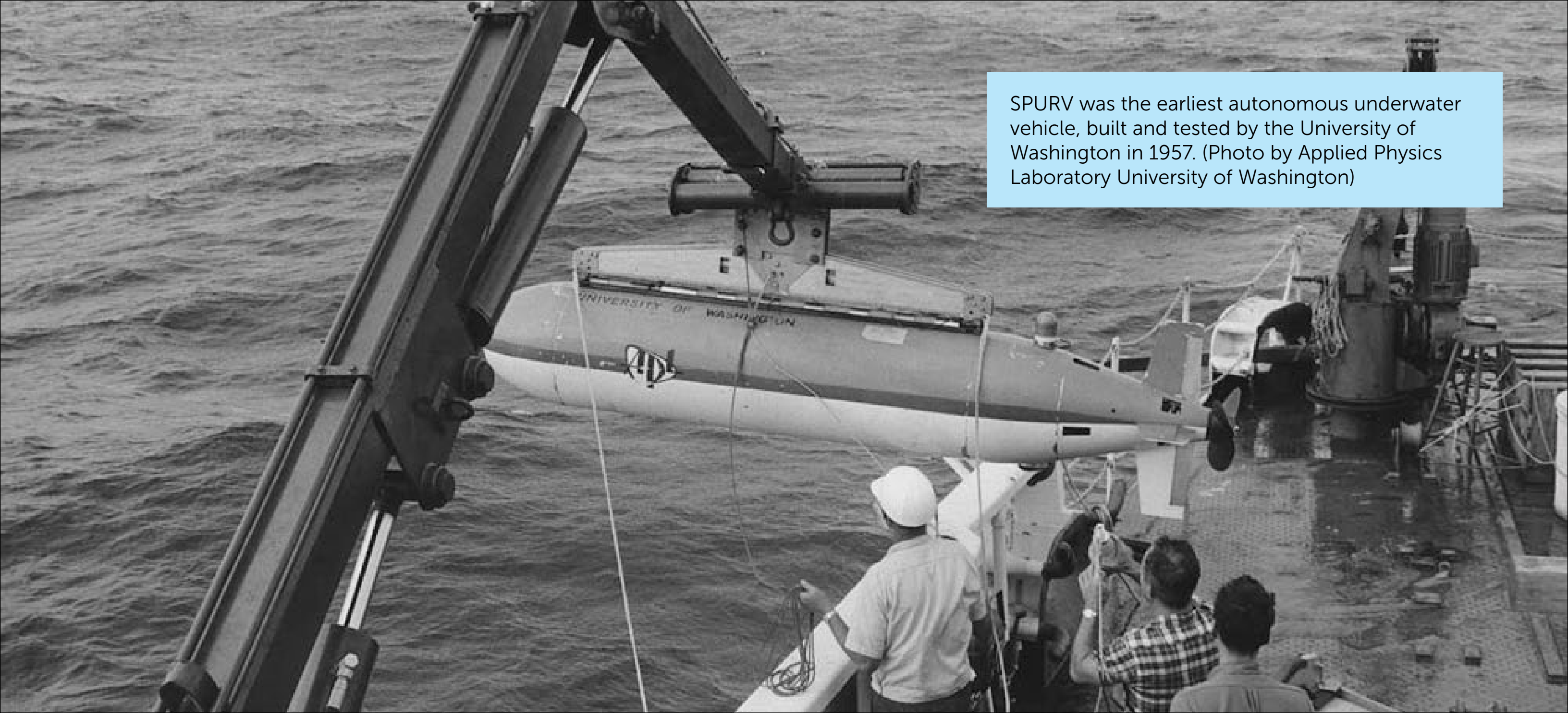
To achieve true autonomy, however, required technology that allowed a vehicle to determine more precisely its position in space. The first satellite navigation system, the predecessor of today's GPS, began in 1964 with the completion of the Naval Navigation Satellite System, or Transit. Developed by a partnership of the U.S. Navy, DARPA, and Johns Hopkins Applied Physics Laboratory, the system used five satellites to create a fix once an hour. The advent of GPS beginning in the 1970s provided a system that was ubiquitous in its global coverage and ability to provide constant fixes in time.

Advances in infrared and motion sensors and lasers also allowed vehicles to better sense their immediate surroundings and determine their positions relative to one another. As with navigation, satellites have provided a way for vehicles to achieve true autonomy in transmitting their data, unshackling craft from line-of-sight connections with traditional communications. Lasers also have proved their ability to provide optical communications underwater, allowing autonomous vehicles the ability to connect with other craft without coming to the surface.

Creating the Artificial Mind

The dream of thinking machines—especially artificial humans—has a long provenance. The Greek god Hephaestus was believed to have created automata in the fires of his forge on Mount Olympus. Jewish legends imagined Golems, artificial men made of clay brought to life by sacred letters written on a piece of paper and placed in the mouth. But it was Czech writer Karel Čapek's 1920 play, *R.U.R.* (Rossum's Universal Robots) that gave a distinctive name to the concept of the thinking machine. It also gave voice to the now common concern about the potential for artificially intelligent creations to turn on their creators (through the play's depiction of a robot rebellion).

As these dreams (or nightmares) were taking concrete shape in the early 20th century, the mechanical means for actually fabricating them were becoming available. Charles Babbage had designed, but did not complete, calculating machines in the 19th century (what he termed "difference engines"). But as with so many technologies, it was the desire to find solutions to military problems that would lead to the most sophisticated practical machines. Specifically, the highly complex calculations necessary for observing, measuring, and plotting the movement of ships and accurately



SPURV was the earliest autonomous underwater vehicle, built and tested by the University of Washington in 1957. (Photo by Applied Physics Laboratory University of Washington)

hitting them with gunfire led to the development of the most advanced analog computers to date in the years just before World War I. The Dreyer Table, first tested in 1911, incorporated technology developed by Royal Navy Cmdr. Frederick Dryer and inventor Arthur Hungerford Pollen. It was the earliest system to plot the movement of ships at sea, and it was used at the Battle of Jutland in 1916. In the United States, comparable technology developed by Hannibal Ford was tested on USS *Texas* (BB 35) that same year, building on decades of work in range keeping and fire control by Navy officers Bradley Fiske and William Sims.

These mechanical computers were the immediate predecessors of the first truly programmable computers (i.e., capable of solving any problem rather than operating on a single task) that began appearing just before World War II. Developed roughly concurrently in Germany, Great Britain, and the United States to solve highly complex problems (analyzing wing dynamics for the Luftwaffe, breaking the German Enigma code for Bletchley Park, and studying artillery ballistics for the U.S. Army, respectively), it was the American ENIAC that reached the highest level of sophistication and capability in 1946. This lead in computing was paired with strengths in the fields of mathematics and neuroscience to create fertile ground for the development of artificial intelligence.

The beginning of artificial intelligence as a definitive area of science is often attributed to a meeting of mathematicians and scientists at a summer workshop at Dartmouth College in 1956. Organized by Nathaniel Rochester, John McCarthy, Marvin Minsky, and Claude Shannon, the workshop was formed under the ambitious proposition that "every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it." Minsky, using a grant from the Office of Naval Research, had helped construct the first artificial neural network in 1951. This early work took its inspiration from the idea, first suggested by British mathematician Alan Turing, that artificial intelligence would be achieved once a human interrogator could no longer tell the difference between the answers of another human or a machine (what is now called the "Turing test").

The early years of artificial intelligence focused on language and gaming, teaching computers how to recognize language and how to solve problems using "simple" games such as chess and checkers. Indeed, the most notable successes of artificial intelligence, such as IBM's Deep Blue beating world chess champion Gary Kasparov in 1997, have been in the realm of game playing. Military applications are now presenting artificial intelligence with much greater challenges than merely winning board games or Jeopardy. As articles in this first issue of *Future Force* demonstrate, the sciences of artificial intelligence and autonomy are being directed at problems as complex as operating vehicles and managing computer networks, and as diverse as running ship systems to flying cargo over hundreds of miles, all without human input.

Despite many advances in the past century, the science of autonomy remains very much in its youth. Turning's optimism that machines would one day perfectly mimic human beings still remains an unfulfilled dream. This issue of *Future Force*, however, illuminates how today's naval researchers are dedicated to making the fleet and force of the future by building on the successes of the past.

About the author:

Colin Babb is a contractor who serves as the command historian for the Office of Naval Research and is also managing editor of *Future Force.*

MAN AND MACHINE: A Revolutionary Synthesis

By Andrea Hein

Imagine an aircraft that deploys from a carrier and encounters enemy fire. With the pilot wounded, it's now up to the co-pilot to take over, navigate back to the carrier, and land.

Now, imagine the co-pilot isn't human.

What used to be considered science fiction is becoming science fact for the Department of Defense, through the research and implementation of autonomous systems spearheaded at Naval Air Warfare Center Aircraft Division (NAWCAD) at Naval Air Systems Command (NAVAIR) in Patuxent River, Md.

From roadside bomb-sniffing robots to machine-piloted aircraft that land without human aid, autonomous systems have a major role in the present and future of warfighters.

What Is an Autonomous System?

Stephen Kracinovich, NAWCAD's director of autonomous systems, describes autonomous systems as possessing the capability to take data from sensors, process the data using sophisticated algorithms, and react accordingly.

"Most autonomous capabilities are software-based," Kracinovich said. "You can basically take any legacy airframe and add a separate mission environment, which is a general purpose processor with a data bus, adding mission software into the system and therefore autonomous capability."

An autonomous system can combine multiple elements under a single operator's control. That operator is supervised by a human mission manager, easing potential concerns of a system taking uncontrolled action.

The systems are meant to augment rather than replace humans, with the collaboration between the computer and its operator or human counterpart being the key.

The increasing complexity of technology used by warfighters ensures autonomous capabilities have a place in both manned and unmanned systems. Humans are faced with performing more difficult tasks that computers are capable of completing more effectively, such as performing several complex actions at the same time, responding quickly to signals, or storing information for a set amount of time.

"If you are a mission manager and you were just presented with vast amounts of data, you could never go through it all," Kracinovich said. "You have all these different sources of information coming at you while an aircraft is flying around at hundreds of knots and taking in information that's changing dynamically. No human could rapidly go through that and effectively sort it out. It's perfect for a computer—this is what they're great at."

Current Research

Future warfighter success depends on staying at the forefront of technology. To do that, NAWCAD leaders emphasize the importance of crucial technological advances in the

workforce to keep up with the complexity of new systems and stay competitive on a global scale.

"Autonomous systems are a focus area of our NAWCAD Strategic Cell to ensure that we remain relevant now and in the future," said Gary Kessler, executive director of NAWCAD and deputy assistant commander for test and evaluation at NAVAIR. "This focus area has game-changing opportunities for warfighting capabilities and manpower effectiveness and efficiencies."

The ability to process information, make critical decisions, and implement those decisions drives a successful mission. Integrating autonomous capabilities into manned platforms bridges the gap between shortfalls by simplifying tasks for humans.

"The focus is to put this capability on our legacy aircraft," Kracinovich said. "We need to re-manage our software architectures, revise our contracting and acquisition strategies, and bring these capabilities to bear on both legacy and new capabilities."

Current tasks that could soon benefit from autonomy architecture are aerial refueling and landing on an aircraft carrier—considered two of the most difficult maneuvers in naval aviation.

Autonomous aerial refueling (AAR) technology using autonomous aircraft that maneuver on their own toward, and engage with, refueling tankers has the potential to make in-flight refueling safer. In addition, the Joint Precision Approach and Landing System (JPALS) could demonstrate that GPS-based technology can help a plane land autonomously in all weather conditions.

These autonomous systems, currently in the testing phase, may be retrofitted into legacy aircraft, making them safer and cutting down on human error because of fatigue or task saturation.

Autonomy is more than simply smart machines: it is the synthesis of the human and the artificial, producing something that is superior to each part alone. (Photo by Sgt. Bobby J. Yarborough)

"Humans have limitations," Kracinovich said, "but coupled with an autonomous tool, we can do things that we were never able to do before, and that's really what we're looking for in autonomous capabilities."

Modern aircraft such as the P-8A Poseidon and the F/A-18E/F Super Hornet have mission management systems that could support an applications-based design. This would allow a third-party vendor to develop brand new capabilities that could be installed on the aircraft.

The Challenges

"One of the challenges comes with our acquisition strategies," Kracinovich said. "Current strategies make it difficult to procure autonomy software because our existing architecture doesn't align with it."

Kracinovich compared integrating autonomy software into existing architectures with purchasing and using applications for smart phones.

"It really comes down to the underlying infrastructure where everything goes into the architecture," he said. "If you purchase an app with your smart phone, that app probably came from a third-party vendor, so your smart phone has to have an open architecture. You don't have any rights to that app, other than you are able to use it. But it can easily be on my phone or somebody else's phone, and the reason is because it was designed to work in a common architecture."

Kracinovich said one solution lies with modular open systems architecture (MOSA). Current Defense Department systems are controlled or managed by a single vendor, meaning any hardware, software, or additional applications for a system must go through that same vendor. The results are long lead times, even in urgent cases, or platform-unique designs that limit the re-use of software and increase costs and barriers to competition within and across platforms.

An RQ-21A Blackjack, part of Naval Air Systems Command's Navy and Marine Corps Small Tactical Unmanned Aircraft Systems Program Office (PMA 263), launches for acceptance testing at a range in Boardman, Ore. (NAVAIR photo courtesy of Insitu Inc.)

MOSA is a standard common operating environment that would support portable capability-based applications across Defense avionics systems. MOSA would reduce life-cycle costs, shorten development and delivery time, and maximize interoperability between systems. Transitioning to a MOSA would provide multiple supply sources and options for integrating new and different technology into existing systems. This cherry-picked approach would allow legacy aircraft to receive upgrades as technology becomes available, regardless of the vendor.

For the Unmanned Combat Air System Carrier (UCAS) demonstration program, F/A-18, and Calspan Learjet surrogate aircraft were used to prove that the autonomous, unmanned aircraft systems and software were ready to be tested in the unmanned X-47B. This led to the eventual launch and recovery of the X-47B on an aircraft carrier, the first catapult launch and recovery of a strike-sized unmanned vehicle. Manned surrogates are also being used to develop AAR capabilities that include rendezvous, approach, and safe separation of the receiver and tanker aircraft. Autonomous carrier landing and AAR capabilities could eventually be integrated into manned systems as well as unmanned.

"The main reason we are developing unmanned systems is because their nature can bring certain capabilities to the table which complement the warfighter," Kracinovich said. "It's going to be a long time before we can develop autonomous systems that are as flexible as a human. We don't want to replace the warfighter; we want to provide tools that can enhance their mission capabilities. That's really what it's all about."

Future Capabilities

Organizations such as the Defense Advanced Research Projects Agency are looking at unmanned vehicles that might have the capability of launching from air-capable ships such as destroyers and frigates. Developmentally tested through NAWCAD, the RQ-21A Blackjack, a program of record with NAVAIR's Navy and Marine Corps Small Tactical Unmanned Aircraft Systems (PMA 263) program office could fit the bill.

The aircraft would provide intelligence, surveillance, and reconnaissance capabilities for the ships, increasing situational awareness and providing support to other vessels in the area. The vision is that multiple autonomous systems could work in conjunction to provide sweeping capabilities.

For instance, if a destroyer had a Blackjack onboard and an MQ-4C Triton providing maritime surveillance discovered a suspicious vessel in the destroyer's vicinity, it could communicate to the destroyer that it should launch the Blackjack to identify the contact and report back.

"Having autonomous components that can easily move between different assets is very important," Kracinovich said. "It not only saves money, it improves interoperability, because if there are similar algorithms running in that Blackjack aircraft that are running in a Triton aircraft, the systems are more easily able to share data."

The Path Forward

Kracinovich said commercial autonomy is going to take the lead in the not-so-distant future, making partnerships with industry critical in order to leverage better and more affordable capabilities for warfighters.

Kracinovich shared his vision of a "Silicon Valley of Autonomy" in southern Maryland that would support the Defense Department and influence the direction of the commercial industry.

"It's our goal in NAWCAD to partner up with academics and contractors in our region to be able to have a lot of this future developed in our region, so we at the DoD can leverage it to provide better capabilities, cheaper, to the warfighter," he said. "We are not going to subsidize it, but we can help create the environment and leverage and influence it. That's in the best interest of the warfighter and so that's one of our goals."

NAWCAD is partnering with the University of Maryland to establish an autonomous systems institute, while the State of Maryland has funded a research center at the Southern Maryland Higher Education Center.

"Our future missions are going to require much more intelligence and much more information, which our autonomous systems lend themselves to," said Kracinivich, because of their high endurance and ability to cooperate with larger systems. "Our country expects us to achieve those goals, and the only way we are going to be able to do that is to bring autonomous capabilities to bear."

"The main reason we are developing unmanned systems is because their nature can bring certain capabilities to the table which complement the warfighter."

About the author:

Andrea Hein is a writer with Naval Air Warfare Center Aircraft Division communications support.

Birds and Bees Use It—Why Not Autonomous Vehicles?

By Terry Bollinger and Keith Hammack

What do birds and bees do that you may want your autonomous vehicle to do?

See polarized light, of course. Birds, bees, and many other forms of life on land, in the air, and even in shallow seas can see and use polarized light to help them navigate in their environments. Since polarized light is free, easy to detect, and abundant, why not use it to help autonomous vehicles glean additional localization and navigation information from their land, sea, air, and shallow-water environments?

This is exactly the question that a company called Polaris Sensor Technologies in Huntsville, Ala., is trying to answer. Using a Small Business Innovation Research (SBIR) grant from the Office of Naval Research's Expeditionary Maneuver Warfare and Combating Terrorism Department, Polaris is looking at how polarization-assisted navigation could help ground vehicles find their bearings in the absence of GPS or other location methods. Success in ground vehicles also would benefit autonomous vehicles traveling through empty stretches of sea or air when GPS cannot be used or trusted.

Seeing the Light

So what is polarized light, and why is it relevant to autonomous navigation?

Human eyes and most cameras treat light as if it consists of a lot of little particles of various colors. While that works well for imaging and

many other uses, light is actually a wave whose dynamics closely resemble those of a jump rope. If you grasp one end of a jump rope and move it quickly back and forth, you will see simple sine waves travel down its length. The orientation of these waves—vertical, horizontal, or anything in between—depends on the orientation of the invisible line along which you moved your hand. The equivalent light waves are said to be "linearly polarized" and, like the waves on the jump rope, can be vertical, horizontal, or have any angle between. Alternatively, you could have moved your hand in clockwise or counterclockwise circular patterns, which would have sent corkscrew-shaped waves down the rope. The light wave equivalents of these are said to be "circularly polarized," and they, too, come in clockwise and counterclockwise versions. Linearly polarized versions of light can be distinguished by using ordinary polarizing sunglasses, and the two forms of circularly polarized light can be seen by using the two lenses of the most common form of 3-D movie glasses.

Most natural light is a mixture of randomly oriented vibrations, which is why we can usually ignore polarization. However, there are two important natural sources of linearly polarized light. The first is light reflected from flat surfaces. Properly processed, this form of polarized light can make manmade objects stand out in a way that is not possible with any other video processing method. Since manmade objects are a relatively new thing in the world, there is no analogue in natural life to this use of polarized light.

The second natural source is the sky, which scatters the light of the sun in a mathematically precise polarization pattern that captures both the direction of the sun and latitude information. Linear polarization in this case behaves roughly like having small arrows painted onto every part of the sky. These polarization arrows make it possible to discern which way is north even when only small fragments of the sky are visible. Birds, bees, fish, and insects all make use of this handy resource to help them navigate. Replicating such capabilities with modern sensors and computer hardware is main focus of this SBIR effort by Polaris. While not a complete substitute for GPS, careful use of this free and inconspicuous source of natural geo-location information can provide an autonomous vehicle with valuable real-time updates and verifications of where it is and what direction it is pointing.

The use of polarized light for navigation has a long history, going back to the days of Viking seafarers who used "sun stones" to locate the sun in the often inclement weather of the North Atlantic. (Photo from Wikipedia)

Clues from the Past

If polarized light is so useful for navigation, why hasn't it been used in the past? The answer is that it has, but without critical advantages made possible by modern computing and data fusion methods. In fact, the very first use of polarization for navigation was by people who sailed the North Atlantic hundreds of years ago: the Vikings. By employing a naturally occurring form of crystalline limestone called Iceland Spar or "sun stones," Viking ship navigators could see and use polarized sky light on overcast days to help find locations and bearings.

Modern military use of polarized light navigation began in 1948 with the Pfund Sky-Compass, a polarized light compass that was intended for use during summer flights in the Arctic. Crossing the Artic was a particularly good application for polarized light navigation, since magnetic compasses fail in that region, the polar sea is featureless, and in the summertime the stars are not visible. Scandinavian Airlines has made the most use of this technology, since many of its flights require it to cross the kind of barren landscapes that baffle conventional navigation systems.

The first use of polarized light in robotic vehicles was in 1997, when the University of Zurich created the Sahabot series of insect-mimicking test vehicles to explore an ant-like use of polarized light for navigation. While proving the concept, this work was focused more on understanding how polarized light is used in biology rather than how the technique could be used more broadly in complex environments. (Photo by University of Zurich)

Moving Forward

The focus of the new work by Polaris is taking examples and hints from past work and moving them into a modern era of radical miniaturization, inexpensive and large computational capacities, and improved algorithms for comprehending and merging the information from polarized light with other resources. One example is that because entire global maps now can be stored in small computational devices, the location and orientation information from polarized light can be used in combination with new resources, such as miniaturized inertial guidance, to verify and validate locations in ways that were not possible in the past. Autonomy itself, with its ability to assess and evaluate data sources in more human-like ways, also adds an important ingredient by allowing an autonomous vehicle to assess and weigh the value of multiple information sources in new ways. Polarized light holds real promise in military and commercial applications to provide critical location data even when other forms are unavailable.

About the authors:

Terry Bollinger is a MITRE employee working full time on autonomy research and technologies for the Expeditionary Maneuver Warfare and Combating Terrorism Department at the Office of Naval Research. He was also chief scientist for a small team at the Office of the Secretary of Defense that looked for emerging commercial technologies.

Keith Hammack manages research programs in ground vehicle autonomy, fuel efficiency, mobile power, mobility, and survivability for the Marine Corps, Naval Expeditionary Combat Command, and Naval Special Warfare Command. He was previously deployed as a combat company commander with the U.S. Army.

(Photo by John Williams)

Autonomy Is a Must for Ship Systems

By Anthony Seman

Integrating—and automating—systems will free personnel for other tasks and help manage increasingly complex ships.

Future naval superiority depends on the need to control the tempo of combat operations, rather than merely to act and react rapidly. The quality and speed of decisions must be superior to those in an adversary's decision cycle. To maintain and improve this capability within the context of a rapidly advancing technological landscape, the Navy must implement new advanced capabilities into its shipboard systems. Future naval ship systems—combat as well as hull, mechanical, and electrical—will embody a much deeper level of integration of functionality. This integration is crucial to achieve greater combat power. Most important, optimizations will be in the context of mission, condition, and environment—all of which evolve dynamically in real time. These systems will not be realized or affordable within the current approach to naval machinery systems design and construction.

Operational characteristics of these "systems of systems" will embody greater interactions and interdependencies, and therefore manifest greater complexities in operation. This complexity will be such that human operators will not be able to implement optimal configurations—especially cross-platform—through traditional direct manipulation. The level of integration of these systems creates a set of possible configurations and states so large it is impractical to identify and evaluate completely, either at design time or during operation. Implementation of autonomy in monitoring and control, which feature predictive and adaptive approaches, will be required.

Capability Assessment

Effective mission planning and execution monitoring not only requires increased state awareness, but also the ability to assess future capability in terms of mission. This capability assessment must be present at the platform level and decomposable down through all ship systems and subsystems. A capabilities-based readiness assessment uses in situ modeling and simulation—again decomposed to the lowest levels—by being embedded into monitoring and control. This capability is constantly running in the background: monitoring, reasoning, performing simulation projection over operational and situational information, and developing options. This reduces the burden on operators so they can focus on critical tasks and decisions. With this intrinsic capability, more effective and timely dynamic planning, replanning, and reconfiguration are possible. Across the spectrum—from battle group mission planning to low-level subsystem control—optimal configurations will be based on mission intent and system capability predictions.

Capability assessments should take the form of an "analysis of alternatives"—including multiple configurations/alignments (plans), their predicted effectiveness against mission over time, and the costs, risks, and confidence level in the analyses. The scope of possible alignments can and should include the options of "run to failure" and "perform maintenance." The idea of assessing capability against mission—reporting out quality of those capability assessments—is not new to warfighters. Embedding this capability into all levels of shipboard machinery control, however, and implementing it using autonomy, will provide the Navy with a leap-ahead capability.

Shipboard Control

Naval shipboard control can be grouped in terms of reasoning into three levels: platform (multisystem) control, system control, and device control. Platform control is performed by human operators, based on mission inputs, to plan a series of tasks the platform needs to accomplish. It is strategic in nature, controlling platform effects over time. System control, currently performed by operators, plans and executes a series of plant configurations over time. This executes the planned platform tasks according to the planned schedule. It is tactical in nature, controlling configuration over time. The lowest level, device control, maintains operation of the machinery in support of the planned tasks. It is operational in nature, controlling physics over time.

Autonomy in System Control

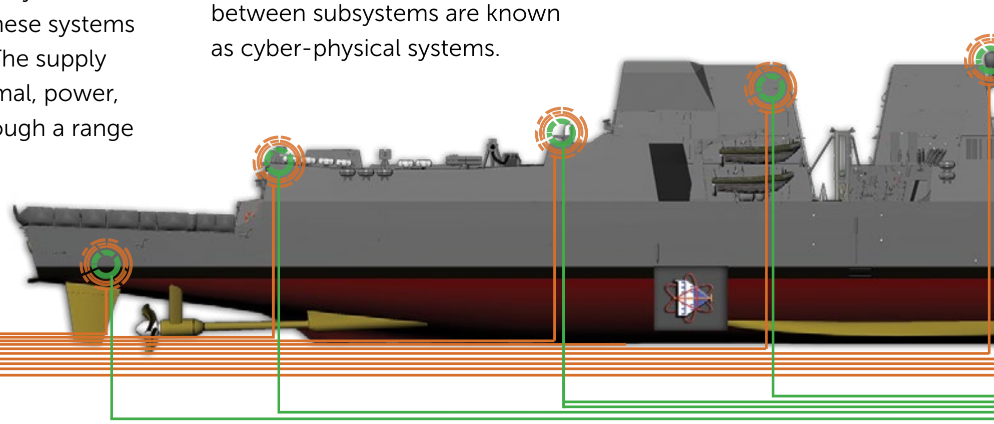
The goal of current research efforts at the Office of Naval Research (ONR) in machinery control is to apply autonomy to the middle layer—system control. This autonomy will perform some of the human reasoning functions to determine optimal system configurations rapidly. The challenge is that the number of possible configurations and states in systems of systems control becomes so large that prior calculation and evaluation of all possible states becomes impractical or even impossible. The large amount of system states also can lead to emerging system behaviors and complexity that would be unaccounted for with traditional control system design. It is an objective of autonomy to address this behavior, as well. Effective control of complex systems can be produced by "intelligent control," which, unlike feedback control, uses reasoning techniques to identify a solution for the current situation.

A primary function of naval ship machinery systems is to supply resources to loads. The nature of these systems is largely distributed and heterogeneous. The supply of these resources—such as air, fluid, thermal, power, and information—must be maintained through a range of possible accidental or deliberate perturbations in a very dynamic environment. The supply of resources is finite, and in the context of new, energy intensive combat systems there will not be excess capacity to service all priority loads simultaneously. Resource distribution throughout the platform will require a sophisticated management approach.

System control autonomy will perform some of the human reasoning functions to rapidly determine optimal system configurations and to free up human operators to concentrate on the platform control. (Photo by Eric Anderson)

Ideally, the control system should enable a configuration that effectively supports the successful execution of a predetermined goal, within specified constraints, and in context of the environment. In this case, it is to supply a resource to a load to achieve a combat objective. The constraints, or optimizations, could be speed of execution, energy used, efficiency, safety, or impact on future combat capability. Today, this type of reasoning is performed by human operators, including how to set and maintain control system inputs to achieve the desired goals. In the context of multiple, large-scale, interconnected, heterogeneous, distributed systems, human operators will not be manipulating these systems at a representation similar to a local machine control panel. Because of the level of integration, the human would not have the state awareness, or the time to amass and assess it, to provide optimal control actions from a larger perspective.

The autonomy required for machinery systems has an added dimension that makes it different from autonomy for remote unmanned vehicles. Unmanned vehicles are primarily coupled together only through information flow—machinery systems are much more complicated because of the strong physical couplings between the subsystems. Systems that have these complex couplings between subsystems are known as cyber-physical systems.

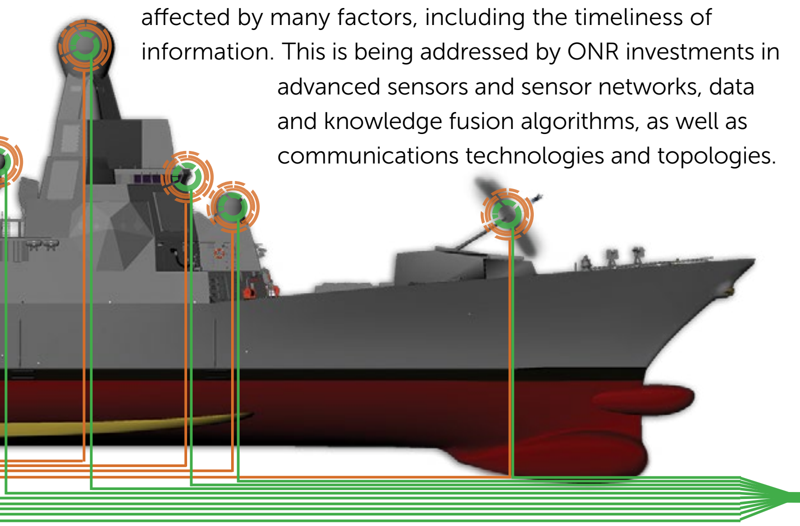


Intelligent Agent-Based Distributed Control

A multi-intelligent-agent-based, distributed-control-system approach is a viable solution for implementation of autonomy in shipboard systems control. An intelligent agent is an independent software entity that manages subsets of the physical plant. Agents are capable of responding very rapidly to devices within their spheres of control. Agents collaborate by communicating observations and commands. In an agent-based system, in which multiple agents work together to address a complex problem, agents address local issues while also communicating and deliberating with other agents to create global solutions. Intelligent agents would be hosted on programmable logic controllers. ONR has invested in agent-based research for shipboard machinery systems for many years and is moving toward transition to full-scale hardware implementation.

This distributed control approach mirrors the distributed nature of the systems themselves. By moving away from a centralized control approach (but not away from top-level directives), there are two advantages: the control system's ability to avoid or mitigate faults and disruptions is improved, and real-time evaluation of a greater set of possible control actions can be performed within practical time and resource constraints. This local optimization, bounded by top-level mission directives, context and constraints, would help achieve better and more timely global optimizations.

A key component to optimal control decisions is accurate and timely state awareness. It is a given that no system will have complete state awareness all of the time, especially at all-system scales. There can be sensor faults, communications channel noise, accidental and malicious disturbances, etc. The control system will always have only an estimate of system state, whose usefulness is affected by many factors, including the timeliness of information. This is being addressed by ONR investments in advanced sensors and sensor networks, data and knowledge fusion algorithms, as well as communications technologies and topologies.



Another intrinsic piece to this architecture is in situ modeling and simulation of the systems of systems under control. Mission directives and system condition and health would be provided as system inputs. Simulations would be run forward in time to assess capabilities. Optimal solutions would be selected based on simulation results. This pervasive modeling and simulation exists at all levels of the machinery control system, at appropriate levels of accuracy and granularity because of time and resource constraints.

Future Development and Acquisition

Naval machinery systems autonomy is planned for full implementation aboard the next future surface combatant platform. This vessel will have multiple high-power weapons and sensors, such as the Free Electron Laser and the new Air and Missile Defense Radar. Each of these systems requires unique types of (pulsed) power that is different from what current ships' power generation will provide.

The Navy cannot afford to have each system bring its own storage and conversion because of size, weight, and cost constraints. The future ship's power system must provide all required storage and conversion, as currently planned for in Naval Sea Systems Command's Electric Ship Architecture and Energy Magazine concept. This new architecture will contain multiple types and multiple quantities of energy storage and conversion technologies, spatially distributed throughout the platform. A new control system is required that will manage power from these multiple shared energy generation and storage devices, as well as concurrently control all other associated resources, such as cooling and information systems.

The system will have to anticipate and pre-position power to where it needs to be—the right type, at the right time, and to the right weapon. It will use the concepts and technologies discussed here to execute optimal configurations of resources to loads, from a total ship perspective. Autonomy in ship machinery control systems will be a capability enabler for the future surface combatant.

About the author:

Anthony Seman is a program officer with the Office of Naval Research's Ship Systems and Engineering Research Division and manages the science and technology portfolio for hull, mechanical, and electrical machinery systems automation. His current research is focused on complex systems-of-systems modeling and control for distributed naval machinery systems.

(Photo by MC3 Kevin J. Steinberg)

Multivehicle Autonomy Is Taking off

By Dr. Marc Steinberg

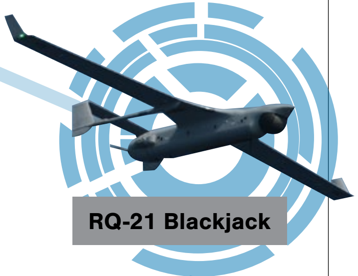
A single naval operator manages a diverse team of air and sea systems to find and track a suspicious vessel covertly. Rather than controlling individual systems, the operator directs the actions and behaviors of the team by specifying high-level mission objectives, constraints, allowable risks, and the types of decisions the system can make even on its own. Elsewhere, unmanned surface vehicles (USVs) escort high-value assets in a contested environment. One USV has unexpected engine problems, and the system automatically readjusts the plan to complete the mission. On a single 11-meter, rigid-hulled inflatable boat, a small explosive ordnance disposal team controls multiple undersea and surface vehicles. The users task the system through a common interface to conduct cooperative area searches, reacquisition, and identification tasks more quickly. Under the sea, networked, mobile autonomous systems sense the environment to support oceanographic research and tactical operations in situations where environmental conditions are highly variable. The systems work together on tasks ranging from following gradients to making decisions on how best to sample the environment based on high-level goals. On the shore, a user requests tactical intelligence services from a distributed group of autonomous systems with a simple app-like interface. Mission tasks are allocated among the group to search, monitor, and patrol in a poor communications environment. To do this, the user does not require detailed understanding of how the autonomy operates.

These may sound like futuristic concepts, but they actually represent real multivehicle demonstrations that leveraged technologies developed by the Office of Naval Research (ONR). These kinds of experiments have become increasingly common both within and outside the defense research community. Examples can be seen in university videos posted on YouTube and in even some commercial applications, such as warehouse robotics. Some naval experiments were done as part of fleet exercises such as Trident Warrior or Rim of the Pacific. Others were done with commercial off-the-shelf systems as part of standalone experiments or in more informal events such as the Naval Postgraduate School/Special Operations Command field experimentation program.

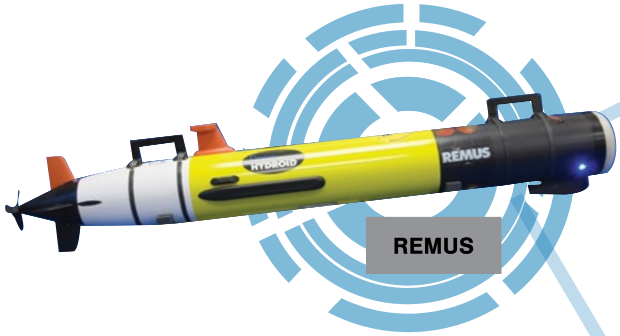
Beyond these examples, laboratory experiments are increasingly using inexpensive and expendable systems managed at a mission rather than individual vehicle or

sensor level. The ultimate goal is robust self-organization, adaptation, and collaboration among highly heterogeneous platforms and sensors in a contested and dynamic battlespace. This kind of collaborative autonomy may be applied to missions as diverse as surveillance, electronic warfare, or logistics. Another goal is reducing the reliance on centralized command and control by using flexible decentralized systems that have the ability to get the right service to the right user at the right time. Collaborating systems may provide a survivable mission capability that cannot be easily defeated simply by losing individual platforms or sensors. They also may be able to do things that would be unaffordable or impractical otherwise. For example, there is a need for large, persistent, and pervasive sensing networks for battlespace awareness. However, it is likely that there never will be a sufficient number of people to manage and control so many platforms and sensors individually or to analyze and assess directly the large amounts of data such systems can collect.

Another important aspect of multivehicle autonomy capabilities is the extent to which the barriers to entry have become very low. Open architectures, such as the Robotic Operations System and the more maritime-oriented Mission Oriented Operating Suite, make many of the underlying component technologies easily available to anyone with the technical sophistication to leverage them. Online forums provide help for less-skilled individuals and groups, including open-source projects such as the DIYdrones.com autopilot and online designs that others can rapidly build, improve on, and share. Inexpensive commercial hardware, such as smart phones and video game motion sensors, combined with commercial vehicles provide the opportunity to scale up multivehicle systems in ways that not that long ago would have taken tens or hundreds of thousands of dollars to accomplish. Desktop and other rapid-manufacturing technologies such as 3-D printers, laser cutters, and desktop milling machines make it easy to add custom parts to the mix. Taken together, this puts the ability to create multivehicle systems into a variety of hands from states to small networked groups. This will only get easier as the relevant technologies advance.



The development of this kind of autonomous capability is expected to be an evolutionary process with systems increasingly able to complete missions independent of humans and cooperate more effectively with warfighters and other systems. Multivehicle collaborative systems build on decades of research advances in enabling technologies in areas such as autonomous planning and optimization, decision making, perception, navigation, and control. For example, ONR has conducted several on-water demonstrations of USV autonomous hazard



avoidance, collision regulations compliance, and tactically relevant autonomous behaviors at ship speeds of up to approximately 30 knots. With this level of enabling autonomy, it becomes possible to consider new multivehicle/human interaction concepts that can leverage human strengths in cognitive skills, judgment, and tactical understanding in managing teams of systems, while freeing warfighters from tasks that can be achieved effectively by machines. Warfighters should be able to leverage their knowledge of the battlespace without needing to be experts on all the low-level workings of autonomous systems.

A number of programs have demonstrated supervisory control of fewer than 20 heterogeneous unmanned systems on the basis of high-level mission criteria such as objectives, priorities, risks, and constraints. What is feasible today can be highly dependent on the challenges of the environment, the complexity and time-criticality of the mission, and the level of skill and experience of the users. The operational tempo and environmental challenges of mine countermeasures, for example, has been a good match with the current state of multivehicle technology. Three of the major enabling technology limiters are the ability of individual vehicles to get on station, navigate through their environments safely in areas with other vehicles/units, and perform useful mission functions on their own with minimal human intervention. These exist to varying degrees in different mission domains, but there are technological limitations that depend on the difficulty of the environment, the complexity of the mission, the type of user, and the limitations of individual platforms. Further, the more mature approaches that have been demonstrated frequently depend on either centralized control or some degree of periodic centralized coordination or calculation.

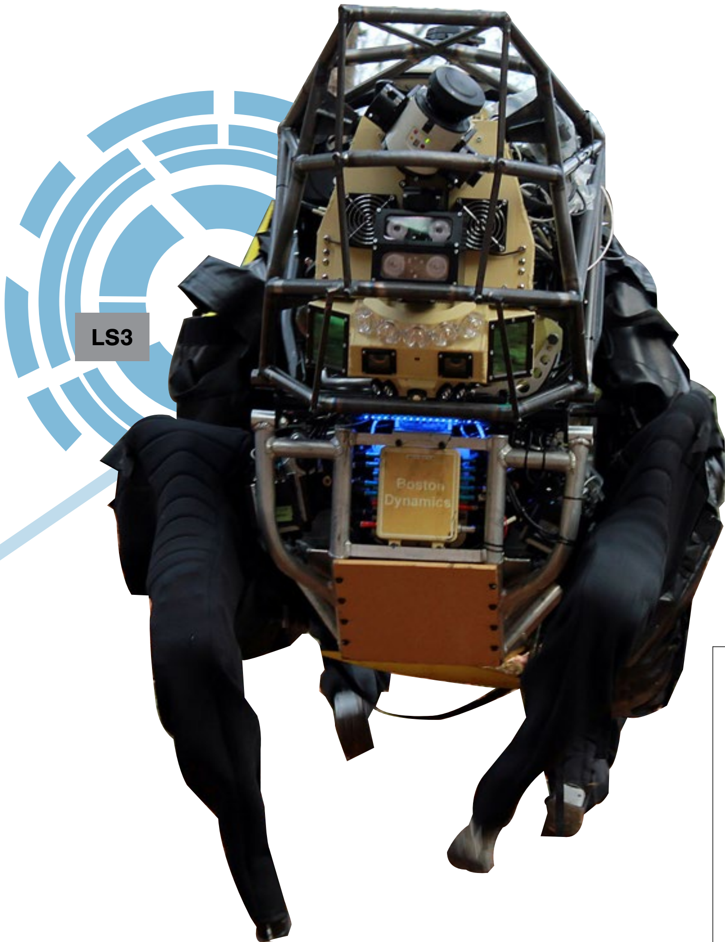
One flight-demonstrated example of this is work on market-based approaches, where individual platforms or sensors "bid" on available mission tasks based on the "costs" (such as time or risk) involved in doing that particular task. In this case, much of the calculation is done at the individual system level. It does, however, ultimately require some centralized nodes to coordinate the task allocation. Another example demonstrated at sea was gradient following with collaborating autonomous undersea vehicles. The vehicles made their own decisions in a distributed way, but there was a need to share data to calculate the gradient at a centralized node and share that amongst the platforms.

Further in the future are research projects looking at highly decentralized concepts that can operate in very limited communications environments and on missions, such as force protection, where individual systems may need to act and adapt rapidly based on locally sensed information. For example, there are new approaches to the above-mentioned gradient-following problem that require no explicit communication—only that the vehicles keep track of the positions of their nearest neighbors. One promising area ONR has been exploring is looking for inspiration from collective animal behaviors in nature.

The natural world provides many successful examples of organizational structures that are scalable and able to operate with limited communications, noisy sensing, and a lack of centralized control. In addition, many of these biological systems have evolved to adapt to considerable amounts of uncertainty in their environments. Inspiration may range from social insects to fish schools to smaller groups of more intelligent animals, such as wolves, dolphins, and nonhuman primates. The resulting engineered systems may be very scalable. Simple individual units with minimal communications can lead to versatile group behavior with minimal or no direct communication. It may be enough just to keep track of a few nearest neighbors visually or coordinate indirectly through effects on environment. In this kind of structure, collective decisions can arise from interactions of simple elements, and actions can be made based on local information. The system does not require a centralized common operating picture or direct sharing of mission data, as there may be mechanisms to make decisions at a collective level that do not require any individual to have all the data. These systems are not necessarily leaderless, but leadership can be an emergent and transient property that is not vulnerable to the loss of a command-and-control hierarchy.

ONR is funding basic research programs that may someday support the ability of a hybrid human/robotic team to operate more effectively than a fully human or machine one by taking advantage of the things each does best. Moving from the current state of the art to more effective human/robotic teaming relationships may require reaching across currently separated disciplines to develop common frameworks that incorporate models of human and animal intelligence, new empirical and experimental techniques, and mathematically rigorous methods.

It also will be important to explore a broad range of human machine relationships. Current interfaces largely allow the human to task the robot, determine when the robot needs help, provide that help, and prevent the robot from doing something undesirable. If there is initiative on the robot's side, it is often to request human help and not the reverse. To be effective team partners, robots will need to be able to recognize when the human needs help or information and then act in an appropriate, trustworthy, and nonintrusive way. Related to this is the general need for autonomous systems to have substantially improved teaming skills. These are critical for high-functioning human teams but may require solving some of the hardest problems in computational intelligence and robotics to achieve human capabilities in an engineered system. Luckily, not all robotics teaming problems require human levels of teamwork. Hybrid human/machine teams may enable new teaming arrangements that are not practical with all human ones. Thus, it is important to consider a broad range of capabilities rather than just focus on an ultimate goal of trying to duplicate the capabilities of high-functioning human teams.



From today's more mature approaches to a possible future of hybrid human/machine teams, there are a rich variety of autonomous systems and concepts that could be leveraged to deal with future naval missions. For some time to come, key limiting factors of autonomous systems are likely to be their capabilities for understanding relevant features of their environment, interpreting and fusing sensor data, navigating through uncertain and dynamic environments, dealing with limited and unreliable communications, and transforming complex mission requirements into both group and individual behaviors. Integrated man/machine systems also must be attuned to these limitations and take advantage of the different strengths and weaknesses of both humans and machines. The technologies being developed and demonstrated under a wide variety of ONR and naval research programs provide stepping stones toward control of much larger numbers of systems on more complex missions. We are still in the early stages in terms of understanding how best to use these technologies to transform future operations. With each new experiment, fleet exercise, and fielding of this type of technology, their future may become more clear.

About the author:

Dr. Steinberg is a program officer at the Office of Naval Research. He manages multidisciplinary autonomy research that cuts across different technical areas and mission domains, as well as applied research that focuses on autonomous air systems and heterogeneous multivehicle collaborative systems.

(Photo from Naval Surface Warfare Center, Carderock Division)

Surface Autonomy Is Heading for the Fleet

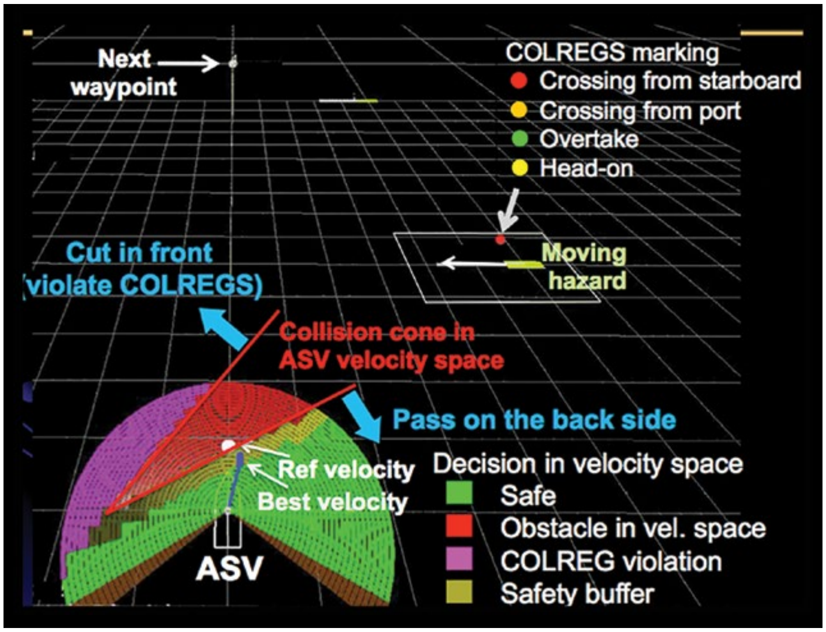
By Dr. Robert A. Brizzolara

The technical challenge of operating an unmanned vehicle with little or no human supervision increases rapidly as a function of the complexity of a mission and its environment. Today, the Navy's unmanned surface vehicle (USV) prototypes require substantial (remote) manpower to perform even relatively straightforward missions—and are therefore dependent on a radio communications link to a human controller. For example, collision avoidance is performed remotely by a human operator; this requires a large amount of bandwidth to transmit video from the USV and places a high cognitive workload on the human operators. This limits USVs to operating close to manned platforms or a ground control station. In addition, a USV's operational capability deteriorates quickly as environmental conditions worsen, in large part because of the degraded situational awareness of the remote human operator.

Science and technology (S&T) will overcome these issues and allow USVs to realize their full potential to make them capable of accomplishing complex tasks in all environments, as directed by the Secretary of Defense in a 2011 memo that made autonomy one of seven priorities for the Department of Defense. As a result of the efforts of the Office of Naval Research (ONR) and other naval S&T organizations over more than 10 years, the Navy's first procurement of USVs began in 2013. USVs are of military interest because they possess outstanding platform performance characteristics, such as range and speed, that result from air-breathing propulsion, access to radio communications, potential for stealth design features, and low cost per quantity of payload.

In 2002, as the Navy's interest in USVs began to increase, ONR's Sea Platforms and Weapons Division engaged with the Navy's USV program office regarding the S&T that would be needed to build what the Navy envisioned. One of the needs identified was autonomous control. In 2004, I initiated a program the objective of which was autonomous control of USVs over long, complex missions in unpredictable or harsh environments. Since then, several sponsoring organizations have contributed to this effort, including ONR, the Unmanned Maritime Systems program within Program Executive Office Littoral Combat Ships, and the Naval Sea Systems Command Engineering Directorate's Technology Office. The autonomous control system developed to date has been installed on eight different USV types, has achieved more than 3,500 nautical miles of testing on the water, and has participated in numerous fleet experiments. One USV, called the "Unmanned Sea Surface Vehicle—High Tow Force," was developed by ONR's Sea Platforms and Weapons Division. It is about 12 meters long and is therefore a "fleet class" USV as defined by the USV Master Plan. An adaptation of this design in conjunction with a mine influence sweep payload developed by ONR's Ocean Battlespace Sensing Department was used for the two "Unmanned Influence Sweep System" prototypes operated by the Unmanned Maritime Systems program office.

Autonomous control of USVs in this context means operation of the craft either with no human operator (after specification of the mission goals and constraints at the start of a sortie) or a limited human supervisory role, perhaps in degraded conditions, in the vicinity of other maritime traffic and performing an operationally useful task. This is a substantial technical challenge because of the unique and often harsh dynamics of the sea surface and their impacts on situational awareness, which degrades the range at which hazards can be detected. There may be only a short warning time of a hazard in a USV's path. Therefore, the USV's autonomous control system must have fast, accurate perception and decision-making capabilities.



A traffic vessel is crossing from the right. The unmanned surface vehicle (USV) autonomously maneuvers around the traffic vessel in compliance with the collision regulations. The colors around the USV indicate in velocity space: safe velocity vectors (green), potential collisions (red) and violations of collision regulations (purple). The white circle in front of the USV is the desired velocity vector and the blue line is the actual velocity vector. (Photo from California Institute of Technology-Jet Propulsion Laboratory)

A team composed of the California Institute of Technology's Jet Propulsion Laboratory, Spatial Integrated Systems Inc., Daniel Wagner Associates, and Naval Surface Warfare Center Carderock Division has made substantial progress toward this goal by developing a technology called Control Architecture for Robotic Agent Command and Sensing (CARACaS). This system consists of two components: a perception component that provides situational awareness, and a decision-making component that determines boat course and speed based on the output of the perception component.

The perception component employs multiple sensing modalities, principally electro-optical/infrared sensors and radar, to increase the probability of detection and accuracy over what a single modality can provide. Commercially available sensors, such as radar, are used in CARACaS when available; if these do not exist, then the sensor is developed. For example, in the ONR program, the Jet Propulsion Laboratory developed a stereo electro-optical system that provides sufficient range and near-real-time processing speed to support high-speed USV operations. Stereo electro-optical was chosen as one of the sensing modalities because of its ability to achieve the range to provide the necessary reaction time for the desired USV speeds, and to support future incorporation of vessel classification algorithms necessary for implementation of certain collision regulation rules. A companion stereo infrared capability for night operations is currently being developed. The perception component provides the range, speed and bearing of all contacts to both the reactive and deliberative decision-making components.

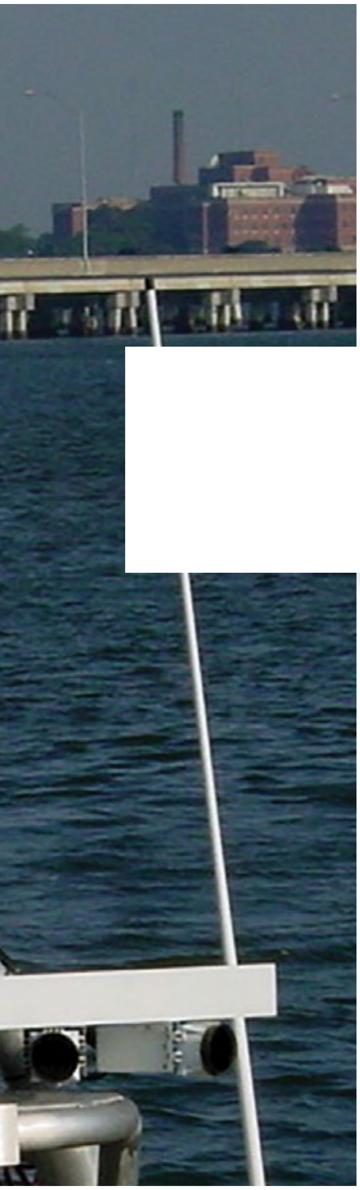
The decision-making component of an autonomous USV must make route planning determinations over a wide range of time scales. Since a particular autonomous planning algorithm works best only within a limited range of time scales, the Jet Propulsion Laboratory employed a hybrid of a short time scale, or reactive, component and a longer time scale, or deliberative, component. For example, since the highly dynamic environment means that some contacts will not be detected until they are at relatively short distance from the USV, commonly available graph theoretic path planners are not suitable for reactive decision making for USVs because they are not fast enough. Instead, the Jet Propulsion Laboratory used its Robust Real-time Reconfigurable Robotics Software Architecture" (R4SA), which employs a behavior-based approach using a very fast path planning algorithm based on "velocity-obstacles." Velocity obstacles is a route planning approach, similar in principle to the maneuvering boards used by human navigators, that can accomplish very fast, reliable computation of routes that accomplish hazard avoidance and compliance with the maritime rules of the road.

In addition to reactive decision making, USVs must plan their routes over periods of hours or days. The velocity obstacles approach is not capable of planning at these longer time scales. So, an existing capability called CASPER (Continuous Activity Scheduling Planning Execution and Replanning) is used within the hybrid framework as the deliberative decision-making component of CARACaS. CASPER employs a graph-theoretic approach that plans a route based on mission goals and constraints. The series of waypoints determined by CASPER is provided to R4SA once every several seconds. R4SA then executes each waypoint in order while avoiding collisions and obeying rules of the road.

A few years ago, when CARACaS was still in early development, it was clear that it would be feasible to accomplish autonomous control of USVs at low speeds and in benign conditions. The notion, however, of being able to achieve the reactive autonomy necessary for a high-speed craft, especially in degraded environments, involved much higher technical risk. Although CARACaS had been tested extensively on water for several years, a key milestone in the ONR program was in 2011 with the first on-water demonstration of the CARACaS reactive autonomy performing a complex action. The CARACaS system combined three behaviors: "go to waypoint;" "comply with collision regulations;" and "avoid collision." This is referred to as parallel behavior composition. The test showed that autonomous control using perception and decision making was fast enough for a fleet-class USV in a relatively complex situation.

There is much that remains to be done in the autonomous control of USVs, such as attaining: accurate and fast situational awareness in higher sea states; efficient and effective algorithms for handling multiple competing objectives; cooperative decision making across multiple unmanned platforms; accurate, fast, distributed fusion of sensor data across multiple unmanned platforms; reliable detection of submerged hazards; activity recognition of other maritime vessels; and compliance with additional collision regulations (e.g., recognition of day shapes and lights). In addition

Pictured here is the sensor suite for the Control Architecture for Robotic Agent Command and Sensing (CARACaS) autonomous control system. From bottom to top: stereo electro-optic, 360-degree electro-optic, radar, and lidar. (Photo from Naval Surface Warfare Center).



to these technical challenges, there is a significant challenge in fostering greater acceptance of autonomously controlled USVs by the Navy. Before turning control over to an autonomous system, a commander must have the confidence that it will perform the appropriate action in a given situation. A "human oversight mode" will be a useful and important initial approach that will enable the Navy to gain trust in the technology. As confidence grows, the degree of human oversight can be reduced. Furthermore, trust in the system can be gained by carefully selecting the situations in which the autonomous capability is initially employed (areas with low-contact density and good environmental conditions) and using the USV to perform relatively simple tasks. As trust grows, autonomous USVs will be used for more complex tasks in more complex environments.

> "Attention is now turning to the possibility of autonomous control of larger unmanned surface vessels"

As autonomous control of fleet-class USVs continues to be developed and demonstrated at sea, attention is now turning to the possibility of autonomous control of larger unmanned surface vessels. There are compelling reasons to explore development of larger unmanned craft—they have larger payload capacities, the ability to operate in higher sea states, and longer ranges (permitting the possibility of self-deployment). Vessel sizes necessary to achieve self-deploying ranges are still quite small compared to today's Navy surface ships, including the littoral combat ship, meaning that their cost still can be modest. A self-deploying unmanned vessel requires a high degree of autonomy since it will operate at long distances from other ships and ground control stations. Achieving autonomous control of a larger vessel involves additional technical challenges since the number and complexity of shipboard systems is much larger. The Defense Advanced Research Projects Agency is addressing these challenges by developing the Anti-Submarine Warfare Continuous Trail Unmanned Vessel, a 130-foot autonomous trimaran scheduled for launching in 2015.

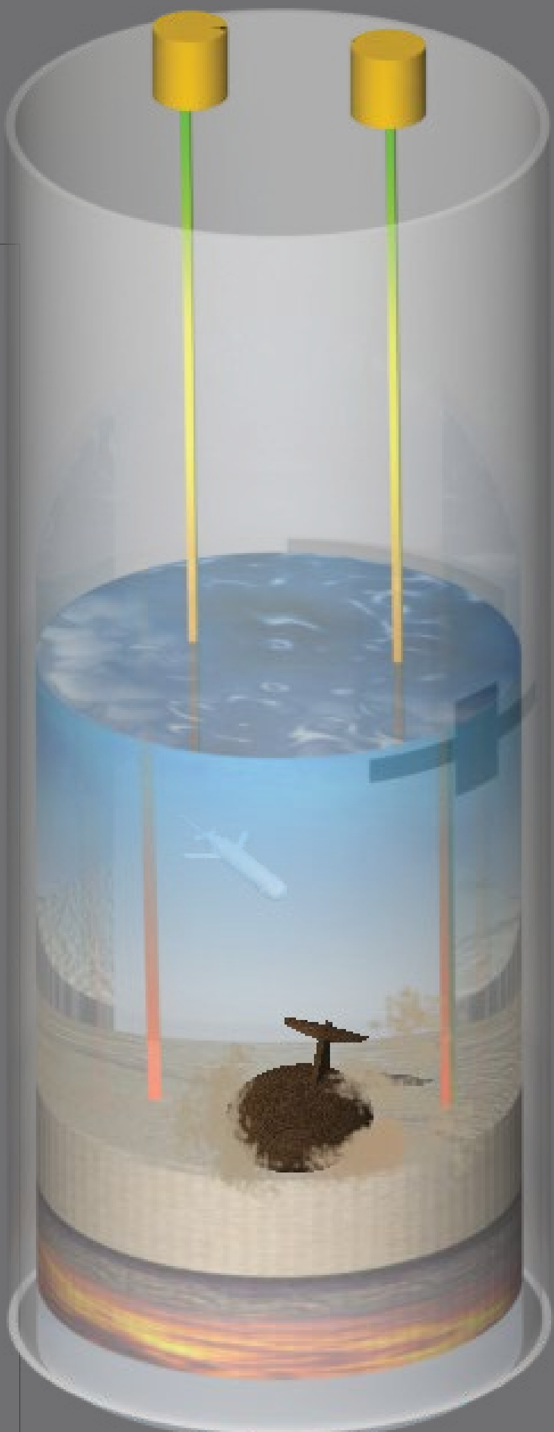
Given current budget realities, the Navy must find innovative ways to perform its missions in more cost-effective ways. Fleet-class USV prototypes have already demonstrated capabilities that previously required much larger and costly manned platforms. Development of autonomous control for USVs will enhance this cost savings by further increasing the capability of the platform. Capability increases will accrue by freeing USVs from the tether of the high-bandwidth communications, thereby allowing them to venture farther from humans. In addition, the USV can be designed such that no one ever has to set foot on board. This benefit is much greater than the space and weight savings derived from the absence of human support systems. There also are benefits from relaxing the structural and safety requirements associated with manned vessels. All of this translates into additional space and weight for payload and fuel, further increasing the warfighting capability that can be delivered using small, unmanned combatant craft.

About the author:

Dr. Brizzolara is a program officer with the Office of Naval Research's Small Combatant Craft science and technology program.

Seeking Energy from the Bottom of the Sea

By Dr. Bart Chadwick, Wayne Liu, and Patric Petrie



Right now, somewhere in the world's oceans, an unmanned, underwater vehicle (UUV) is collecting much-needed data, but its batteries are beginning to fail.

In the age of working smarter, not harder, the U.S. Navy and Department of Defense are actively searching for ways to create sustainable intelligence, surveillance, and reconnaissance (ISR) networks. The Navy's burgeoning network of unmanned ISR sensor and vehicle platforms is typically powered by onboard batteries that must be recharged using traditional manned recovery methods—an approach in which operational risks and manpower costs multiply rapidly with the number and distribution of unmanned systems.

What if the Space and Naval Warfare Systems Center Pacific could create a smart phone-like charging station for UUVs, where the vehicle could automatically dock and recharge itself underwater, instead of having to recover the vehicle for shipboard recharging?

What if the energy source needed to sustain this undersea network was as convenient as the ocean floor and could be extracted using the ebb and flow of tidal currents? And what if the battery needed to store the captured energy could run on seawater?

Operational Relevance

If energy could be exchanged wirelessly in seawater for downloading or uploading from ocean charging stations, then a remote undersea energy network could be formed to sustain unmanned sensors and vehicles through renewable or even planted energy sources.

"Mudfish" is an innovative Space and Naval Warfare Systems Center Pacific project designed to exploit energy from the ocean floor by integrating microbial fuel cell (mud-charging) technology in the underside of a bottom-dwelling, undersea glider vehicle. This will enable sustainable, covert, forward-deployed surveillance platforms that do not require a human presence to recharge the vehicles.

The stealthy UUV cited above is an example of a solitary, large, forward-deployed ISR platform in need of power, but the Mudfish is actually an example of a small "sleeper" platform that is deployed in swarms, gathers and sends data when at the surface, and then returns to "sleep" and recharge on the mud bottom. The difference between the two is that Mudfish is a much smaller, minimally mobile, less capable platform that is deployed in swarms which can sustain themselves on site, unlike the larger UUV, which must return to a charging station for energy. Both are examples of information dominance extended through remote charging methods.

New Technologies

Scientists are actively designing innovative energy platforms to meet these hypotheticals and potentially extend the Navy's mission of information dominance into remote areas by wirelessly transferring or generating power in undersea environments. To achieve a maritime energy network, researchers are collaborating to develop critical capabilities in undersea energy transfer, harvesting, and storage.

Much like commercially available wireless consumer electronics charging platforms, the Naval Innovative Science and Engineering-funded research effort seeks to use inductively coupled power transfer methods to upload/download energy between unmanned systems, which can transfer energy wirelessly between proximate coils.

The challenge for the Navy is transmitting energy through conductive seawater while avoiding any potential biofouling effects. Consumer and electric vehicle applications operate in much cleaner atmospheric conditions, where inductive energy is less likely to be lost to the environment.

By first modeling the effect of coil dimensions, wire diameter, and transmission frequencies, researchers can explore numerous design parameters to optimize power transmission through centimeter-scale gaps of seawater.

If undersea charging becomes possible, then far-reaching strategic changes can be made in the deployment of fixed and mobile unmanned systems. Some examples:

- A fuel-cell or renewable energy-based docking station can replenish a rotating patrol of UUVs for harbor security or covert surveillance in forward regions.
- A UUV "fuel truck" can download energy to a network of sensors.
- A UUV can harvest energy from a distributed grid of renewable energy sources that would otherwise be able to offer their stored energy only to adjoining hardwired systems.

Undersea Energy Harvesting

Engineers also are developing hydro-kinetic oscillators to drive kinetic energy harvesting devices in low-flow applications to power sensor, communications, and UUV charge platforms.

Unlike traditional offshore and structural engineering goals that seek to minimize wind-and flow-driven vibrations, this research aims to amplify undersea vibration effects for greater power output.

Commercial power platforms simply scale up for greater flow capture, but the research focus here is on how to exploit flow-induced, vibration fundamentals in slow ocean currents using narrow diameter (one inch or less) cylinder oscillators.

Researchers have demonstrated how oscillator devices can be designed to resonate (vibrate at maximum amplitudes) at the flow excitation frequencies that result when a cylinder is exposed to threshold flow speeds.

If successful, this research will lead to compact energy harvesting devices that can be individually bundled with undersea sensors or deployed as a dispersed grid of energy nodes to enable energy collection by a UUV, much as crops or fruit trees are harvested by a farm vehicle.

Mudfish

A different energy-harvesting problem is encountered when covert unmanned systems (fixed or mobile) must be deployed in sensitive, high-traffic regions where tidal or current flow is limited or when shallow water depths discourage tethered or off-bottom approaches (e.g., harbors, sheltered littoral waters).

In this scenario, a sediment-charged or microbial fuel cell can be implanted in the underside of a bottom-resting vehicle to replenish batteries in between mission "bursts." Unlike a remote sensor or UUV that operates continuously in between energy replenishments, this vehicle concept enables a "sleeper" asset that surfaces daily from the harbor bottom for brief intelligence gathering operations and then returns to the bottom for continuous, hidden recharging.

Researchers were challenged by the fact that nearly all MFCs are designed to be buried in the mud to power fixed sensors. However, this concept of a migrating MFC-powered vehicle requires mud charging while resting on the sediment surface—and no restart time after separating from, and reattaching to, the mud surface.

Researchers have demonstrated how an MFC could operate while resting on, separating, and reattaching to the mud surface. If successful, this research will provide a game-changing capability in which swarms of low-cost, bottom-dwelling surveillance vehicles can be deployed to littoral waters and then continuously sustained through sediment contact alone.

About the authors:

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RobotX to Foster Research in Asia-Pacific

By Kelly Cooper and Dr. Liming W. Salvino

The Office of Naval Research (ONR) is helping to sponsor the Maritime RobotX Challenge, which will be held on 20-26 October 2014 in Singapore. This 15-team, five-nation international student challenge will focus on the development of surface vessel autonomy. Singapore's Ministry of Defense will host the event for the United States, Australia, South Korea, and Japan. The Office of Naval Research Global also is helping to coordinate and prepare for this competition.

ONR chose the Association for Unmanned Vehicles Systems International Foundation (AUVSI) as its executive agent for this inaugural competition, taking advantage of AUVSI's extensive experience in organizing these large competitions. The RobotX Challenge is scheduled to take place every two years. The long-term goal is to enable the launch of micro air vehicles and autonomous underwater vehicles from the current modular vessel platform to demonstrate multidomain, autonomous platform interoperability.

This competition of autonomous surface vehicles (ASVs) will stimulate student interest in the engineering of autonomy and encourage collaboration with other Asia-Pacific countries. Each student team must design, choose, and integrate sensors, propulsion, and control software that permit a small surface vessel to perform five routine maritime tasks without human direction.

The naval science and technology (S&T) community increasingly needs to maintain close connections with its international counterparts to capitalize on global capabilities, including science, technology, engineering, and mathematics (STEM) education solutions. In recent years, several emerging nations, primarily in Asia, have been investing heavily in research and development (R&D) and education. Since 2012, the R&D investment of Asian countries has surpassed the investments by the United States and Europe. This Asian-Pacific-focused RobotX competition not only will jump-start students' knowledge of naval architecture and autonomy, but also will provide them with early exposure to Asian culture and its rapid pace of development. It will introduce American students to Asian and Pacific S&T and help foster relationships that will grow future international collaborations. Even the location of the event is significant: Singapore is one of the most important and strongest American partners in Asia. As the location of an ONR Global office since 2006, Singapore is a natural fit for the inaugural competition.

Autonomous Surface Vessels

To focus the competition on autonomy, ONR provided each team with a standard wave-adaptable modular vehicle (WAMV) built by MAR Inc. as the ASV platform.

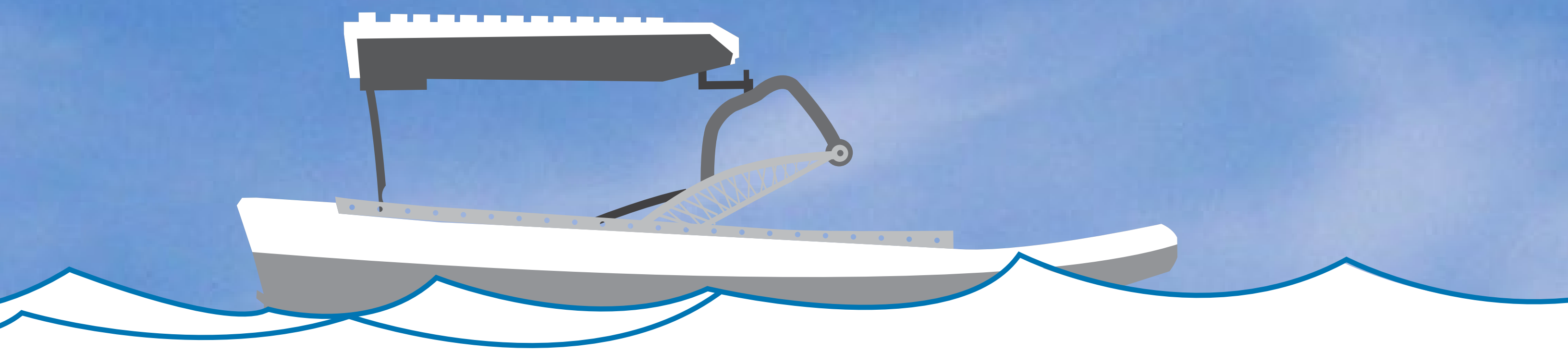
A WAMV has two articulated, inflatable pontoons to skim atop waves instead of plunging through them. This arrangement reduces drag and maintains transverse stability. Each pontoon is fitted with an integral strongback that carries an articulated aluminum suspension system. This system, consisting of springs, shock absorbers, and ball joints, is designed to isolate the payload tray from the motions induced by waves. As designed by MAR, the WAMV has gasoline or electric motors contained in pods that are joined to the stern of each pontoon. The WAMVs delivered to teams did not have propulsion pods. Using a stipend provided by ONR, each team designs and fits its own custom electric propulsion system to the WAMV and integrates it into their autonomy scheme.

During the competition, each WAMV will perform five maritime tasks autonomously: basic navigation, obstacle avoidance, docking, underwater search, and above-water observation. For each task, the craft must sense the environment, make decisions based on sensors, decide a course of action, and control and propel itself to complete the task. In two of these tasks, the vessels will generate reports of their performance and send them to a shore site.

Teams

This inaugural competition has attracted prestigious competitive teams from the elite of the world's S&T universities. Five competitors rank in the top 20 engineering universities worldwide. In the U.S. competition, two other finalists (not selected) were also ranked in that top-20 list.

Three teams each from each participating country will compete for $100,000 (SGD) in prize money. The teams were chosen using competitive/recommendation selection criteria established by a national committee. In the United



Chief of Naval Research Rear Adm. Matthew Klunder meets with students at a conference sponsored by the Association for Unmanned Vehicle Systems International (AUVSI) in Phoenix, Ariz. New robotics competitions such as RobotX are a continuation of decades of support by the Navy for high school and college science and technology education and research. (Photo by John Williams)

States, in late August 2013, more than 300 invitations were sent to colleges, universities, and robotics organizations seeking proposals to participate in the competition. In early October, the U.S. committee selected teams from MIT and Olin College (combined team), Villanova and Florida Atlantic University (combined team), and Embry-Riddle Aeronautical University.

Japan's three teams are from Osaka University, Tokyo Institute of Technology, and the University of Tokyo. From Australia: Queensland University of Technology, Flinders University/Australian Maritime College (combined team), and the University of Newcastle. From South Korea: Seoul National University, Korea Advanced Institute of Science and Technology, and the University of Ulsan. The host country chose the National University of Singapore, Nanyang Technological University, and Singapore University of Technology and Design.

Autonomy

Student teams will approach the engineering of autonomy in different ways, but most will use some combination of similar equipment, sensors, and software. For locating crafts, GPS and inertial-measurement sensors will be part of most sensor suites. One team plans to incorporate a fiber-optic gyro. Several teams are expected to use forward-looking infrared, lidar, active and passive sonar, magnetometers, stereo vision systems, and multispectral cameras to create virtual scenes representing the competition environment and courses. These systems will identify boundaries, markers, and obstacles to the autonomy computers.

Multiple versions of command and control operating systems also are expected, such as the Robot Operating System, Mission Oriented Operating System, and others. There will be a variety of network communication and control systems such as Light Wave Communication and Marshalling, Wi-Fi, Bluetooth, even Microsoft Kinnect to connect sensors to control systems, deliver outputs to propulsion systems. and make reports as required.

Each team will write, download, modify, review, test, and manipulate software programs to do edge detection, color identification, decision making, propulsion control, and maneuvering, as well as autonomous reporting. Electric propulsion power systems will likely range broadly, from direct attachments of commercial trolling motors powered by familiar lead-acid batteries up to sophisticated lithium-ion electric propulsion pods using sophisticated rudder controls. The broad array of sensor choices, available commercial and custom software, and propulsion methods can all be fitted, powered, and arranged within the generous 300-pound payload limit for the sturdy and stable WAMV.

Tasks

The five Maritime RobotX Challenge autonomy tasks progress from rudimentary to complex:

• The navigation task requires that the craft maneuver over a short, straight course through two sets of buoys.

• In the obstacle avoidance task, the craft enters the course by an identified gate, traverses a short course without colliding with any randomly placed floating obstacles, and exits via a specified gate.

• To complete the underwater search task, the craft seeks out an active underwater emitter, simulating location and recovery of an aircraft black box, and autonomously reports its location.

• The docking task requires vehicle visual recognition of the correct dock (of three) and maneuvering to enter and exit.

• The final observation task requires the vehicle to recognize and locate a specific buoy, send a request to activate a light sequence on the buoy, and report that sequence (which will be randomly generated) to the team shore site.

Each team in the Maritime RobotX Challenge will use a standard wave-adaptable modular vehicle (above) that they will then modify with their own electric propulsion system. Embry-Riddle Aeronautical University (opposite) is one of 15 teams competing in the event (Photos courtesy of AUVSI Foundation)

All these tasks will be done without direction from the team once the vehicle begins its attempt. This combination of tasks requires sensitive, discriminating, flexible, and extensive autonomy to be engineered and integrated into these identical vehicles. Each team's innovation in engineering the WAMV's autonomous behavior will be one of the rewards of the competition.

Why Do This?

In the early 1990s under the leadership of technical director Dr. Fred Saalfeld, ONR assumed responsibility for developing the national naval engineering research capacity and sustaining STEM education. ONR supports STEM investments focused in part on providing experiential learning through student competitions. Together with the most prestigious science and engineering universities, ONR has long recognized that hands-on learning is a necessary component of education and training. In addition to teaching engineering and autonomy theory, universities engage students to set up experimental equipment, design and construct prototypes, participate in tasks with industry partners, and execute long-term scientific endeavors specifically to solve real-world problems by applying the latest technologies in innovative ways. This experiential learning is the foundation of student confidence in understanding the theories they have been taught and transforming theoretical knowledge into practical solutions.

Competitive experiential learning, in particular, develops desirable qualities in students. In the Maritime RobotX Challenge, performing the complicated tasks will require more than one scientific specialty or engineering field. To achieve the competition's goals, students educated in individual science and engineering disciplines, from different cultural backgrounds and with widely varying skill levels, must learn to work together to achieve a single objective. In the international competition setting, teams from different countries are likely to take different approaches. But the ultimate goals demand performing as a team under the firm pressure of competition. This requires teams to organize themselves and work together effectively, to reinvestigate details of theory (or adopt alternate theories), to cultivate extensive technical communication skills, and, for many, to acquire leadership competencies that will serve them well in their later professional lives.

The Navy conducts student competitions such as the Maritime RobotX Challenge to attract the widest range of students to opportunities for a satisfying professional life filled with meaningful challenges and interesting work. Student competitions sharpen STEM skills and teach students to work in technical groups toward an objective within a definite timeline. The Maritime RobotX Challenge competitions stimulate interest in the Navy generally, provide essential experiential learning for student preparation, and encourage the development of new applications of technology—all of which underpin the future technological superiority that the Navy must maintain to defend the country at sea.

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Computing at the Speed of *Unconscious* Thought

By Ashley Nekoui

The autonomic nervous system controls our basic bodily functions so adeptly we literally do not know it is there. Research is under way to make the same kind of control possible in computer systems.

Autonomic computing is a branch of autonomy modeled after the autonomic nervous system, which operates faster than conscious thought to control critical aspects of the human body. Just as you don't have to actively control and command every muscle in your legs when you walk—an otherwise incredibly complex action if had to do it consciously—synthetic autonomics mimics our unconscious mind by providing swift adaptations to networks when alterations occur in system performance and stability, based on high-level objectives.

"Currently, the primary approach for network management is to provide enough information to a human controller for manual intervention," said Doug Lange, principal investigator of the Space and Naval Warfare Systems Center Pacific's Autonomic Command and Control of Networks project. "Not only is this difficult in the case of large complicated networks, but human error can be attributed as a source of the problems."

A primary goal in the creation of autonomics was to augment information technology (IT) systems, in which the autonomics, rather than the administrator, would accomplish a majority of the work.

"The scale and speed necessary to manage today's complex IT systems are overwhelming human capability," said Lange. "Autonomics overcomes this by autonomously managing systems according to rules and conditions set by the IT supervisors. The lack of supervisor capacity is especially relevant in the command and control of teams of autonomous unmanned systems. Because humans have a limited attention capacity, there will be situations that the operator cannot anticipate."

Autonomics can address this limitation by acting as a semi-collaborative operator. When an individual cannot effectively change a situation, the

Illustration by Eric Anderson

autonomics can act as an autonomous operator. This form of autonomy would be subject to a sliding scale of autonomy, meaning that the level of autonomy used would depend on factors within the system. Varying situations could have autonomy that simply enhances situational awareness by suggesting actions, provides an optimizer to manage ongoing operations initiated by the operator, or acts as an operator to make decisions and initiate actions on its own.

Space and Naval Warfare Systems Center Pacific is currently evaluating "Rainbow," an autonomic management framework system developed by Carnegie Mellon University, to identify its capability for naval networks and provide enhancements to the framework for operation in the naval environment. The center developed an initial proof-of-concept demonstration of this idea using the Rainbow framework. A basic task manager was developed, along with a simulation providing tasks through the command and control system, for a supervisor managing a team of autonomous vehicles. Tasks were created with random deadlines based on arrival and completion times. System effectiveness was measured by tasks completed on time. The Rainbow portion of the prototype monitored operator workload based on the tasks in the queue and automatically executed tasks when it identified an overload.

The Rainbow framework consists of four primary components: the model manager, architecture evaluator, adaptation manager, and strategy executor. A translation infrastructure provides the means to send data to Rainbow and for Rainbow to effect changes for each target system being managed.

"A key feature of Rainbow is the definition of constraints that the system must follow," said Lange. "For example, a web business may desire the minimization of response time for its customers and define a constraint that the response time experienced by any customer be below a certain threshold. In turn, Rainbow would probe these response time values from the real system and then evaluate the model for constraint violations. If a constraint is violated, Rainbow adapts the model through predefined strategies and then executes these strategies on the real system through effectors."

In addition to this demonstration, the center conducted various experiments in the laboratory's developmental environment using different types of simulated naval networks. Tests included a team of autonomous unmanned systems performing a surveillance mission, a command and control system composed in a software-oriented architecture, and a software distribution and upgrade capability representing the evolving Department of Defense "App Store."

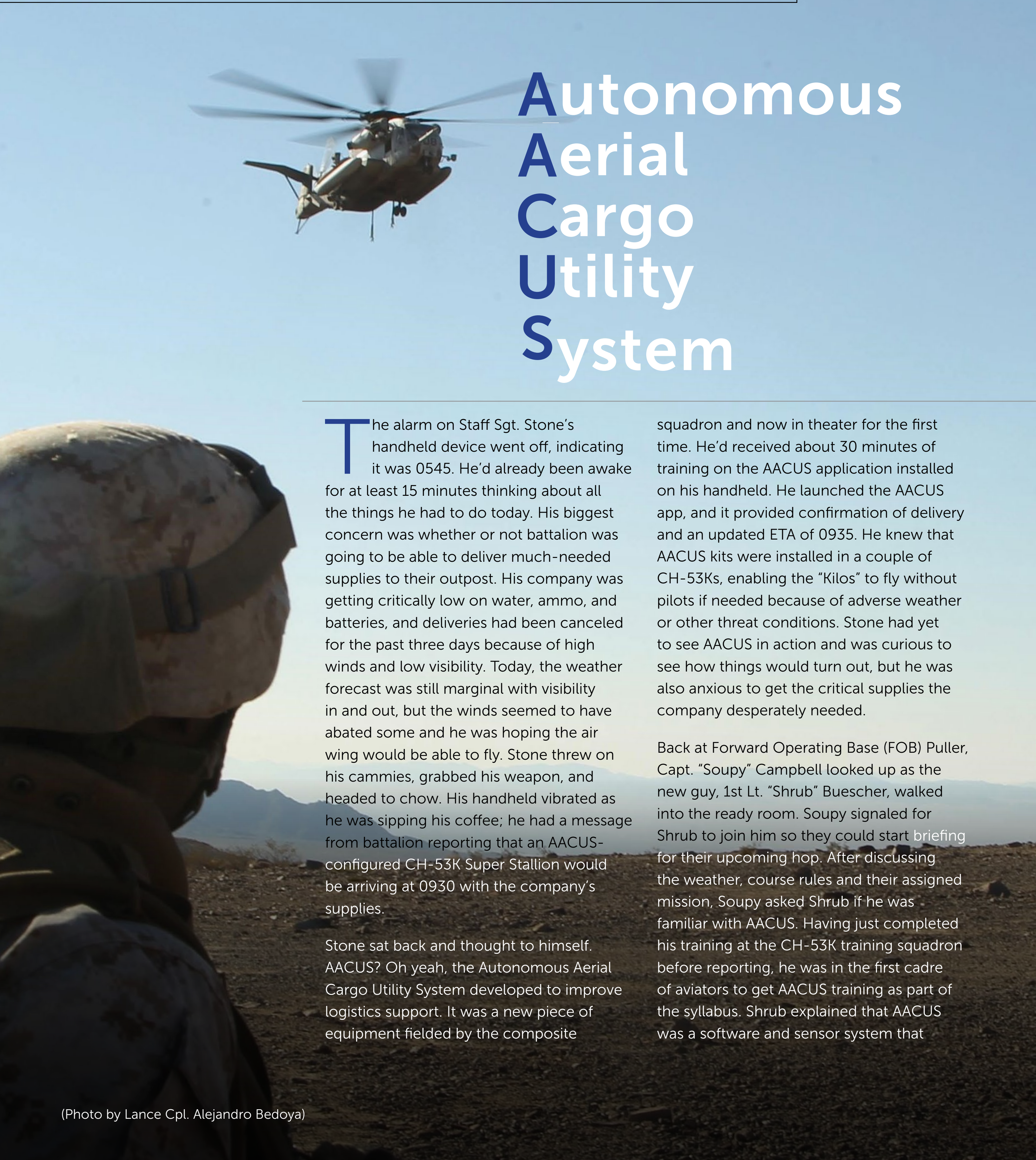
"We have also started incorporating machine learning into the gauges of Rainbow to handle decision-making on large complex networks, and performed experiments that represent large-scale command and control networks," said Lange.

"Our next steps will include managing a real service-oriented architecture based command and control capability. We will also begin experimenting with strategies derived through evolutionary computing techniques, rather than those solely coded by human developers."

About the author:

Ashley Nekoui is a public affairs specialist at Space and Naval Warfare Systems Center Pacific, and also a public affairs officer in the Navy Reserve.

►► By Cmdr. Max Snell, USN (Ret.), and Col. J. Kevin Dodge, USMC (Ret.)



Autonomous Aerial Cargo Utility System

The alarm on Staff Sgt. Stone's handheld device went off, indicating it was 0545. He'd already been awake for at least 15 minutes thinking about all the things he had to do today. His biggest concern was whether or not battalion was going to be able to deliver much-needed supplies to their outpost. His company was getting critically low on water, ammo, and batteries, and deliveries had been canceled for the past three days because of high winds and low visibility. Today, the weather forecast was still marginal with visibility in and out, but the winds seemed to have abated some and he was hoping the air wing would be able to fly. Stone threw on his cammies, grabbed his weapon, and headed to chow. His handheld vibrated as he was sipping his coffee; he had a message from battalion reporting that an AACUS-configured CH-53K Super Stallion would be arriving at 0930 with the company's supplies.

Stone sat back and thought to himself. AACUS? Oh yeah, the Autonomous Aerial Cargo Utility System developed to improve logistics support. It was a new piece of equipment fielded by the composite squadron and now in theater for the first time. He'd received about 30 minutes of training on the AACUS application installed on his handheld. He launched the AACUS app, and it provided confirmation of delivery and an updated ETA of 0935. He knew that AACUS kits were installed in a couple of CH-53Ks, enabling the "Kilos" to fly without pilots if needed because of adverse weather or other threat conditions. Stone had yet to see AACUS in action and was curious to see how things would turn out, but he was also anxious to get the critical supplies the company desperately needed.

Back at Forward Operating Base (FOB) Puller, Capt. "Soupy" Campbell looked up as the new guy, 1st Lt. "Shrub" Buescher, walked into the ready room. Soupy signaled for Shrub to join him so they could start briefing for their upcoming hop. After discussing the weather, course rules and their assigned mission, Soupy asked Shrub if he was familiar with AACUS. Having just completed his training at the CH-53K training squadron before reporting, he was in the first cadre of aviators to get AACUS training as part of the syllabus. Shrub explained that AACUS was a software and sensor system that

(Photo by Lance Cpl. Alejandro Bedoya)

could be used on a variety of platforms and enabled the Kilo to become an optionally piloted aircraft vehicle. In the manned configuration, the AACUS sensors could be used while airborne to detect and avoid obstacles, such as power lines, as well as to survey the landing area during final approach when visibility was poor to avoid hazards on the ground. AACUS was particularly handy in their current theater of operations since they could expect to encounter such conditions regularly. In the unmanned autonomous mode, the Kilos were capable of executing the entire mission profile even in degraded weather. With AACUS, the Kilos could take off, navigate en route, avoid threat areas, select a landing site, make a final approach, and land in unprepared locations while avoiding all obstacles. AACUS maintains communication using a satellite data link to both the ground control station at the FOB and the field operator's handheld at the destination.

Soupy and Shrub finished their brief, donned their flight gear, signed out Wolfpack 733 from maintenance control, and stepped onto the flight line. As they were preflighting their bird they both looked over as Wolfpack 731 taxied by on its logistics resupply mission. They both stared at the cockpit, shaking their heads in a bit of amazement as the aircraft passed them without anyone. Both pilots exchanged a "not sure if I'll ever get used to that" look. The buzz had started; AACUS was a game-changer.

Back at Combat Outpost (COP) Butler, Staff Sgt. Stone received another AACUS message on his handheld providing a mission status and cargo manifest. Wolfpack 731 was airborne with an ETA of 0931. Stone checked his watch and saw that it was 0915 when he started to hear some small-arms fire from the east. As the company commander organized a response, Stone whipped out his handheld, typed in a no-fly zone, and transmitted the coordinates to the fire support coordination center, which approved the control measure and simultaneously transmitted it to the direct air support center and Wolfpack 731 received and processed the threat information and immediately calculated a new flight plan that avoided the no-fly zone and transmitted an updated ETA to the COP.

Stone's handheld gave him an updated ETA of 0936. He headed to the supply tent, grabbed two Marines, geared up, and headed to the landing zone. They could hear the CH-53K approaching from the north. Wolfpack 731 sent a final message to Stone's handheld that identified the landing point. Stone smiled as he saw that it was only 50 meters from his current position. One of the Marines instinctively popped a smoke flare and tossed it toward the landing point. Stone shook his head and growled a few words at the Marine, who immediately turned beet red when he realized

What is AACUS?

AACUS is an Office of Naval Research Innovative Naval Prototype program established in fiscal year 2012 that conducted its first flight demonstrations in February and March 2014. AACUS represents a substantial leap over both present-day operations as well as other more near-term development programs as it is focused on autonomous obstacle avoidance and unprepared landing site selection, with precision landing capabilities including contingency management until the point of landing. AACUS includes a goal-based supervisory control component such that any field personnel can request and negotiate a desired landing site. The system is designed to be "platform agnostic" with an associated open architecture framework that allows it to be integrated into either manned or unmanned rotary-wing aircraft.

the pointlessness of his actions. The Kilo made its final approach and flared onto the exact spot it had indicated to Stone. The automatic cargo loading/unloading system immediately began jettisoning pods full of the company's requisitioned supplies. Wolfpack 731 then sent Stone a message that all the pods had been offloaded, and it was preparing for takeoff to the south for its next delivery.

Just as Stone was going to approve the AACUS request to depart, he was informed of a casualty evacuation request followed immediately by a request to hold Wolfpack 731 in the zone. A light armored vehicle pulled up shortly and two corpsmen hopped out and began to unload a wounded Marine for transfer to the Kilo. Stone rushed over and pointed out that this was an unmanned aircraft, and he wasn't sure if they should load the wounded Marine. The leading corpsman explained that if the Marine didn't make it back to the battalion aid station within the next 30 minutes he probably wouldn't live. Stone got on the horn with his company commander who verified the request. Stone got out his handheld and programmed in the emergency casualty evacuation for immediate liftoff. AACUS, as well as the ground control station operator at the FOB, acknowledged and concurred. The corpsmen loaded the wounded Marine aboard the aircraft. Wolfpack 731 then lifted off and headed back to FOB Puller. Stone wondered how he would feel about riding in a helo

without a pilot on board. He growled again at the Marines to get the supply pods into the Humvees that were waiting for the cargo. Once the cargo was loaded he headed to the supply tent and was alerted to a message on his handheld that Wolfpack 731 had landed and the wounded Marine was being offloaded.

Soupy and Shrub had just returned from their mission and shut down Wolfpack 733 when they watched the wounded Marine being unloaded from Wolfpack 731. They did a quick post-flight inspection of their helo, filled out the required paperwork in maintenance control, and then headed to the mess tent. As they were sitting down to eat the word began to pass that the wounded Marine had been stabilized and that it appeared he would survive as a result of his rapid arrival at the aid station. Soupy took a bite of his slider, washed it down with some bug juice, and quipped, “Wonder where they’ll pin the Air Medal on Wolfpack 731?”

“The leading corpsman explained that if the Marine didn’t make it back to the battalion aid station within the next 30 minutes he probably wouldn’t live.”

About the authors:

Cmdr. Snell is a retired A-6E bombardier/navigator and aeronautical engineering duty officer. He is a civil servant assigned to the Chief Technology Office at the Naval Air Systems Command and is currently on detail to the Office of Naval Research as the AACUS program manager.

Col. Dodge is a retired Marine aviator and former V-22 test director and Deputy Assistant Secretary of the Navy for Littoral and Mine Warfare. Currently the vice president/director of the American Systems Science and Technology Integration Center, he is active in the concept development for AACUS and serves as a member of the AACUS advisory group.

FUTURE WATCH ►► By David Smalley

AUTONOMY

Naval leaders say they never want to see our Sailors and Marines in a "fair fight." Instead, they want our warfighters to have a clear, overwhelming, and recognized advantage—so much so that potential adversaries refrain from aggressive action because they know it would be swiftly and decisively defeated.

It's no secret that unmanned systems and autonomy are considered pivotal elements of that advantage moving forward. Indeed, autonomy is already an essential component of naval strategy writ large, and promises to become more so as technology advances. The Chief of Naval Operations (CNO) has listed autonomy as one of his top priorities, and work being done at the Office of Naval Research (ONR), across all departments—from the Expeditionary Maneuver Warfare and Combatting Terrorism Department to the Air Warfare and Weapons Department—supports that directive.

The Chief of Naval Research, Rear Adm. Matthew Klunder, recognized that ONR and its subordinate commands, the Naval Research Laboratory and ONR Global, will best succeed in bringing new thinking to the forefront on behalf of the warfighter through a regular exchange of ideas with partners from across the services, academia, and industry. As conferences and events have scaled back in the face of tight budgets, those face-to-face opportunities have become fewer.

Accordingly, he directed that ONR host a series of Focus Area Forums, with the first one centered on autonomy and unmanned systems. The inaugural event, held in January of this year, brought together leading minds from across the country to engage in dialogue, exchange ideas, and learn of potential opportunities in a field that is changing the face of battle.

More than 200 experts participated in the first forum.

"This event provides a unique opportunity to learn and share ideas," Klunder said in his introductory remarks. "Today we will foster collaboration and new partnerships on complex autonomy challenges, and your participation will influence the future of naval autonomy."

Klunder told the gathering that, quite simply, the Navy and Marine Corps need more autonomous capabilities. "Unmanned systems and autonomy are force multipliers," he said, "with the potential to increase affordability for future mission capabilities."

Challenges and Opportunities

Participants at the forum learned that ONR's vision supports the CNO's directive for an affordable, hybrid manned and unmanned future force. ONR's work in autonomy crosses missions and disciplines; according to Klunder, research proceeds with the understanding that autonomous systems are and will be applied to all of operating domains, used for many different kinds of operations, and incorporate a variety of systems.

Some of the topics covered included:

Basic Research/Science of Autonomy: Dr. Mark Steinberg, who oversees ONR's basic research into the science of autonomy, as well as unmanned aerial systems (and who has contributed an article to this edition of *Future Force*; see p. 18), kicked off the presentations. He introduced the audience to some of the core areas his team is exploring, including human/unmanned systems collaboration and perception/intelligent decision-making.

With long-term goals including reduced manning requirements, producing scalable approaches to greater numbers of autonomous systems, and improving reasoning, learning and decision-making capabilities in contested or uncertain environments, Steinberg noted that the science of autonomy touches a wide range of engineering and scientific disciplines—providing many opportunities to support warfighters, but also entailing multidisciplinary challenges.

"There have been significant advances across the fields that underlie autonomy," he said, "but many challenges still remain in creating systems that can work effectively with warfighters and carry out missions at useful operational tempos across the full range of naval environments. ONR's Science of Autonomy program

REMUS

Autonomous underwater vehicles such as the REMUS, shown here being lowered from R/V Moana Wave into the waters off California's San Clemente Island, can collect enormous amounts of data for a wide range of missions from oceanographic surveys to mine countermeasures.

(Photo by John Williams)

#autonomy

looks across the different academic disciplines and warfighting domains to provide a broad foundation of possibilities for the future Navy and Marine Corps."

In the long term, ONR researchers say they are looking toward new operational concepts, longer-term missions incorporating unmanned systems, more effective manning, and improved human/machine and machine/machine teaming—all done with improved command and control capabilities.

Undersea Autonomous Systems: Several speakers outlined the state of research in undersea autonomous systems. Among their central goals was better incorporating the ocean environment to our tactical advantage. That includes advancing capabilities in mobile autonomous environmental sensing; improving predictive capabilities; and adapting warfighting systems to better incorporate environmental variability.

Other domains of interest to the undersea community include mine clearance; enabling unmanned undersea systems to have longer endurance; antisubmarine warfare; persistent surveillance; Arctic and global prediction; and more.

Autonomous Surface Vehicles: The Sea Warfare and Weapons Department is actively developing advanced autonomous capabilities for our Sailors and Marines. As outlined by subject matter expert Dr. Bob Brizzolara (whose article appears in this edition on page 24), one of the broad goals of unmanned surface vehicles (USV) is to improve long, complex missions in dynamic, unpredictable and harsh environments. Some of the future research directions of interest include improving intent determination; activity recognition and motion prediction of maritime vessels; improved situational awareness and accuracy in degraded conditions like high sea state/poor visibility, etc.; cooperative decision-making among groups of USVs; and more.

Aerial Autonomous Systems: Researchers say they're looking to autonomy to improve safe and high-operational tempos; enhance effective collaboration with the warfighter; and increase operational options. Just a few of the domains of interest discussed were cargo delivery and casualty evacuation (see page 36 of this issue for a look at the Autonomous Aerial Cargo/Utility System); air combat; and shipboard landing and flight-deck operations.

The Future Force

Events like the Focus Area Forum illustrate how far naval research has come, and how many unexplored horizons lie ahead in autonomy and unmanned systems development. On the one hand, some of the systems already in progress will bring significant new capabilities to the future force—AACUS, for instance, will enable manned or unmanned helos to safely land supplies and ultimately extract casualties; the Experimental Fuel Cell (XFC) is an unmanned aerial system that can be launched from the torpedo tube of a submerged submarine; and the Shipboard Autonomous Firefighting Robot (known as SAFFiR) is a human-sized autonomous robot that will be capable of finding and suppressing shipboard fires and working seamlessly with human firefighters. All have been developed with ONR support.

Yet challenges remain for naval unmanned and autonomous systems, which need to work in dynamic and uncertain environments; to accomplish increasingly complex missions; to function with potentially limited and/or intermittent communications; and to serve an ever-evolving range of warfighter requirements.

All of that must be done within the context of cost and budget realities. New technological advances cannot come with a price tag that will bankrupt the Navy, Marine Corps or nation, officials note.

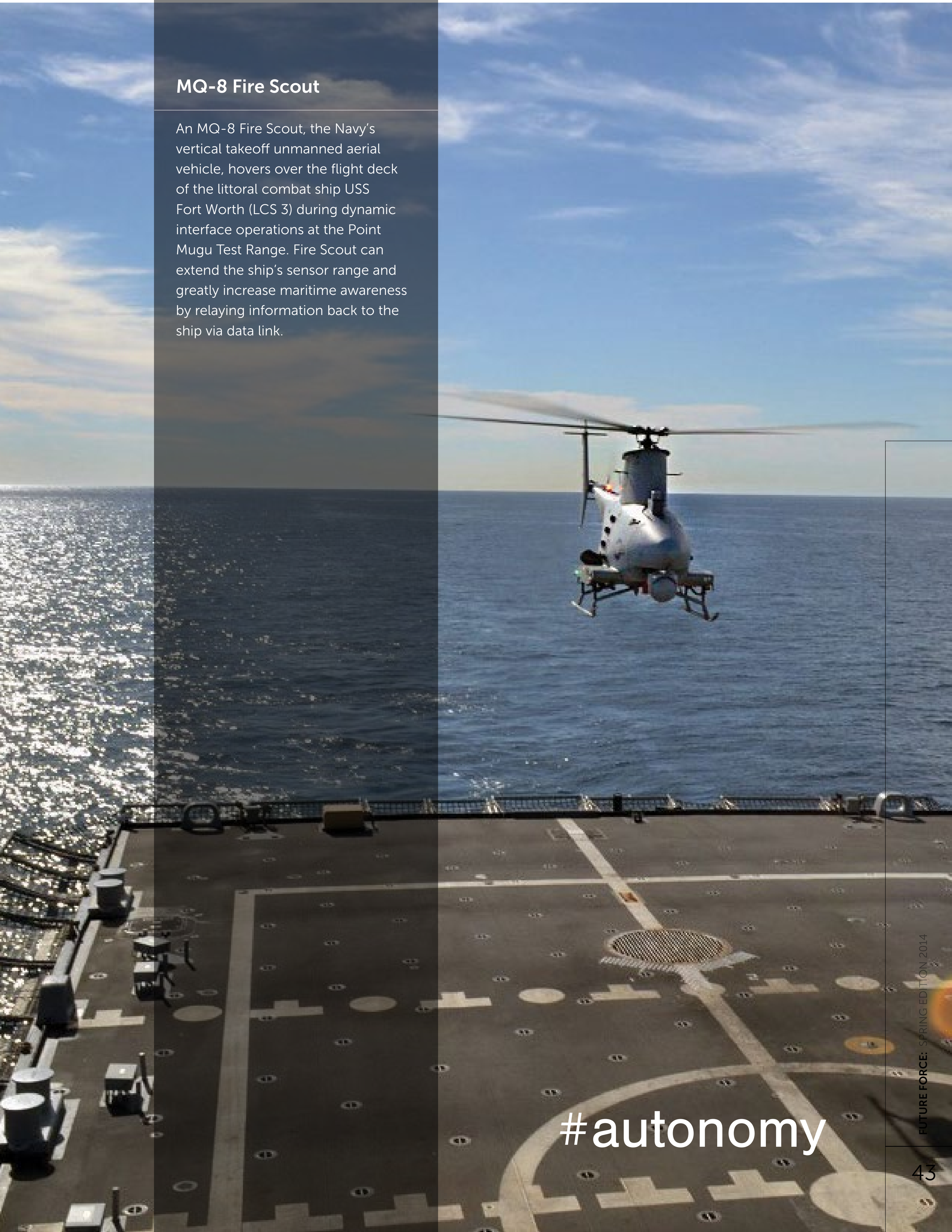
Naval scientists at ONR, NRL, Marine Corps Warfighting Laboratory, and elsewhere know that advances in autonomy will help ensure America's Sailors and Marines never have to engage in a fair fight with the enemy.

About the author:

David Smalley is a contractor who serves as the lead editor for the Office of Naval Research Corporate Strategic Communications

MQ-8 Fire Scout

An MQ-8 Fire Scout, the Navy's vertical takeoff unmanned aerial vehicle, hovers over the flight deck of the littoral combat ship USS Fort Worth (LCS 3) during dynamic interface operations at the Point Mugu Test Range. Fire Scout can extend the ship's sensor range and greatly increase maritime awareness by relaying information back to the ship via data link.



#autonomy

Science in Review ▸▸ Autonomy

To illustrate the depth and diversity of cutting-edge science and technology efforts within the naval research community, Science in Review presents a critical selection of recently published articles in major science, technology, and engineering journals. This issue's column focuses on research in autonomy and autonomous vehicles.

"An IPMC-Enabled Bio-Inspired Bending/Twisting Fin for Underwater Applications"
Smart Materials and Structures, Volume 22, Issue 1 (January 2013).
By Viljar Palmre, Joel J. Hubbard, Maxwell Fleming, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper discusses the design, fabrication, and characterization of an ionic polymer-metal composite (IPMC), actuator-based, bio-inspired active fin capable of bending and twisting motions when used as a means of propulsion for autonomous underwater systems.

"Controlling Autonomous Underwater Floating Platforms Using Bacterial Fermentation"
Applied Microbiology and Biotechnology, Volume 97, Issue 1 (January 2013), 135-142.
By Justin C. Biffinger, Lisa A. Fitzgerald, Erinn C. Howard, et al.
Participating Naval Agencies: Naval Research Laboratory, Office of Naval Research
Abstract: This study describes the use of biogenic gases—produced by living organisms—from the bacterium Clostridium acetobutylicum for a new application-renewable ballast regeneration for autonomous underwater devices.

"Active Planning for Underwater Inspection and the Benefit of Adaptivity"
International Journal of Robotics Research, Volume 32, Issue 1 (January 2013), 3-18.
By Geoffrey A. Hollinger, Brendan Englot, Franz S. Hover, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper discusses the problem of inspecting an underwater structure, such as a submerged ship hull, with an autonomous underwater vehicle. Unlike a large body of prior work, it focuses on planning the views of the vehicle to improve the quality of the inspection, rather than maximizing the accuracy of a given data stream.

"An Electronic Circuit for Trickle Charge Harvesting from Littoral Microbial Fuel Cells"
IEEE Journal of Oceanic Engineering, Volume 38, Issue 1 (January 2013), 32-42.
By Promode R. Bandyopadhyay, Daniel P. Thivierge, Frank M. McNeilly, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper considers the design of an electronic circuit for harvesting energy trickling from benthic sources and the long-term performance in powering sensors and devices in a littoral tidal basin.

"Time-Critical Cooperative Path Following of Multiple Unmanned Aerial Vehicles over Time-Varying Networks"
Journal of Guidance Control and Dynamics, Volume 36, Issue 2 (March-April 2013), 499-516.
By E. Xargay, I. Kaminer, A. Pascoal, et al.
Participating Naval Agencies: Office of Naval Research, U.S. Special Operations Command
Abstract: This paper addresses the problem of steering a fleet of unmanned aerial vehicles along desired three-dimensional paths while meeting stringent spatial and temporal constraints.

"Observability-Based Optimization of Coordinated Sampling Trajectories for Recursive Estimation of a Strong, Spatially Varying Flowfield"
Journal of Intelligent & Robotic Systems, Volume 70, Issue 1-4 (April 2013), 527-544.
By Levi DeVries, Sharanya J. Majumdar, and Derek A. Paley.
Participating Naval Agencies: Office of Naval Research
Abstract: Autonomous vehicles are effective environmental sampling platforms whose sampling performance can be optimized by path-planning algorithms that drive vehicles to specific regions containing the most informative data. This paper applies various tools to derive a multivehicle control algorithm that steers vehicles to an optimal sampling formation.

"Central Pattern Generator Control of a Tensegrity Swimmer"
IEEE-ASME Transactions on Mechatronics, Volume 18, Issue 2 (April 2013), 586-597.
By Thomas Bliss, Tetsuya Iwasaki, and Hilary Bart-Smith.
Participating Naval Agencies: Office of Naval Research, Naval Surface Warfare Center Carderock Division
Abstract: Rhythmic motion employed in animal locomotion is ultimately controlled by neuronal circuits known as central pattern generators. It appears that these controllers produce efficient, oscillatory command signals by entraining to an efficient or economic gait through sensory feedback. This property is of great interest in the control of autonomous vehicles.

"Temporal Logic Robot Control Based on Automata Learning of Environmental Dynamics"
International Journal of Robotics Research, Volume 32, Issue 5 (April 2013), 547-565.
By Yushan Chen, Jana Tumova, Alphan Ulusoy, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: This project developed a technique to automatically generate a control policy for a robot moving in an environment that includes elements with unknown, randomly changing behavior.

"Distributed Reference-Free Fault Detection Method for Autonomous Wireless Sensor Networks"
IEEE Sensors Journal, Volume 13, Issue 5 (May 2013), 2009-19.
By Chun Lo, Jerome P. Lynch, and Mingyan Liu.
Participating Naval Agencies: Office of Naval Research
Abstract: Compact and low-cost sensors used in wireless sensor networks are vulnerable to deterioration and failure. As the number and scale of sensor deployments grow, the failure of sensors becomes an increasingly paramount issue. This paper presents a distributed, reference-free fault detection algorithm that is based on local pair-wise verification between sensors monitoring the same physical system.

"Elements of Underwater Glider Performance and Stability"
Marine Technology Society Journal, Volume 47, Issue 3 (May-June 2013), 81-98.
By Shuangshuang Fan and Craig Woolsey.
Participating Naval Agencies: Office of Naval Research
Abstract: Underwater gliders are winged autonomous underwater vehicles that can be deployed for months at a time and travel thousands of kilometers. As with any vehicle, different applications impose different mission requirements that impact vehicle design. This paper investigates the relationship between a

glider's geometry and its performance and stability characteristics.

"Measurement of the Magnetic Signature of a Moving Surface Vessel with Multiple" *Magnetometer-Equipped AUVs*
Ocean Engineering, Volume 64, 15 May 2013, 80-87.
By Christopher R. Walker, Jordan Q. Stringfield, Eric T. Wolbrecht, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: Measurement of the magnetic signature of naval vessels allows one to determine their vulnerability to mines, and thus whether the signatures must be reduced. Hypothetically, a formation of magnetometer-equipped autonomous underwater vehicles could be used to perform a magnetic signature measurement. In this work, a formation of three magnetometer-equipped vehicles was used to assess the feasibility of performing a magnetic signature measurement on a moving surface vessel.

"Remus100 AUV with an Integrated Microfluidic System for Explosives Detection"
Analytical and Bioanalytical Chemistry, Volume 405, Issue 15 (June 2013), 5171-78.
By Andre A. Adams, Paul T. Charles, Scott P. Veitch, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: Measuring explosive materials at trace concentrations in real-time on-site within the marine environment may prove critical to protecting civilians, waterways, and military personnel. This paper presents recent field trials that demonstrate detection and quantitation of small aromatic molecules using novel high-throughput microfluidic immunosensors aboard a REMUS100 autonomous underwater vehicle.

"Real-Time Visual SLAM for Autonomous Underwater Hull Inspection Using Visual Saliency"
IEEE Transactions on Robotics, Volume 29, Issue 3 (June 2013), 719-33.
By Ayoung Kim and Ryan M. Eustice.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper reports a real-time, visual simultaneous localization and mapping (SLAM) algorithm and results for its application in the area of autonomous underwater ship hull inspection. The proposed algorithm overcomes some of the specific challenges associated with underwater visual SLAM, namely, limited field of view imagery and feature-poor regions.

"Field Testing of Moving Short-Baseline Navigation for Autonomous Underwater Vehicles Using Synchronized Acoustic Messaging"
Journal of Field Robotics, Volume 30, Issue 4 (July-August 2013), 519-35.
By Eric Wolbrecht, Michael Anderson, John Canning, et al.
Participating Naval Agencies: Office of Naval Research, Naval Surface Warfare Center Carderock Division

Abstract: This paper presents the results from field testing of a unique approach to the navigation of a fleet of autonomous underwater vehicles using only onboard sensors and information provided by a moving surface ship. The approach uses two transponders mounted on a single surface ship that alternately broadcast acoustic messages containing one of the parameters of the movement of the ship.

"Minimum Time Heading Control of Underpowered Vehicles in Time-Varying Ocean Currents"
Ocean Engineering, Volume 66, 1 July 2013, 12-31.
By Blane Rhoads, Igor Mezic, and Andrew C. Poje.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper presents a numerical method for minimum time heading control of fixed-speed autonomous underwater vehicles such as gliders in known, spatially complex, 2-D, time-varying flow fields. This problem is difficult because locally optimal trajectories abound and, worse, currents stronger than the vehicle can push it far off course.

"Relocating Underwater Features Autonomously Using Sonar-Based SLAM"
IEEE Journal of Oceanic Engineering, Volume 38, Issue 3 (July 2013), 500-513.
By Maurice F. Fallon, John Folkesson, Hunter McClelland, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper describes a system for reacquiring features of interest in a shallow-water ocean environment, using autonomous underwater vehicles equipped with low-cost sonar and navigation sensors. In performing mine countermeasures, it is critical to enable such vehicles to navigate accurately to previously mapped objects of interest in the water column or on the seabed, for further assessment or remediation.

"Active Sound Localization in a Symmetric Environment"
International Journal of Advanced Robotic Systems, Volume 10, 29 July 2013,
By Jordan Brindza, Ashleigh Thomas, Spencer Lee, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: Localization for humanoid robots becomes difficult when events that disrupt robot positioning information occur. This holds especially true in symmetric environments because landmark data may not be sufficient to determine orientation. This project uses a system of localizing humanoid robots in a known, symmetric environment using a particle filter and a sound localization system.

"An Experimental Setup for Autonomous Operation of Surface Vessels in Rough Seas"
Robotica, Volume 31, Part 5 (August 2013), 703-15.
By Farhad Mahini, Leonard DiWilliams, Kevin Burke, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper presents a small-scale experimental setup for autonomous target tracking of a surface vessel in the presence of obstacles. The experiments were performed in simulated rough seas through wave, current, and wind generation in a small indoor pool.

"A 3-D Motion Estimation from Feature Tracks in 2-D FS Sonar Video"
IEEE Transactions on Robotics, Volume 29, Issue 4 (August 2013), 1016-30.
By Sharhriar Negahdaripour.
Participating Naval Agencies: Office of Naval Research
Abstract: For the computation of 3-D motion by automatic video processing, the estimation accuracy and robustness can be enhanced by integrating the visual cues from shadow dynamics with the image flow of stationary 3-D objects, both induced by sonar motion. This paper presents mathematical models of image flow for 3-D objects and their cast shadows, uses them in devising various 3-D sonar motion estimation solutions, and studies their robustness.

"Constrained Interaction and Coordination in Proximity-Limited Multiagent Systems"
IEEE Transactions on Robotics, Volume 29, Issue 4 (August 2013), 930-44.
By Ryan K. Williams and Gaurav S. Sukhatme.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper considers the problem of controlling the interactions of a group of mobile agents, subject to a set of topological constraints. This project proposes a distributed scheme

that consists of hybrid controllers with discrete switching for link discrimination, coupled with attractive and repulsive potentials fields for mobility control, where constraint violation predicates form the basis for discernment.

"Three-Dimensional Coverage Planning for an Underwater Inspection Robot"
International Journal of Robotics Research, Volume 32, Issue 9-10 (August 2013), 1048-73.
By Brendan Englot and Franz S. Hover.
Participating Naval Agencies: Office of Naval Research
Abstract: To support autonomous, in-water inspection of a ship hull, this project proposes and implements new techniques for coverage path planning over complex 3-D structures.

"A State Observation Technique for Highly Compressed Source Coding of Autonomous Underwater Vehicle Position"
IEEE Journal of Oceanic Engineering, Volume 38, Issue 4 (October 2013), 796-808.
By Toby Schneider and Henrik Schmidt.
Participating Naval Agencies: Office of Naval Research
Abstract: In this paper, a novel technique is presented for using state observers in conjunction with an entropy source encoder to enable highly compressed telemetry of autonomous underwater vehicle position vectors. In this work, both the sending vehicle and receiving vehicle or human operator are equipped with a shared real-time simulation of the sender's state based on the prior transmitted positions.

"Reconfigurable Acquisition System with Integrated Optics for a Portable Flow Cytometer"
Review of Scientific Instruments, Volume 84, Issue 11 (November 2013),
By Matthew A. Kirleis, Scott A. Mathews, Jasenka Verbarg, et al.
Participating Naval Agencies: Naval Research Laboratory, Office of Naval Research
Abstract: Portable and inexpensive scientific instruments that are capable of performing point of care diagnostics are needed for applications such as disease detection and diagnosis, for water quality and food supply monitoring, and for biosurveillance activities in autonomous vehicles. This paper describes the development of a compact flow cytometer, which analyses cells using laser technology.

"Biomimetic Autonomous Robot Inspired by the Cyanea Capillata (Cyro)"
Bioinspiration and Biomimetics, Volume 8, Issue 4,
By Alex A. Villaneuva, Kenneth J. Marut, Tyler Michael, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: A biomimetic robot inspired by Cyanea capillata, the lion's mane jellyfish, was developed to meet the functional demands of underwater surveillance in defense and civilian applications. The vehicle was designed to mimic the morphology and swimming mechanism of the natural counterpart.

"High-Bandgap Solar Cells for Underwater Photovoltaic Applications"
IEEE Journal of Photovoltaics, Volume 4, Issue 1 (January 2014), 202-7.
By Phillip P. Jenkins, Scott Messenger, Kelly M. Trautz, et al.
Participating Naval Agencies: Naval Research Laboratory, Office of Naval Research
Abstract: Autonomous systems are increasingly used to provide situational awareness and long-term environment monitoring. Solar energy is favored as a long-endurance power source for many of these applications. This paper demonstrates that high-bandgap indium gallium phosphide solar cells can provide useful power underwater.

"Online Determination of the Potential Benefit of Path Adaptation in Undersea Search"
IEEE Journal of Oceanic Engineering, Volume 39, Issue 1 (January 2014), 165-78.
By John g. Baylog and Thomas A. Wettergren.
Participating Naval Agencies: Naval Undersea Warfare Center
Abstract: This paper examines a problem of autonomous vehicle decision making for search operations performed by undersea autonomous vehicles. It considers the problem of determining whether to continue with preplanned search paths or to switch to focused local search efforts in the presence of limited contact information.

"Exploiting Adaptive and Collaborative AUV Autonomy for Detection and Characterization of Internal Waves"
IEEE Journal of Oceanic Engineering, Volume 39, Issue 1 (January 2014), 150-64.
By Stephanie Petillo and Henrik Schmidt.
Participating Naval Agencies: Office of Naval Research
Abstract: Advances in the fields of autonomy software and environmental sampling techniques for autonomous underwater vehicles have recently allowed for the merging of oceanographic data collection with the testing of emerging marine technology. The Massachusetts Institute of Technology's Laboratory for Autonomous Marine Sensing Systems group conducted an internal wave detection experiment in August 2010 with these advances in mind.

"CAPTURE: A Communications Architecture for Progressive Transmission via Underwater Relays with Eavesdropping"
IEEE Journal of Oceanic Engineering, Volume 39, Issue 1 (January 2014), 120-30.
By Chris Murphy, Jeffrey M. Walls, Toby Schneider, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: As analysis of imagery and other science data plays a greater role in mission execution, there is an increasing need for autonomous marine vehicles to transmit these data to the surface. Communicating imagery and full-resolution sensor readings to surface observers remains a significant challenge. Yet, without access to the data acquired by an unmanned underwater vehicle, surface operators cannot fully understand the mission state of a vehicle. This paper presents an architecture capable of "multihop" communication across a network of underwater acoustic relays.

"Safe Maritime Autonomous Navigation with COLREGS, Using Velocity Obstacles"
IEEE Journal of Oceanic Engineering, Volume 39, Issue 1 (January 2014), 110-119.
By Yoshiaki Kuwata, Michael T. Wolf, Dimitri Zarzhitsky, et al.
Participating Naval Agencies: Office of Naval Research
Abstract: This paper presents an autonomous motion planning algorithm for unmanned surface vehicles to navigate safely in dynamic, cluttered environments. The algorithm not only addresses hazard avoidance for stationary and moving hazards, but also applies the International Regulations for Preventing Collisions at Sea (known as COLREGS).

A LOOK AHEAD

INFORMATION DOMINANCE

►► **Rear Adm. Matthew L. Klunder**

It's always wonderful to be present at the dawn of a new era. When developing the innovative technologies that will support our future naval forces, it can still be something very special. As we look to provide our future Sailors and Marines with the technological advances they deserve, I am very proud to be a part of this inaugural issue of *Future Force.*

Explaining the process of science and technology, how things work, and why we research some things and not others can sometimes be challenging. That's the main reason why we created *Future Force*, as a way to communicate better what the entire naval science and technology family is doing and why. Even more than that, I hope that *Future Force* will help our community build a tremendously cohesive unit that truly is collaborative—from the university lab to the future naval prototypes installed aboard our ships, aircraft, submarines, and vehicles.

As a way to help conceptualize the grand, overarching concepts that are driving today's cutting-edge naval science and technology, we're focusing the first issues of *Future Force* on particular themes. This issue deals with autonomy, one of the most important areas of science that is this driving everything from helping Marines deliver cargo by unmanned helicopter to providing our next generation of maritime domain awareness over and under the world's oceans. In our next issue, we'll be dealing with information dominance, in many ways a companion to autonomy. Both of these areas of science and technology inform and support each other. Much of our information and data is increasingly gathered by autonomous and unmanned systems, while our future autonomous systems will depend heavily on information gathering in order to carry out their other missions such as strike or transport.

In parallel with the publication of *Future Force*, the Office of Naval Research is hosting a series of focus area forums, the first of which, on autonomy, took place this past January. We hope to have our next one, on assured information for tactical naval forces, take place this summer. These forums bring together our academia and industry partners with naval science and technology program managers for face-to-face discussions about what's next in new technology. Innovation can't take place without collaboration and the sharing of ideas, and that's what we hope to foster with these new initiatives for communication and dialogue.

I hope you will find *Future Force* an effective tool for learning more about what naval science and technology is all about, and how it shapes the Navy and Marine Corps—and nation—of the future.

Adm. Klunder is the Chief of Naval Research.

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