updates on

NRL'S AUTONOMY RESEARCH

THE LEADING EDGE

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Welcome to the fourth issue of SPECTRA, a magazine designed to inform you of exciting science and technology developments at the U.S. Naval Research Laboratory (NRL).

In the spring of 2012, NRL opened the Laboratory for Autonomous Systems Research (LASR). Our vision for this shining, state-of-the-art facility was that it would be a focal point for basic and applied research related to unmanned and autonomous systems – a place to develop, integrate, and test systems and prototypes, to advance the Navy's scientific leadership in this domain. Now, a little more than two years later, the LASR has become the collaborative and energetic research space we envisioned, with scientists and engineers from all across NRL working together on interdisciplinary projects in the one-of-a-kind facilities and environments that LASR offers. Autonomy research for the Navy and Department of Defense benefits greatly from this convergence of diverse talent and expertise.

In its simulated desert, jungle, and littoral environments and other well-equipped laboratories, the LASR is hosting creative and innovative research in intelligent autonomy, sensor systems, power and energy systems, human–system interaction, networking and communications, and platforms. This issue of SPECTRA provides a snapshot of some of the LASR projects now moving forward:

- an autonomous underwater vehicle named WANDA that borrows its design from a coral reef fish,
- a next-generation hydrogen fuel cell built using 3-D printing,
- a battery that draws its power from the ocean bottom sediment,
- a robot that is learning to understand how people think, and
- a vehicle that travels through air and through water – a flying submarine.

We hope you enjoy this issue of SPECTRA and share it with others. To request additional copies or more information, please email spectra@nrl.navy.mil.

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Flight-testing the Flimmer UAV.
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# Bio-Inspired Designs for Near-Shore AUVs

Autonomous underwater vehicles (AUVs) have demonstrated many capabilities in inspection, surveillance, exploration, and object detection in deep seas, at high speeds, and over long distances. However, the low-speed, high-maneuverability operations required for near-shore and littoral zone missions present mobility and sensing challenges that have not been satisfactorily solved, despite nearly half a century of AUV development. Very shallow water and littoral environments are complex operating zones, often turbid, cluttered with obstacles, and with dynamically changing currents and wave action. AUVs need to be able to maneuver around obstacles, operate at low speeds, hover, and counteract surge and currents. To develop AUVs that can successfully navigate and operate in these dynamic and challenging environments, Naval Research Laboratory (NRL) researchers have taken

inspiration from nature — from fish, in particular — to design and develop novel underwater propulsion, control, and sensing solutions.

For AUV propulsion and control, NRL has developed an actively controlled curvature robotic fin based on the pectoral fin of a coral reef fish, the bird wrasse (*Gomphosus varius*). In the most recent fin iteration, four rib spars connected by a flexible synthetic membrane define the fin geometry, and control of each rib deflection angle enables the shape deformation needed to generate 3-D vectored thrust. Using computational fluid dynamics (CFD) tools in conjunction with experiments, sets of high-thrust-producing fin stroke kinematics, or fin gaits, have been identified. This kind of artificial fin technology can adapt to varying flow conditions and provide the thrust control necessary for low-speed maneuvering and precise positioning.

The NRL artificial pectoral fin has been integrated into a man-portable, unmanned vehicle named WANDA, the Wrasse-inspired Agile Near-shore Deformable-fin Automaton. Four side-mounted fins, two forward and two aft, provide all the propulsion and control necessary for the vehicle. A set of custom control algorithms uses information about the vehicle motion and surrounding environment to inform changes to the fin stroke kinematics. By weighting and combining various fin gaits, the magnitude and direction of thrust generated by each fin can be controlled to produce the desired effects on vehicle motion.

Computational and in-water experimental results have demonstrated WANDA's capabilities. WANDA can perform low-speed maneuvers including forward and vertical translation, turn-in-place rotation, and station keeping in the presence of waves.
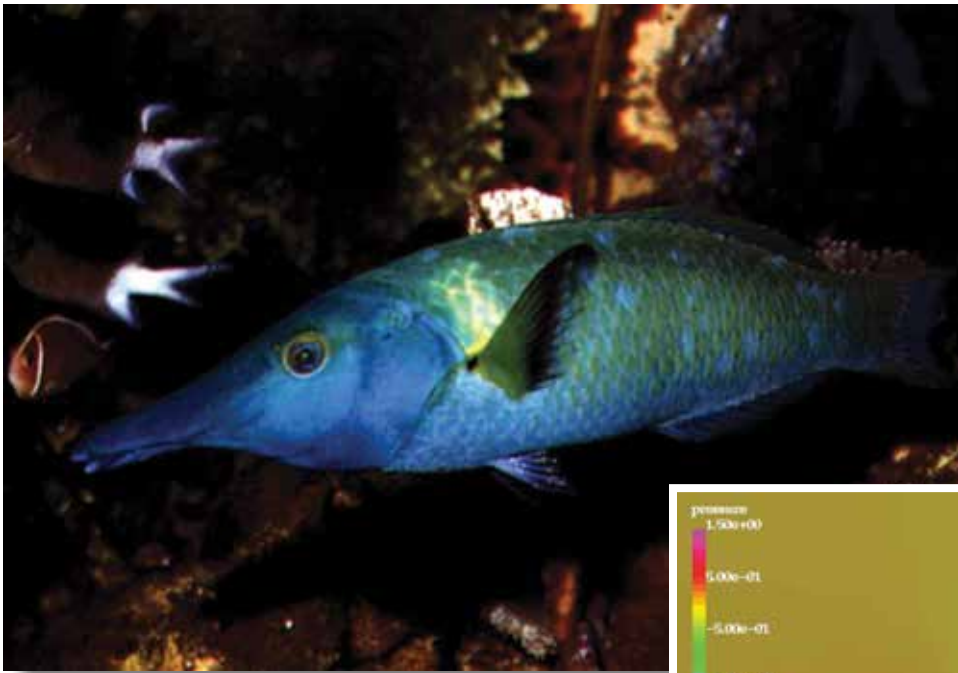
The bird wrasse (*Gomphosus varius*) is a coral reef dwelling fish operating in depths of 1 to 30 meters. It is known to use its paired median pectoral fins to produce thrust for maneuvering in these complex environments.

The geometry of the bird wrasse was modeled and computational fluid dynamics simulation was validated against experimental results.
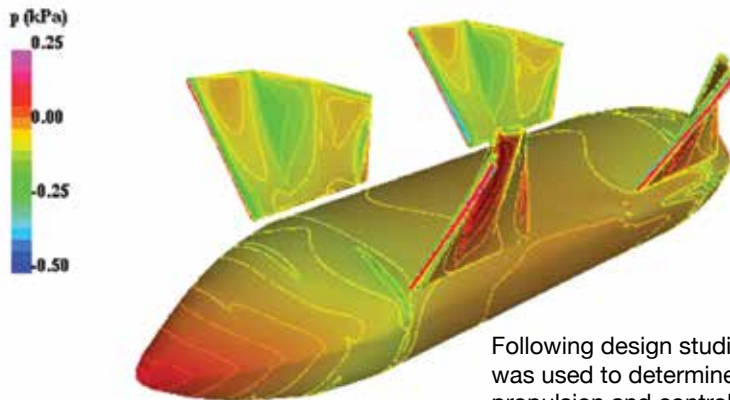
Following design studies for a robotic pectoral fin, CFD simulation was used to determine effectiveness of this device as a means of propulsion and control for an AUV.

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

Solutions for vehicle propulsion and control address only part of the challenge of operating in shallow underwater areas, so NRL is also developing new sensor systems for AUVs, and again looking at fish for ideas. A reliable system for navigating littoral environments requires real-time knowledge of current velocities and object positions. Conventional onboard sensors such as sonar and vision-based systems have shortfalls in a cluttered, shallow environment: sonar can suffer from multipath propagation issues, and vision-based systems are limited by turbidity.

Additionally, these are active systems that emit sound or light, which uses energy and exposes an AUV to detection.

Fish use a system of hair-like flow and pressure sensors, called a *lateral line*, to detect changes and obstacles in the environment around them. NRL has studied these natural systems and is developing an artificial lateral line, a system of pressure sensors mounted on the AUV hull to provide
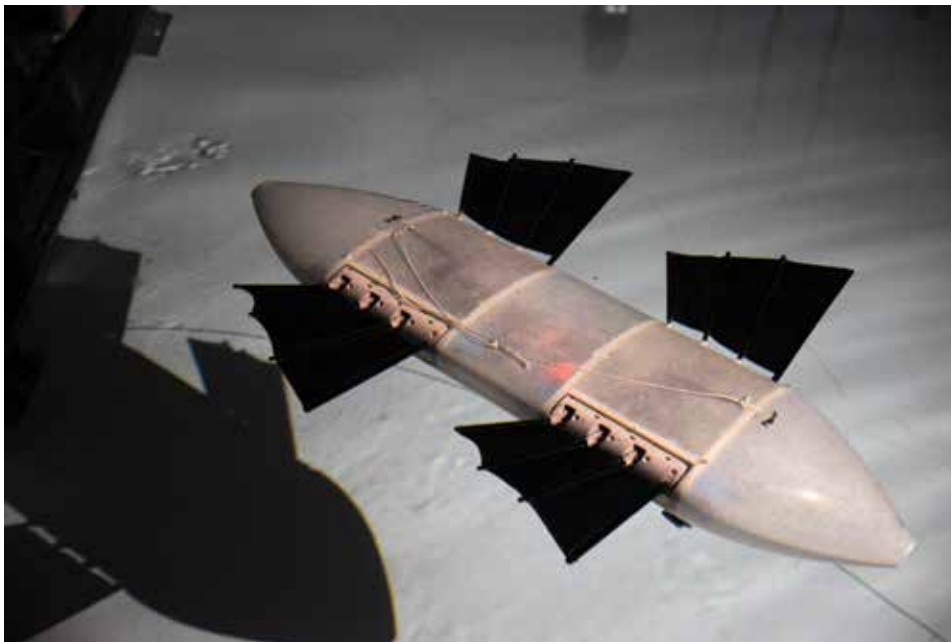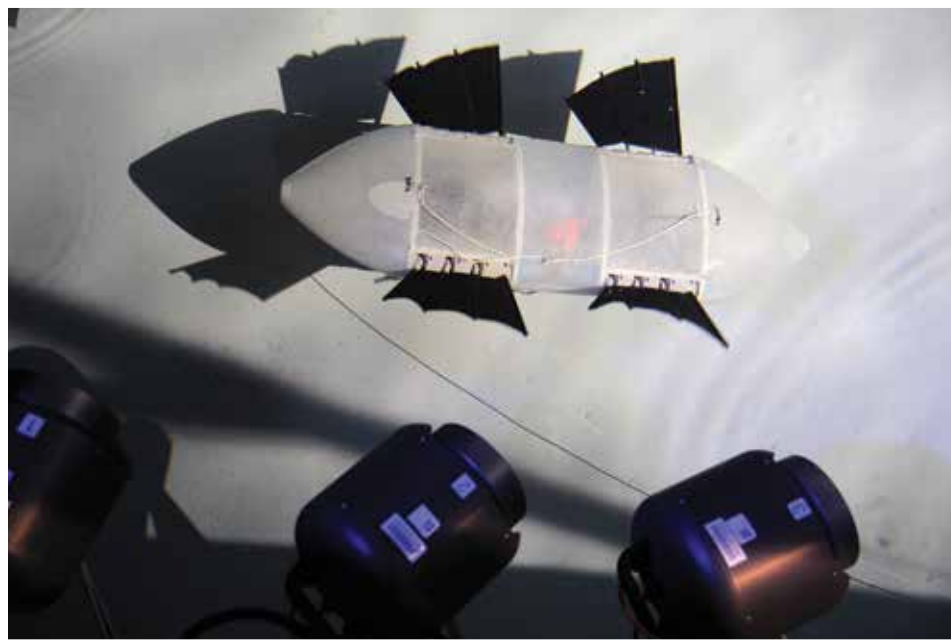
Demonstrating the WANDA AUV in the Littoral High Bay pool in NRL's Laboratory for Autonomous Systems Research. The four-fin design enables the propulsion and control needed for station-keeping and maneuvering in the presence of external disturbances such as waves and currents. The cameras in the foreground of the top photo are used to capture the three-dimensional motion of the vehicle in real time.

passive sensing of surrounding water velocities and near-field objects. This system uses quartz crystal–based pressure sensors with high sensitivity to measure minute pressure differentials between various points on the vehicle hull. The amplitude and phase differences between sensor signals provide information about the surrounding environment that the ve-

hicle can use to perform maneuvers such as orienting into a flow or avoiding obstacles. NRL's artificial lateral line will help WANDA and other AUVs achieve better performance in environments where sonar or vision alone cannot be relied on.

Much of the development and testing of the WANDA platforms takes place

in NRL's Laboratory for Autonomous Systems Research (LASR). This facility houses vehicle prototyping tools, such as 3-D printers and metalworking equipment, and large-scale test environments. The 45 foot by 25 foot pool in the LASR Littoral High Bay serves as the primary underwater test environment for WANDA, where a 16-channel wave generator creates
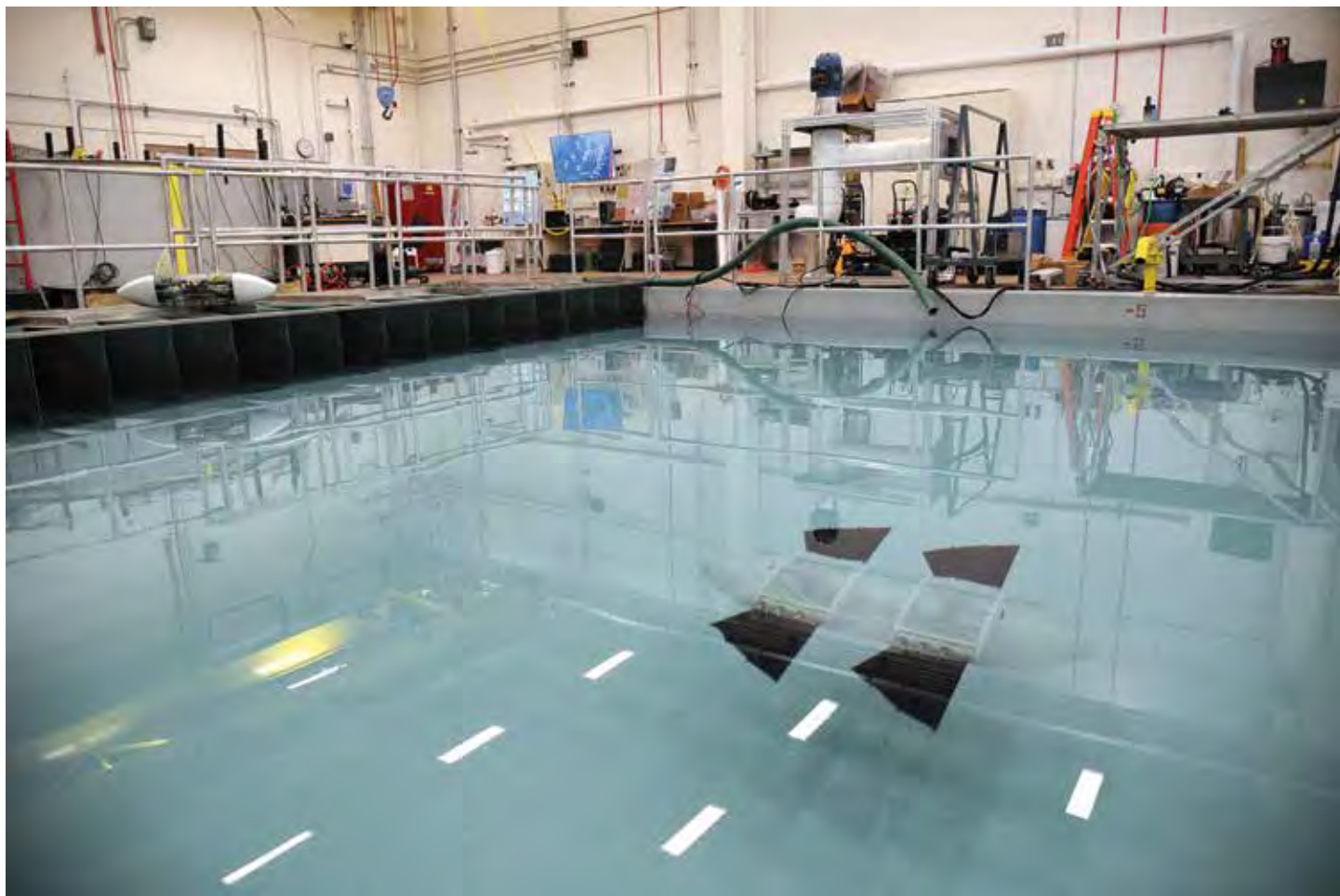
The WANDA AUV deployed for testing in the Littoral High Bay in NRL's Laboratory for Autonomous Systems Research.

real-world simulated near-shore conditions, and a 12-camera underwater tracking system provides ground truth position and orientation measurements for validation of vehicle performance.

As WANDA's fish-inspired technologies are perfected, the AUV is being prepared for payload testing. The vehicle's modular construction enables easy integration of different mission-specific payload packages, and one such payload that will be developed and tested on WANDA starting this year is a biochemical sensing system for trace level detection of chemical signatures. This sensor system built onto a capable low-speed platform such as WANDA will enable missions in plume tracking and target localization in shallow water environments.

The WANDA program has spawned other related programs to enable Navy critical missions using AUVs. NRL's new Flimmer (Flying Swimmer) program seeks to develop an unmanned platform that will be deployed from the air, glide to a water surface landing in an area of interest, and transition into a swimming AUV. NRL is leveraging its expertise in unmanned air vehicle (UAV) technologies to design and build the Flimmer vehicle. Modifications have been made to the WANDA fins to enable them to function as aerodynamic control surfaces and to survive the impact of landing (see page 6 for further details on Flimmer).

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

By **Jason Geder**
NRL Laboratories for Computational Physics and Fluid Dynamics

Flimmer team (left to right): Trent Young, Jason Geder, Dan Edwards, Marius Pruessner (not shown: Ravi Ramamurti).

Flimmer:
A Flying Submarine

The Flimmer (Flying Swimmer) program at the Naval Research Laboratory (NRL) is merging two research areas to provide a novel airborne delivery method for unmanned underwater vehicles (UUVs). Underwater vehicles are limited in top speed by the drag produced in water. However, air is approximately 1000 times less dense than water, so the power required to overcome drag is substantially reduced in air. By flying over the surface of the water rather than swimming long distances through it, delivery of a UUV to an operational area can be accomplished much more quickly, and delivery is possible to areas not directly accessible through continuous water

pathways. The Flimmer program seeks to investigate the potential of rapidly flying a submarine over the ocean's surface into position, transitioning from flight to underwater, and then enabling a swimming mode once underwater.

Major Design Considerations
In general terms, an aircraft is a specific outer shape held rigidly in place with a series of internal structural elements. Weight is the enemy of an aircraft designer: an increase in weight requires additional lift to keep the vehicle aloft. Drag is increased due to this extra lift, which requires more power to overcome that drag. To keep aircraft lightweight, they are typically manufactured as a thin skin

supported by minimal internal structures with low safety factor margins.

On the other hand, underwater vehicles are built completely the opposite way. As an underwater vehicle descends, the pressure applied by the water column increases rapidly, requiring the use of a strong pressure vessel to protect the electronics from water. These pressure vessels are typically thick metal pressure-resistant shapes with substantial seals. Inherent to enclosing air volume is an increase in the vehicle's buoyancy, requiring sufficient ballast weight to bring the overall vehicle to near neutral buoyancy. Instead of using ballast weight, many UUV designers elect to make the pressure vessel

heavier than required for the desired depth pressure.

Combining these two diametrically opposed vehicles to design a flying submarine comes down to a balancing act between buoyancy, weight, and structural elements. For a submarine to fly, the enclosed air volume, which is the main driver of weight for a submarine, needs to be reduced as much as possible. For an aircraft to land on the water, its structural elements need to be more robust to survive the high impact of splashdown.

The Flimmer program adds a further complication into the design: flapping fins are used for underwater propulsion. As learned from NRL's WANDA UUV (see article on page 2), a four-finned configuration provides high maneuverability and good stability underwater. In air, however, the fins add weight and are relatively fragile mechanisms that need to be able to survive the forces of splashdown. Bringing all these design elements together is the central challenge of the Flimmer program.

Test Sub

The Flimmer program started with just the combination aircraft and submarine, without the additional complexity of fins. The "Test Sub" configuration was born from combining a traditional submarine shape with a traditional aircraft shape. Test Sub uses a fixed geometry in both air and water, carrying the drag penalty of large surface area wings in the water, instead of spending weight and complexity on a wing folding mechanism. Test Sub also carries a weight penalty in the aircraft mode so that it can enter the water at full flight speed, spending weight to make the structures survive this high impact loading.

The Littoral High Bay test pool in NRL's Laboratory for Autonomous Systems Research (LASR) was home to Test Sub during its initial development. Underwater testing focused on development of the submarine sub-

Test Sub maneuvering as a submarine in the Littoral High Bay pool in NRL's Laboratory for Autonomous Systems Research.
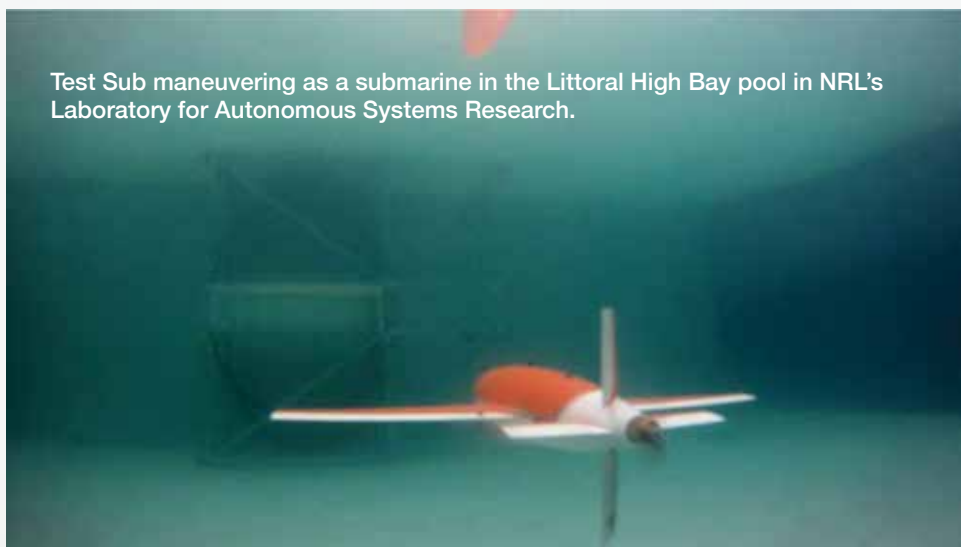
systems, to include primarily buoyancy control and kinematic controls. A custom-built buoyancy control system uses two inflatable bladders placed at the front and rear inside the hull fairing. A control loop pumps air into the two bladders for a combination of both pitch and heave control when the vehicle is stationary (in motion, the tail surfaces are used). Air is scavenged from inside the pressure vessel to inflate the bladders. While using air in bladders is a lightweight solution, it does have the drawback of being unstable with depth, requiring constant control inputs.

The most interesting aspect of running Test Sub in the LASR pool was that controlling the vehicle in forward motion underwater was identical to "flying" the aircraft. The configuration of an aircraft shape and traditional aircraft control surfaces of rudder, elevator, and ailerons functions exactly the same whether in air or water. Several test runs showed excellent controllability and maneuverability of Test Sub in the water while moving forward.

For flight testing, Test Sub was taken to a local test range. Three free-flights started with an air-drop of the vehicle from a mother ship at approximately 1000 feet altitude. Test Sub was guided manually in a series

of descending orbits to a splashdown landing in the water. Test Sub flew as any other aircraft, controllable in three axes and exhibiting sufficient stability for man-in-the-loop flight. Once nearing the water surface, Test Sub was guided along a standard approach at an airspeed of approximately 40 knots before splashdown with wings level. Upon touching the water surface, the aircraft saw a dramatic increase in drag and decelerated abruptly. After the splash, Test Sub submerged and started moving underwater.

Flying WANDA

With the success of Test Sub, the Flimmer team applied the lessons to designing a method for flying NRL's WANDA vehicle. The "Flying WANDA" configuration has four fins and the addition of a wing, with the two aft fins mounted on the tips of the wing. This allows keeping the same control techniques developed for the four-finned UUV design, but provides a lifting surface for carrying the weight of all the flapping mechanisms.

As the fins are a significant surface area relative to the wing area, they have been designed to pull double-duty. While swimming, the fins act as flapping propulsors. In flight, the wingtip-mounted fins are turned up

Test Sub splashdown sequence.

to act as fixed vertical stabilizers for lateral stability, and the forward-mounted fins act as close-coupled canards ahead of the wing. With this dual-use of the fin mechanisms, the incremental drag penalty for Flying WANDA is only the addition of the wing.

Four test flights of this configuration have confirmed acceptable stability and control. Half-area forward fins have been flown and show strong control power for acting as canards. Full-area wingtip fins have been flown in a fixed configuration and provide sufficient vertical tail surface for stable lateral modes.

Test flights have also begun exploring the landing mode that will best protect the fin mechanisms. Flying WANDA is designed for a traditional approach and splashdown, with a planing hull surface to stretch the deceleration time across a longer landing maneuver. All four fins are well protected using this landing technique, as they are on upper portions of the vehicle. However, in moderate to heavy sea states, this planing landing is not possible without large increases in vehicle size or autopilot complexity. Therefore, two nose-down landing styles have been tested to investigate survivability of the canards in a load condition consisting primarily in the drag direction. Since the flapping propulsion mode already must be stiff in the drag direction, the fins' survivability in the plunge style landing has been better than initially expected.

Experimentation with the Flying WANDA configuration continues. Future flights will explore the performance envelope using the fins as active control surfaces in the air and will continue the landing technique work. A hollow, floodable wing is under construction so that the swimming phase of experimentation can begin in the LASR pool.

The Sky's the Limit for this Submarine

While the diametrically opposed requirements for a flying vehicle versus a swimming submarine vehicle seem incompatible, the Flimmer program is showing a feasible path can be found somewhere in the middle. There are important trade-offs between enclosed air volume and structural weight, with a particular emphasis on surviving a splashdown in water at flight speeds. However, testing has already shown that Test Sub cruises well above 50 knots in the air, while top speed in the water is below 10 knots, illustrating the ultimate benefit of a flying submarine: assuring quick-reaction access to underwater areas.

By **Dan Edwards**
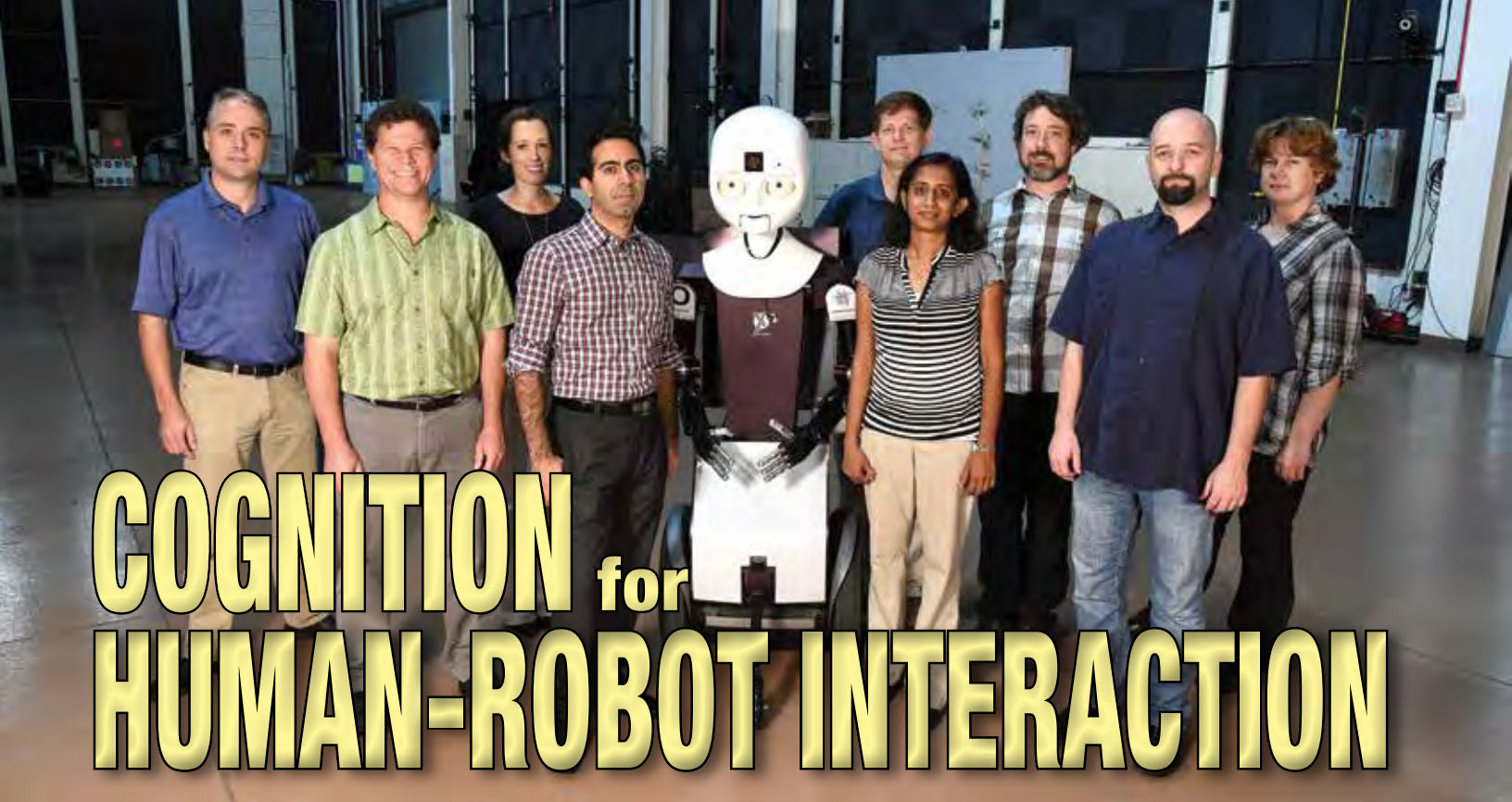*NRL Tactical Electronic Warfare Division*

Flying WANDA takes flight, moments after departing the pneumatic launcher.

The Flimmer vehicle is an adaptation of NRL's WANDA for air-delivery.

Flying WANDA approaches splashdown in the Potomac River.

COGNITION for HUMAN-ROBOT INTERACTION

Scientists from the Naval Research Laboratory's Navy Center for Applied Research in Artificial Intelligence demonstrate advances in cognitive science, cognitive robotics, and human–robot interaction with the help of teammate Octavia (center). Left to right: Ed Lawson, Greg Trafton, Laura Hiatt, Sunny Khemlani, Bill Adams, Priya Narayanan, Frank Tamborello, Tony Harrison, Magda Bugajska.

Our overarching goal is to give robots a deep understanding of how people think. There are three benefits of this to the scientific community. First, by improving understanding of how people think and interact with the world, we are pushing the boundaries of the field of cognitive science. Second, we can leverage this knowledge of people to help robots be better at tasks they typically are unable to perform well, such as multimodal communication and computer vision. Third, this deep understanding of humans allows robots to better predict and understand a human partner's behavior and, ultimately, be a better and more helpful teammate.

To accomplish this, we build process models of fundamental human cognitive skills – perception, memory, attention, spatial abilities, and theory of mind – and then use those models as reasoning mechanisms on robots and autonomous systems. Most of our work is done using the computa-

tional cognitive architecture ACT-R/E. A cognitive architecture is a process-level theory about human cognition. It provides a rich environment for modeling and validating different hypotheses about how people think. ACT-R/E provides a set of computational modules, correlated with different functional regions of the brain, that work together to explain both the limitations of human cognition (i.e., we don't have unlimited working memory) and the strengths (i.e., we are good at inferring connections between concepts and interacting with the physical world):

- **Declarative Module**: Manages the creation and storage of factual knowledge; selects what *chunks* (facts or memories) will be thought about at any given time.

- **Procedural Module**: Manages the creation and storage of procedural knowledge, or chunks; selects what production (if-then rule) will fire at any given time.

- **Intentional and Imaginal Modules**: Provide support for goal-oriented cognition and intermediate problem state representations.

- **Visual and Aural Modules**: Enable the architecture to see and hear perceptual elements in the model's world.

- **Configural and Manipulative Modules**: Enable the architecture to spatially represent perceptual elements in the model's world.

- **Temporal Module**: Allows the architecture to keep track of time; acts as a noisy metronome.

- **Motor and Vocal Modules**: Provide functionality for the model to move and speak with an appropriate time course.

Each module, save the procedural module, is associated with a limited-capacity buffer, representing what the model is thinking about / planning to

say / looking at / etc. Together, the contents of these buffers make up *working memory* in ACT-R/E. While each of the modules and buffers is theoretically motivated and validated on its own, ACT-R/E's strength lies in the complex interaction of these components, shown below.

The ACT-R/E architecture. The complex interaction of ACT-R/E's many theoretically motivated and validated components provides its true predictive and explanatory power.
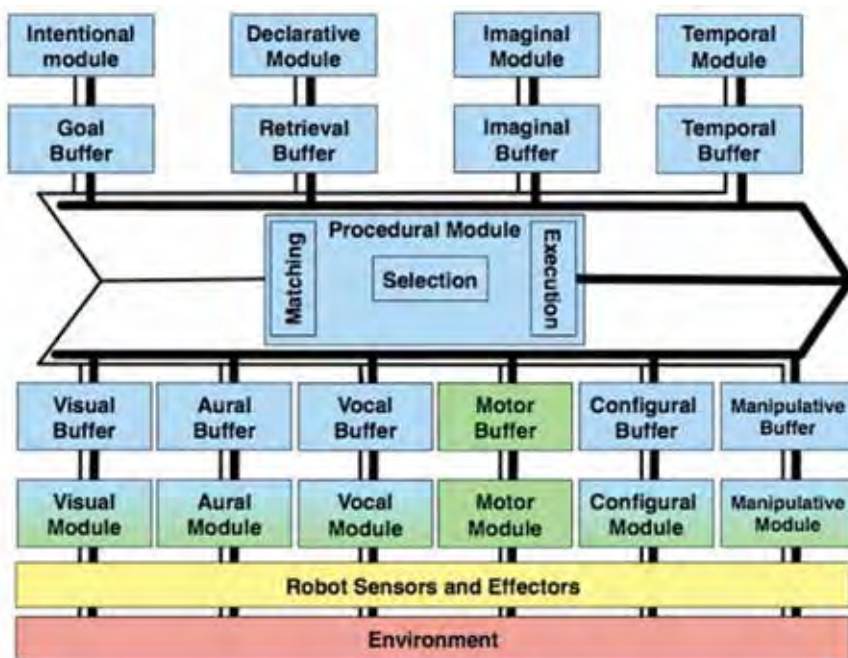
would allow the memory to become familiar enough to be remembered.

ACT-R/E's fidelity to the way the human mind integrates, stores, and retrieves all this information is what provides its true predictive and explanatory power. In this case, model-

To illustrate, consider an example of a conference attendee meeting someone at the conference and then attempting to remember his or her name later in the evening. The attendee would need to not only attend to the new person's face, voice, and clothing, but also bind those individual concepts to the name of the individual. The attendee would then need to rehearse the name several times so it would not be forgotten. When the attendee saw the new person a bit later, he or she would need to take available cues (perhaps only visual cues like face and clothing) and attempt to retrieve from memory the name associated with those cues. Priming from contextual cues, like the face, clothing, and the party itself, would boost the activation of the memory, and the earlier rehearsal

ing the human's experiences at the conference provides both descriptive information about how a human could err in this situation (e.g., people that look similar, or that were met at similar times or similar parties, may be easily confused) and predictive information (e.g., someone's name is unlikely to be remembered after a long break without further rehearsal or strong contextual cues).

In this article, we present two different systems in which ACT-R/E's fidelity to human cognition is leveraged to develop intelligent systems that can more functionally assist a human teammate. In the first example, ACT-R/E's familiarity and context mechanisms help an autonomous system better perceive ambiguous or obfuscated objects that a robot might

see in the real-world environments our warfighters encounter (such as jungles, deserts). In the second, ACT-R/E's goal structure, together with its familiarity and context mechanisms, allow an intelligent system to help humans avoid certain classes of errors, such as those commonly made in Navy vehicle maintenance procedures.

Computer Vision
Recent work in computer vision, performed by Hoiem, Efros, and Herbert in 2006, and Oliva and Torralba in 2007, among others, has shown that including contextual information can greatly affect the efficiency of object recognition in terms of both the speed and the accuracy of the processing process. These existing computer vision approaches, however, typically rely on static, aggregated statistics of various features in the scene to provide their context. While such approaches are promising, this limitation renders them unable to perform competitively with human perception; a richer, more human-like representation of contextual inference, learned over time, like that in ACT-R/E, may be the key to their success.

Context in ACT-R/E takes the form of associations between related concepts that are learned over time. Concepts become associated when they are thought about at roughly the same time; the more they are thought about in proximity to each other, the stronger their association becomes. This type of context is rich, in that it can capture nuanced relationships between concepts and facts that are not explicitly linked; this context is also dynamic, in that it is learned online and adjusted over time based on the model's experience. Object recognition algorithms, like LVis, a biologically plausible object recognition system developed by Randall O'Reilly at the University of Colorado Boulder, can utilize this information to improve recognition in cases where using visual features alone is difficult.

For example, when looking in the kitchen, context may suggest related concepts such as oranges or lemons. Any ambiguities that might arise from other similar objects (such as an orange ball) can be quickly resolved by incorporating contextual information, resulting in the correct identification.

Our initial experiments using a large database of objects have shown that a system that combines context and LVis's object recognition algorithms is able to increase recognition accuracy as compared to using LVis without context (see below). While these results are simple, they shed light on the powerful tool that context can be, and demonstrate how it can be used to build to autonomous systems that are better able to support and extend the Navy's capabilities.

Sample objects from the RGB-D dataset developed by Lai et al. at the University of Washington. The objects in the dataset are relatively low resolution, similar to what a robot would see as it moves around the world. Here, a battery (left) and dry eraser (right) can potentially have very similar visual outlines and contours, but are typically found in different situations; context can help differentiate between these two object classes.

Error Prediction

With the rapid rise of communication technologies that keep people accessible at all times, issues of interruptions and multitasking have become mainstream concerns. For example, the *New York Times* in 2005 and *Time* magazine in 2006 both reported stories about interruptions and multitasking, and how they affect performance by increasing human error. In 2005, the information technology research firm Basex estimated the economic impact of interruptions to be around $588 billion a year due to losses from increased task

One of our robots, Octavia, correctly recognizes an orange ball when it is in context. Octavia is a humanoid robot we use to investigate how to build intelligent systems that can serve as better teammates to their human partners.

completion time or errors. Given the prevalence of interruptions, building systems that can help remind an individual what they were doing or where they were in a task can have a large impact on individual and group productivity.

We built an ACT-R/E model that emulates the process people go through as they get interrupted during a procedural task and then

have to resume it. As ACT-R/E progresses through a task, it maintains a representation of where it is currently engaged in the task. For familiar tasks, this representation always associates, via context, an action to the next action to be performed. When a task is interrupted, the model loses track of its goal and, upon resumption of the task, must remember what it was working on. Sometimes, contextual cues associate to future steps

beyond the next correct one, and the system skips a step. Alternately, sometimes the familiarity of past actions surpasses the familiarity of the current action, and ACT-R/E remembers an action prior to the last one it completed, and repeats a step.

Using ACT-R/E in this way, we can explain (and thus can better predict) how, when interrupted, people tend to skip or repeat steps, even in a familiar task, based on the task's context and strengthening. This accomplishment will help us develop intelligent systems that can mitigate human error risks in dangerous procedures, with both monetary and functional benefits.

Conclusion

Our approach to intelligent systems is multidimensional. First, in the cognitive science tradition, we attain a deep understanding of how people think: our ACT-R/E models faithfully capture people's behavior as they perceive, think about, and act on the world around them. Second, we use this understanding to make intelligent systems better by taking advantage of people's strengths. Finally, the models help to reveal limitations and potential failings of human cognition, which our intelligent systems can then take steps to correct. Overall, our efforts to attain a deep understanding of human cognitive strengths and limitations allow us to build more functional intelligent systems that are better able to serve their human teammates.

By Laura M. Hiatt, Frank P. Tamborello, II, Wallace E. Lawson, and J. Gregory Trafton
Navy Center for Applied Research in Artificial Intelligence

Navy Center for Applied Research in Artificial Intelligence

The **Navy Center for Applied Research in Artificial Intelligence (NCARAI)** has been involved in basic and applied research in artificial intelligence, human factors, and human-centered computing since its inception in 1981. It is part of the Information Technology Division of the Naval Research Laboratory and is directed by Alan Schultz, who is also director of the Laboratory for Autonomous Systems Research.

The **Adaptive Systems** group conducts research focused on techniques that allow systems to change their level of autonomy on the fly, adapt to changes in their environment and in their own capabilities, learn new behaviors through interaction with the world, and interact more naturally with humans.

The **Intelligent Systems** group performs research in cognitive science, cognitive robotics and human-robot interaction, predicting and preventing procedural errors, the cognition of complex visualizations, interruptions and resumptions, and spatial cognition, to enable intelligent systems that can work more effectively with people.

The **Interactive Systems** group develops and enhances computer interfaces for autonomous and intelligent systems, spanning human-computer and human-robot interactions. Research includes linguistic, auditory, and phonological analyses to link natural language to modes of human-machine interaction.

The **Perceptual Systems** group examines issues related to sensors required to support autonomous platform navigation, scene interpretation, and teamwork. Techniques include passive monocular vision, and passive and active stereo and triocular ranging methods, along with algorithms to rapidly interpret the scene.

http://www.nrl.navy.mil/itd/aic/

NRL Autonomy Lab Hosts
Shipboard Fire Robotics Consortium

The U.S. Naval Research Laboratory (NRL) Laboratory for Autonomous Systems Research (LASR), a partner in the Navy's Damage Control for the 21st Century project (DC-21), recently hosted robotics research teams from the Virginia Polytechnic Institute and State University (Virginia Tech) and the University of Pennsylvania (Penn) to demonstrate the most current developments of advanced autonomous systems to assist in discovery, control, and damage control of incipient fires.

Fighting fires can at times prove challenging to even the most seasoned firefighting veteran — a firefighter must deal with extreme unpredictability, high temperatures, and rapid decline of environmental and structural integri-

ties. Add to this scenario a cloistered platform, say many levels down inside a seagoing ship, and the challenge is exponentially increased, resulting in extreme risks to human life. Despite these risks, a shipboard fire must be contained and extinguished for the safety of the crew and continued mission readiness of the ship.

To mitigate these risks, NRL researchers at LASR and NRL's Navy Center for Applied Research in Artificial Intelligence (NCARAI), under direction and funding from the Office of Naval Research (ONR), are working with university researchers to develop advanced firefighting technologies for shipboard fires using humanoid robots, an effort led by the NRL Chemistry Division.

"As part of the Navy's 'leap ahead' initiative, this research focuses on the integration of spatial orientation and the shipboard mobility capabilities of future shipboard robots," said Dr.

Thomas McKenna, managing program officer of ONR's Computational Neuroscience and Biorobotics programs. "The goal of this research is to develop the mutual interaction between a humanoid robotic firefighter and the rest of the firefighting team."

This highly specialized research, to promote advanced firefighting techniques, includes development of a novel robotic platform and fire-hardened materials (Virginia Tech), algorithms for perception and navigation autonomy (Penn), human–robot interaction technology, and computational cognitive models that will allow the robotic firefighter to work shoulder-to-shoulder and interact naturally with naval firefighters (NCARAI).

"These advancements complement highly specialized NRL research that focuses specifically on the human–robot interaction technology and shipboard-based spatial interrogation technology," said Alan C. Schultz, director of LASR

and the NCARAI. "Developments made from this research will allow a Navy firefighter to interact peer-to-peer, shoulder-to-shoulder with a humanoid robotic firefighter."

The NRL LASR, where the artificial intelligence portion of the research is performed, hosted the consortium of university researchers to demonstrate their most current developments.

The LASR facility allows the researchers from Virginia Tech and Penn to demonstrate, in a controlled environment, progress in the critical steps necessary for shipboard fire suppression using variants of their Shipboard Autonomous Firefighting Robot, or SAFFiR. In 2013, human–robot interaction technology and cognitive models developed by NRL were also demonstrated at the laboratory.

"The LASR facility, with its unique simulated multi-environments and state-of-the-art labs allows us to 'test out' our ideas before we go to the field," Schultz said. "In essence, our facility gives us a cost-saving method for testing concepts and ideas before we go to the expense of field trials."

While at LASR, the researchers demonstrated the complex motion, agility, and walking algorithms of the robots over natural and manmade terrain and simulated shipboard sea state (pitch and roll) conditions. Also demonstrated were "seek-and-find" algorithms for locating a fire emergency, in this case an open flame, and the use of "artificial muscle" for the lifting and activation of fire suppression equipment, such as opening a water valve, lifting and walking with a fire hose, and activating a nozzle.

"SAFFiR is being designed to move autonomously throughout a ship to learn ship layout, interact with people, patrol for structural anomalies, and handle many of the dangerous firefighting tasks that are normally performed by humans," McKenna said. The robot is designed with enhanced multimodal
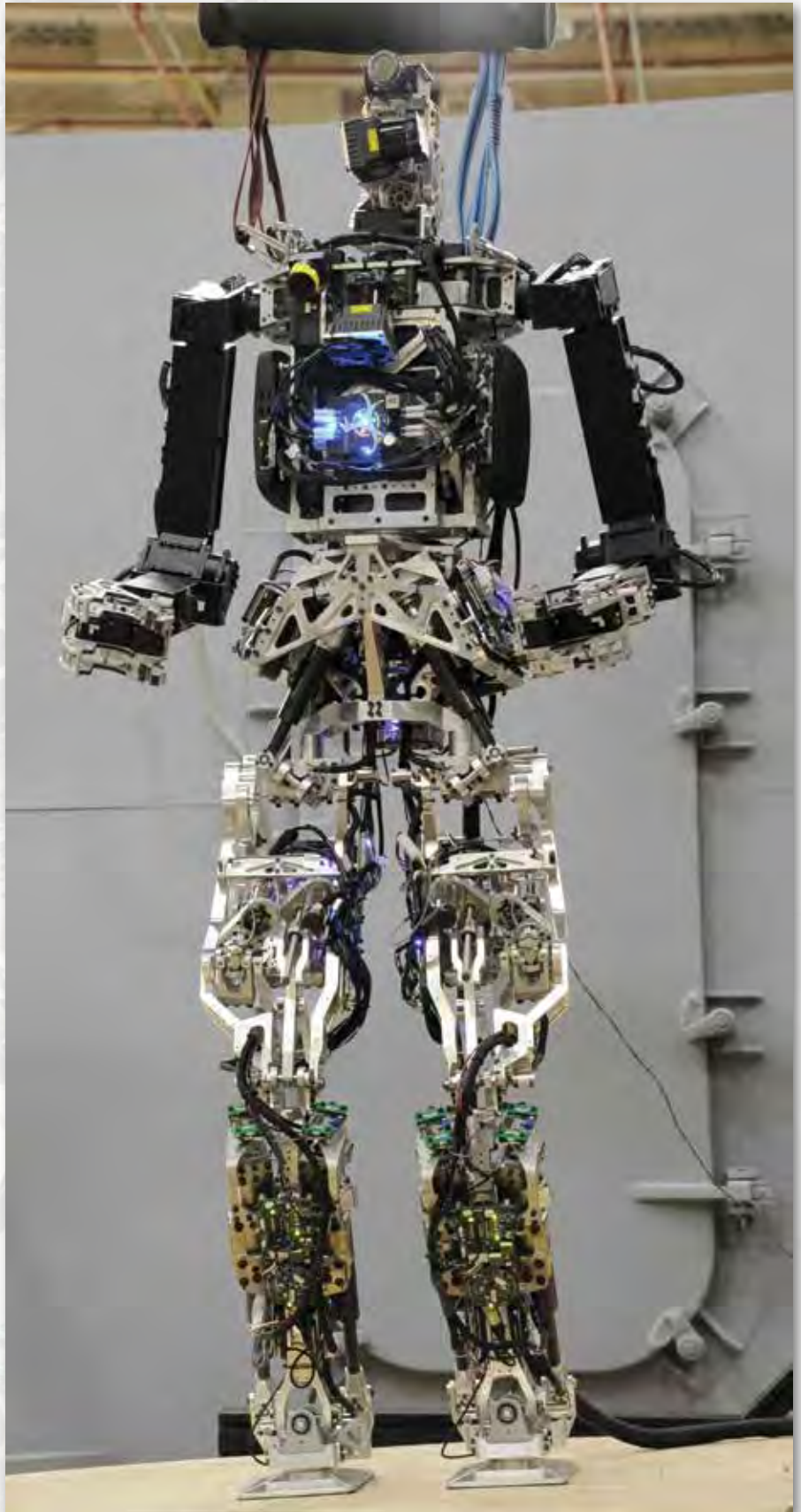
SAFFiR — the Shipboard Autonomous Firefighting Robot.
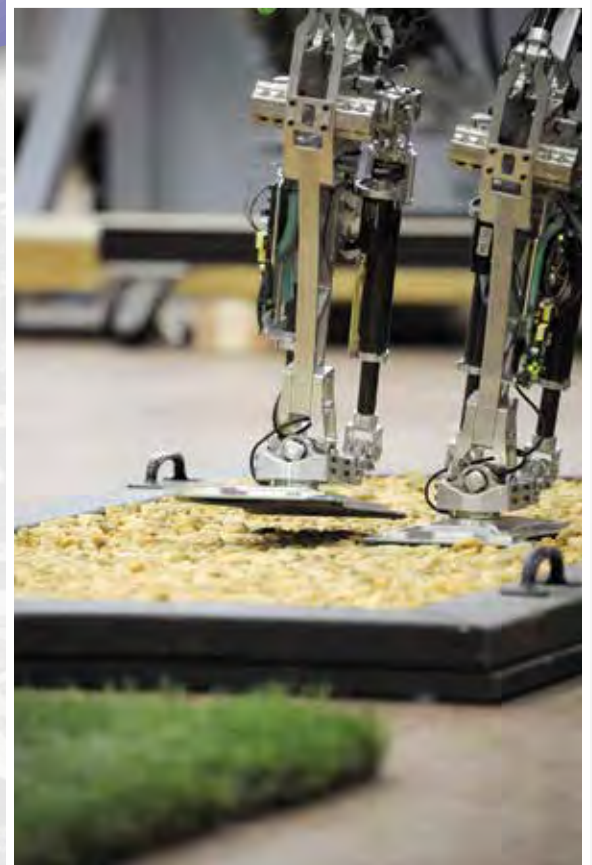
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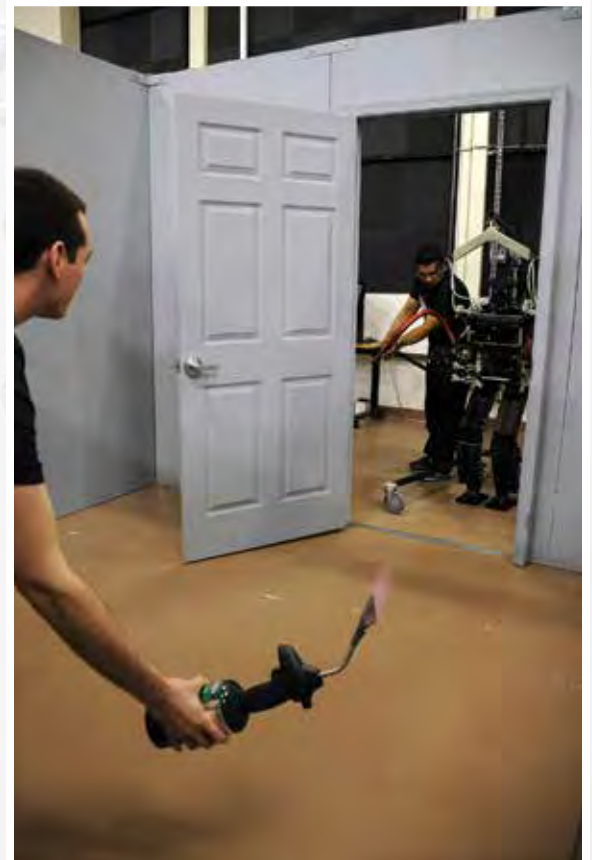
sensor technology for advanced navigation and a sensor suite that includes a camera, gas sensor, and stereo infrared (IR) and ultraviolet (UV) cameras to enable it to see through smoke and detect sources of excess heat. SAFFiR is also capable of walking in all directions, balancing in sea state conditions, and traversing obstacles such as "knee-knocker" bulkhead openings.

"Today's display demonstrates the integration of perception through multiple sensors, and of locomotion through biped walking," said Dr. Daniel Lee, director of the General Robotics Automation, Sensing, Perception Lab and professor at the University of Pennsylvania. Tasks as humans we take for granted, such as standing and remaining upright, become increasingly complex with the addition of full body mobility required for walking and lifting. Dr. Brian Lattimer, associate professor at Virginia Tech's Department of Mechanical Engineering, additionally commented that what we are now seeing is the result of a multidisciplinary project combined to perform all the critical tasks necessary for fire suppression by a humanoid robot.

"In dark or smoke-occluded and noisy environments found in shipboard firefighting conditions, tactile feedback — touch — is an important form of communication between human firefighters," said John Farley, project officer of the fire test ship ex-USS *Shadwell*, NRL Chemistry Division. "Moving forward, the team will integrate NRL's human–robot interaction technology with the SAFFiR platform so that there is a greater focus on natural interaction with naval firefighters."

In the short term, however, to protect robotic mechanisms and electronics from intense heat, researchers in the Advanced Materials Section of the NRL Chemistry Division have developed a class of lightweight, high-temperature polyetheretherketone (PEEK)-like phthalonitrile resin that can be molded to any shape and remain strong at temperatures up to 500 degrees Celsius. The robotic teams are expecting to soon conduct shipboard trials aboard *Shadwell*, the Navy's only full-scale fire test ship, moored in Mobile, Alabama.

By **Daniel Parry**
NRL Public Affairs Office

SAFFiR is being designed to move autonomously throughout a ship to learn ship layout, interact with people, patrol for structural anomalies, and handle many of the dangerous firefighting tasks that are normally performed by humans.

SAFFiR taking a break after a hard day at work.

NRL Technology Assists FDNY David DeRieux (right) of the Naval Research Laborat[ory]
RFID tracking system grew out of the realization during the events of 9/11 that first responders did not have
FDNY vehicles and helps to answer, Who exactly is on scene? Where are they? Are they safe? NRL receive[d]
saving work. See details on page 35. (Photo, left to right: George Arthur, Dan Orbach, and David DeRieux.)

...ory invented a system for Fire Department New York (FDNY) to automatically track firefighters. NRL's active-

...a reliable method to account for all members responding to an incident. The system is now in use on 15

...d a 2014 Federal Laboratory Consortium Award for Excellence in Technology Transfer for this potentially life-

The Benthic Microbial Fuel Cell

A benthic microbial fuel cell (BMFC) is an oceanographic power supply that can generate power indefinitely. The BMFC sits at the sediment/water (benthic) interface of marine environments, where it generates electrical power using organic matter naturally residing in marine sediments as its fuel, and oxygen in overlying water as its oxidant. At the Naval Research Laboratory (NRL), we are developing BMFCs to power persistent, in-water intelligence, surveillance, and reconnaissance capabilities presently limited in operational lifetime by battery depletion.

Thousands of battery-powered sensors are deployed each year that provide valuable scientific information about marine environments. The prospect of using BMFCs to power these sensors indefinitely, or at least far longer than possible with batteries, is enticing – we can acquire long-term uninterrupted data and significantly reduce the cost and logistics burden of keeping sensors running. A BMFC is maintenance free and nondepleting: the organic matter and oxygen are constantly replenished by naturally occurring diffusion and advection; the electrode catalysts consist of self-forming biofilms comprised of microorganisms naturally inhabiting the benthic interface; and there are no moving, degradable, or depletable components.

NRL has been a leader in developing the BMFC and optimizing it for Navy operational use. We have conducted laboratory and field research to study the microbial activity underlying power generation: to determine the effects of different oceanographic and biogeochemical parameters, to pair prototype BMFCs with sensors, and to develop easily deployable configurations. We have successfully powered many useful devices with small-scale BMFCs (less than 0.1 watt continuous output), and have just begun development of full-scale BMFCs (greater than 1 watt continuous output).

Early Laboratory Experiments
The bottom sediment of many marine environments is reductant enriched, due to metabolic activity of sediment-dwelling microorganisms, whereas the overlying water is oxidant enriched due to supply of oxygen from the atmosphere. This transition is referred to as the benthic redox gradient. As a result of this

The combined power from six small-scale BMFCs was used to persistently operate a meteorological buoy (center) in the Potomac River. The buoy measured local weather conditions and transmitted data every five minutes to a land-based receiver.

gradient, when an inert electrode is stepwise inserted into such sediments from overlying water, its open circuit potential shifts by as much as −0.8 volts.

Taking advantage of this natural voltage gradient at the sediment/water interface, my colleagues and I set out to create a battery for powering oceanographic sensors by embedding one electrode into reductant-enriched marine sediment, where it would act as an anode, and placing the other in oxidant-enriched overlying water, where it would act as a cathode. Our first experiments involved a benchtop shoebox-sized aquarium containing marine sediment, seawater, and a platinum anode and platinum cathode, which generated miniscule current across a resistive load. The notion at the time was that the anode was oxidizing microbial-generated reductants in the sediment (such as sulfide), and the cathode was reducing oxygen in the overlying water. Since the net reaction is thermodynamically favorable (electron transfer from a reductant to an oxidant, just like in a battery or fuel cell), it was reasonable to expect that power could be expended across a resistive load connecting the electrodes as long as oxygen was

replenished at the cathode, and mass transport (assumed to be diffusion) supplied the anode reactants and removed the anode products. A most interesting result was that current increased over time to a steady-state level. In most electrochemical experiments, current decreases over time due to depletion of the reactant and/or diminished catalytic activity of the electrode. I remember being dumbfounded watching the current rise.

We immediately followed with another benchtop experiment using graphite electrodes for the anode and cathode, resulting in a significantly higher current density. After the system generated power for some time across a resistor, we removed the anode from the sediment and examined it to find a biofilm adhering to its surface — a coating comprised of a community of microorganisms from the sediment. A genetics-based analysis of the biofilm indicated that it was enriched in a specific class of microorganisms, *Deltaproteobacteria*. The microorganism available in pure culture most similar to the microorganism enriched on the BMFC anode was *Desulfuromonas acetoxidans*, a dissimilatory metal-reducing bacteria (DMRB) found in marine sediment that couples oxidation of sedimentary acetate with

reduction of insoluble iron oxide mineral deposits. Such microorganisms are fascinating (especially to an electrochemist like me) for their ability to transport respired electrons from inside the cell to insoluble oxidants residing outside the cell (referred to as extracellular electron transport), acquiring a small amount of energy for themselves in the process. It is thought that *D. acetoxidans* in a BMFC anode biofilm oxidizes organic matter in marine sediment and transports the acquired electrons to the underlying anode as if it were a mineral deposit, effectively catalyzing the anode reaction.

Early Field Deployments
In one of our first field experiments, at the Rutgers University Marine Field Station in the Great Bay, New Jersey in 2002, a BMFC with graphite electrodes generated power continuously for nine months without indication of depletion in power before the experiment was terminated. This and subsequent longer-term field and laboratory experiments revealed an important attribute of microbial anode catalysts: as living entities metabolically benefiting from the reaction they catalyze, they self-maintain themselves and do not degrade over time as long as their environment

is hospitable. In this way, they can maintain catalytic activity indefinitely. Analysis of the anode biofilm of the New Jersey BMFC indicated enrichment not only of *D. acetoxidans*, but also of microorganisms in the *Desulfobulbus* or *Desulfocapsa* genera that oxidize and disproportionate sulfur. In sulfide-enriched sediment such as the New Jersey site, a graphite anode can develop a passivating sulfur precipitate on its surface that can shut down current. It is thought that these microorganisms act to clear the sulfur from the anode surface, forming sulfate and sulfite, both soluble.

The next BMFC field experiments were performed in 2003, at 1000 meters depth in the Monterey Canyon off the coast of California on a cold seep, a fissure on the seafloor effusing organic-rich water. We had hypothesized that the high mass transport rate of organic matter would benefit BMFC power generation and we were correct. This BMFC, equipped with a spear-like graphite anode inserted vertically into the seep, generated significantly more power per unit footprint area and geometric surface area of the anode compared to our earlier experiments. This was exciting because it demonstrated that placement of a BMFC in an area with a high rate of organic matter mass transport, such as a subliming methane hydrate outcrop, could result in very high power output, which could be of great use to the Navy.

We next deployed a BMFC in 2004 in the Potomac River off the NRL pier. Here, the BMFC consisted of graphite electrode slabs attached with zip ties to the top and bottom of milk crate spacers that were positioned on the river bottom with one electrode in the mud and the other in the overlying water. An attached buoy floating on the water surface measured air temperature, pressure, relative humidity, and water temperature, and transmitted this data to my office every five minutes. The entire buoy including the radio transmitter was powered by the BMFC. This required a novel solution to convert the low DC voltage output of the BMFC from 0.35 volts (dictated by the benthic redox gradient) to 6 volts to charge a capacitor, which in turn was used to power the buoy. The capacitor was needed to buffer the low but steady power output of the BMFC with the duty cycle of the buoy, whereby nearly 99% of energy consumption by the buoy occurred during the fraction of a second during which the data was transmitted. Between transmissions, the BMFC recharged the capacitor. This was the first time that a BMFC was used as a free-standing power supply. The buoy ran flawlessly for seven months. The river froze that winter, trapping the buoy in ice, but it kept running until the ice thawed enough that large pieces began to flow down river, dragging the buoy and severing the mooring line connecting it with the BMFC. I got a call from the Coast Guard who found the buoy resting against a pier of the Wilson Bridge. (Lesson: always put your phone number on any oceanographic instrument you want back.)

A Practical Power Supply
Since 2004, a number of researchers have been working to develop BMFCs into practical power supplies that are straightforward to deploy. I am fortunate to pursue this concept with my NRL colleagues Dr. Jeff Book, Mr. Andy Quaid, and Mr. Justin Brodersen, oceanographers; Dr. Yoko Furukawa, marine geochemist; and Dr. Jeff Erickson and Mr. Marius Pruessner, engineers; with funding from the Office of Naval Research and NRL. We have deployed small-scale BMFCs in coastal locations including California, Gulf of Mexico, Maine, New Jersey, North Carolina, and the Adriatic Sea. These BMFCs have operated over durations ranging from less than six months to more than two years without indication of depletion in power output. They have powered a hydrophone with a radio transceiver link, an acoustic modem, and a surveillance camera with a cellular link.

We are working to optimize the BMFC design to maximize power output while making anode embedment a simple and reliable procedure. Maximizing power involves anode designs that expose as much mass-transport-accessible surface area to sediment as possible within mass and volume constraints of the intended deployment platform, all while being easy to properly embed into sediment. We have been making steady progress, hampered at times by the vagaries of field research: in 2012, all our measurement equipment and 26 BMFCs deployed at a New Jersey site were lost when directly hit by Hurricane Sandy.

In 2013, we began development of full-scale BMFCs in NRL's newly opened Laboratory for Autonomous Systems Research (LASR), where we have assembled a six-meter-diameter, 8000-gallon benthic mesocosm, essentially a large indoor aquarium filled with sediment and seawater to replicate the benthic interface. This facility enables full-scale BMFC testing in a controlled environment, greatly reducing the cost and risk of BMFC design development compared to field testing. We have already made seven deployments of a two-meter-diameter, 900-kilogram oceanographic mooring equipped with various BMFCs to test new designs. The LASR mesocosm is greatly compressing the BMFC development horizon and I feel we are on track to transition the BMFC in 2015.

By **Leonard Tender**
NRL Center for Bio/Molecular Science and Engineering

BMFC graphite bottlebrush cathodes.

Dr. Leonard Tender (above, and with Marius Pruessner at right) working in the benthic mesocosm in the Laboratory for Autonomous Systems Research. The mesocosm contains 18 inches of seawater and 24 inches of synthetic marine sediment that has been inoculated with real marine sediment to provide necessary microbial activity. On the water surface are BMFC graphite bottlebrush cathodes; when deployed in the field, these cathodes are beneath the water surface but above the sediment surface. The vertical tubes indicate the locations of BMFC anodes embedded in the sediment.
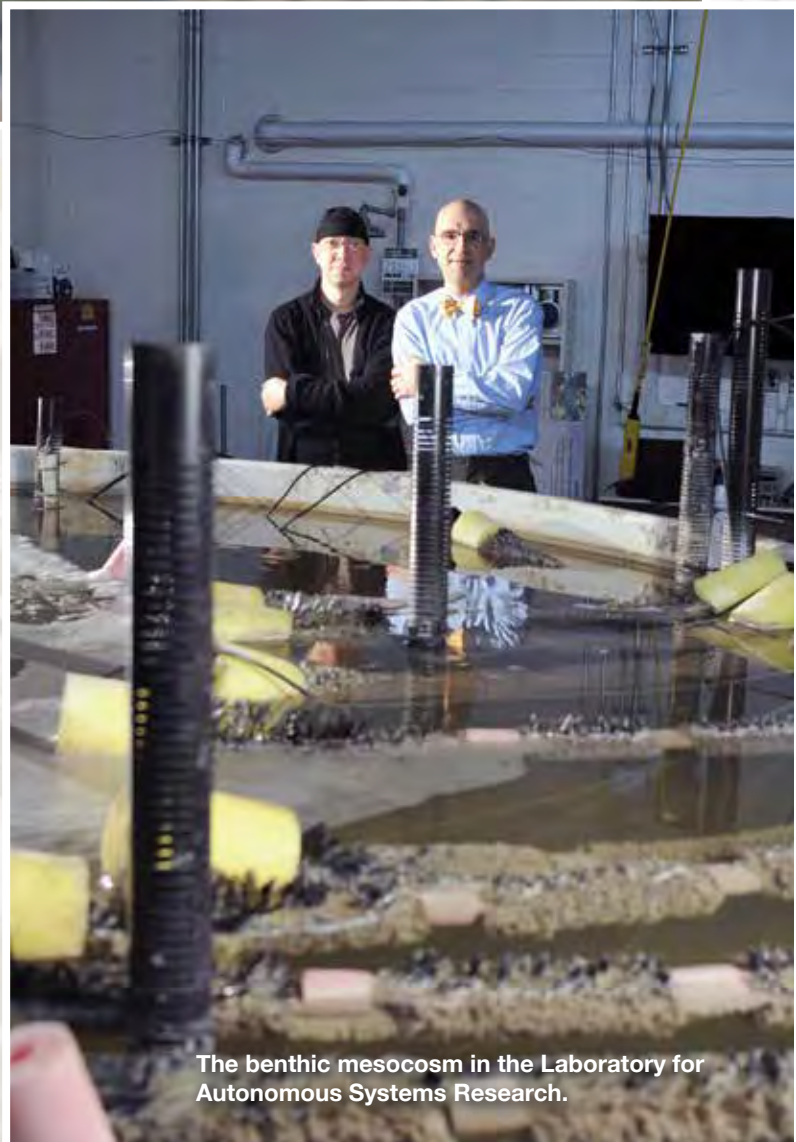
The benthic mesocosm in the Laboratory for Autonomous Systems Research.

3-D Printing in Hydrogen Fuel Cells

for Unmanned Systems

The NRL crew after the successful flight of a 3-D printed fuel cell aboard the Ion Tiger UAV. Left to right: Dan Edwards, Drew Rodgers, Ben Gould, Steve Carruthers, Mike Schuette, and Karen Swider-Lyons. Not shown: Chris Bovais.

The Naval Research Laboratory (NRL) has been leading the development of lightweight hydrogen fuel cell systems for long-endurance unmanned air vehicles (UAVs), starting with **the modest 3-hour flight of the** Spider Lion in 2004, followed **by the 24-hour flight of the Ion Tiger in 2009, the 48-hour flight** of the Ion Tiger in 2013, and the deployment of the XFC tactical UAV from the torpedo tube of a submarine in 2013. NRL also as**sisted in a demonstration flight** of Insitu's ScanEagle vehicle on a hydrogen fuel cell in 2010.

In a recent project, an NRL team leveraged 3-D printing and other prototyping tools in NRL's Laboratory for Autonomous Systems Research (LASR) for developing and integrating their next generation of hydrogen fuel cells into unmanned systems. Additive manufacturing processes such as 3-D printing promise rapid prototyping of new designs so they can be tested and verified without the expense of traditional manufacturing. The team used new tools in the LASR, plus commercial tools, to investigate how 3-D printing can be used toward improving fuel cells for unmanned systems.

The motivation for NRL's research into hydrogen fuel cells is clear. Fuel cells directly convert the energy in hydrogen to electricity by electrochemically combining with the oxygen in air.

The only byproducts are water and low-grade heat, and no combustion occurs. The electrochemical reactions are efficient, resulting in systems that are over 50% efficient and operate at low temperatures (near 80 degrees Celcius). Combined with the high energy of hydrogen, the result is an electric power source that is lightweight and has high energy per unit weight. For the Ion Tiger system, this meant a sevenfold increase in endurance over battery propulsion when gaseous hydrogen was used for the 24-hour flight. Hydrogen fuel cell systems also respond rapidly to changes in throttle, and are easily turned off and on. The fast response time and high energy density are two reasons major automobile manufacturers such as General Motors, Toyota, Honda, and Daimler have invested cumulatively $10 billion to $12 billion in hy-
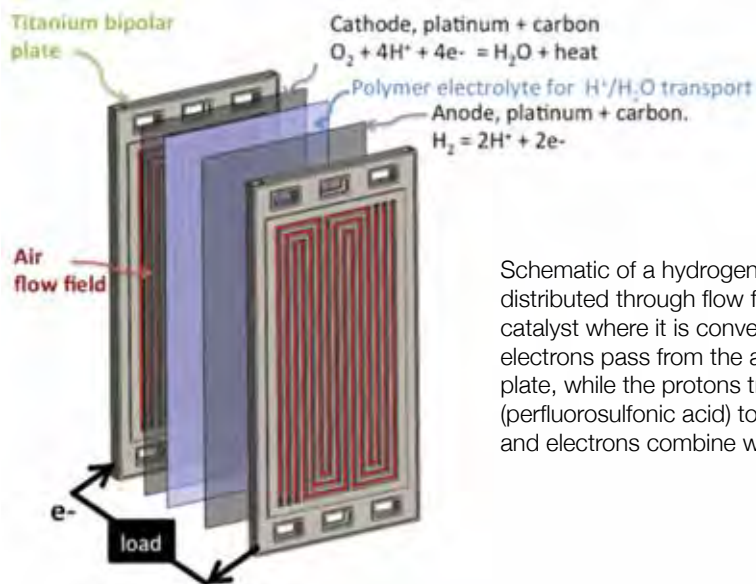
Schematic of a hydrogen fuel cell. Pressurized hydrogen (H_2) is distributed through flow fields in the bipolar plate to the anode catalyst where it is converted to protons (H^+) and electrons. The electrons pass from the anode bipolar plate to the cathode bipolar plate, while the protons travel through the polymer electrolyte (perfluorosulfonic acid) to the cathode. At the cathode, the protons and electrons combine with oxygen from air to form water and heat.

drogen fuel cells for next-generation automobiles.

Despite integration into many successful vehicles, hydrogen fuel cells are still too costly for commercial use, coming in about 5 to 10 times more expensive than a battery system. Platinum electrocatalysts were once a significant cost factor, but efforts by the automotive industry have cut the precious metal content of fuel cell systems drastically. The bigger cost now is in the *balance of plant* used to operate the fuel cell: this includes air blowers to push air through the system, a humidifier to keep the fuel cell at the right humidity, hydrogen recirculation systems to make sure 99% of the hydrogen fuel is used, and power electronics to convert the voltage of the fuel cell to one usable by the air blower, autopilot, and payloads. Another major cost driver is the bipolar plates that are used as the backbone of the fuel cell to physically hold together catalyst layers and to provide channels for air, fuel, and coolant flow, and electric pathways for the power produced by the system. These plates are where NRL focused much of its most recent research.

The bipolar plates hold a lot of the science and engineering of the fuel cells. The air, fuel, and coolant flow fields are typically created through iterations of design, computational fluid design (CFD) modeling, fabrication, and testing. Traditionally, bipolar plates have been made of carbon, but these are being replaced in favor of metal bipolar plates made of stamped foils that are coated for corrosion-proofing against the acidic environment in the fuel cell and then welded together. Looking at the complexity of developing new metal plate designs for NRL's UAV systems, senior mechanical engineer Mike Schuette
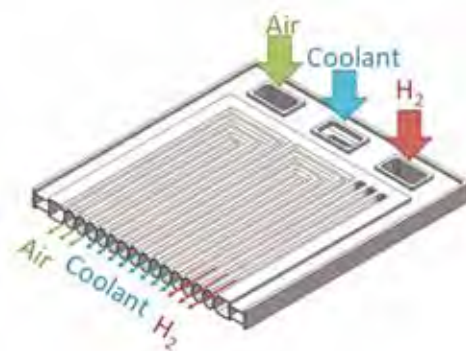

Concept drawing for a bipolar plate, showing air, coolant, and fuel channels.

said, "Stamping of metal foils is a proven industrial practice, but I was concerned about how long it would take to design the fuel cell flow fields, develop custom tools to stamp the

plates, and develop the welding processes. So I thought this was a great opportunity to try 3-D printing of metal plates so we could quickly try out several designs without having to commit to any tooling or welding."

First, the NRL team came up with several flow field designs. To check their viability, the team used the 3-D printing tools in the LASR to build up prototype plastic flow fields for flow visualization. In parallel, physicist Dr. Ravi Ramamurti carried out CFD predictions of the gas and coolant flows and heat rejection. A successful plate design was achieved through several rounds of design, building, testing, and model verification.

The challenge now was to make a hollow metal bipolar plate with external channels for air and fuel and an internal channel for coolant in a single three-dimensional structure that was also thin enough to meet the stringent low-weight requirements for flight. The team investigated different 3-D metal printing processes and found that direct metal laser sintering, DMLS, had the most potential for fabrication of this kind of geometry. NRL successfully worked with the DMLS company 3T RPD Ltd. (UK) to make thin titanium bipolar plates from NRL designs.
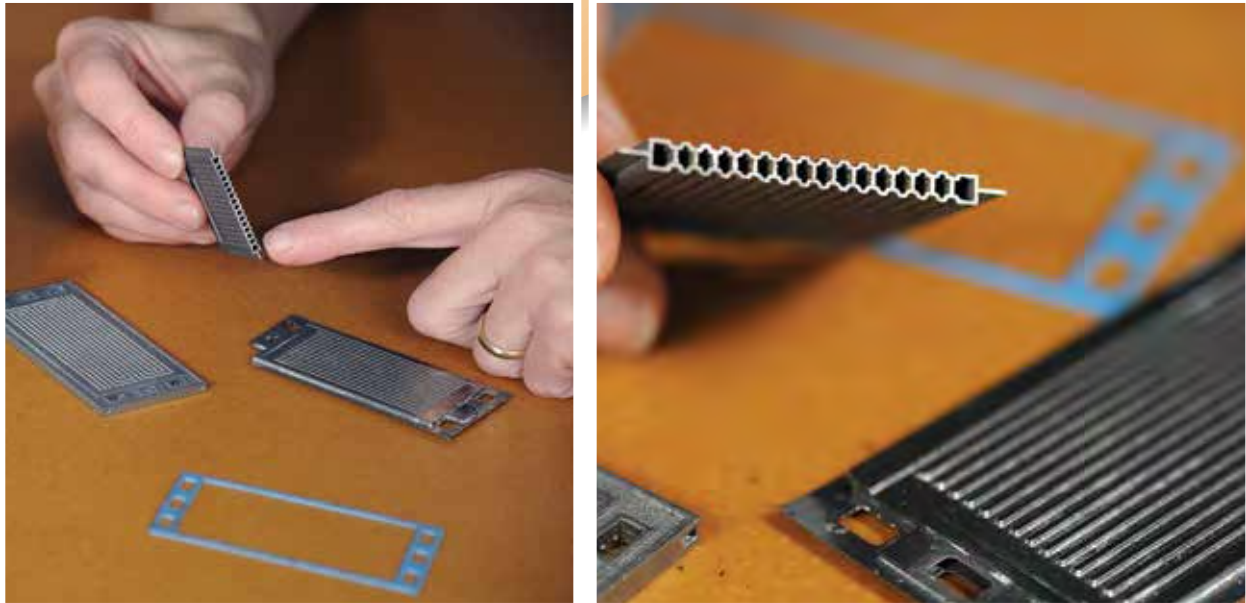
Details of the hollow titanium bipolar plates made by the 3-D printing process of direct metal laser sintering (DMLS).
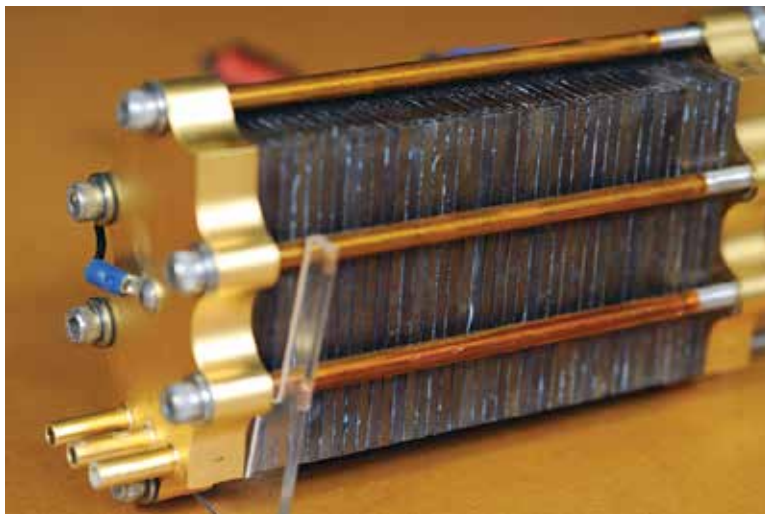
The bipolar plates assembled into a gas-tight stack.

The next challenge was to compress several bipolar plates together in a fuel cell stack with no leaks. "The no-leak part is really tough," says mechanical engineer (Joseph) Drew Rodgers. "You have to put all the catalyst layers together with the gas diffusion media, and properly align the gaskets so that none of the gas channels are blocked, and then compress them together in a gas-tight block." A consultant to the team, Doug Wheeler (who had worked at International Fuel Cells on fuel cells for the space shuttle), pointed us to high-performance softgood materials, including gasket materials and commercial catalyst membranes, which we precision-cut with NRL's laser cutting tools.

Once the full stack was together, chemical engineer Dr. Benjamin Gould found that it was much more electrically resistive than he had expected. "We looked through the literature and found that the finish on the bipolar plates strongly affects the plate-to-plate conductivity." Ben then worked with Morris Technolo-

gies (Cincinnati, OH) to develop the appropriate surface roughness for the plates, and aeronautical engineer Chris Netwall joined the team to work on processes to compress the plates and softgoods together effectively to eliminate as much resistance as possible. Additionally, NRL worked with TreadStone Technologies Inc. (Princeton, NJ) to apply a coating of titanium oxide impregnated with nanoscale dots of gold to provide a highly conductive, robust coating to the titanium bipolar plates. With these improvements, the team

put together 41 bipolar plates for a working stack. With help from the University of Hawaii, quality assurance processes were developed to confirm the fuel cell performance.

Putting the plates together in a stack exposed a critical problem with the 3-D metal printing process: warping. In DMLS, titanium particles are sintered into place with a laser, and then the whole body is sintered. Classic metallurgy teaches that residual strains in the metal-to-metal contact points lead to deformations as the material undergoes strain relief. The first set of metal bipolar plates had dimensions of 4 centimeters (cm) by 8 cm and could be pressed together effectively with other plates to make good contact; however, an attempt to make larger 8 cm by 12 cm plates was unsuccessful, as they all came in from the manufacturer warped by several thousandths of an inch. NRL is still investigating how to eliminate warps so that the plates have an adequate flatness tolerance. Developing accurate tolerancing is likely to be a key aspect of future research in metal 3-D printing.

With the stack ready, we built some new balance of plant and electronic control components, and soon a complete fuel cell system was running on the bench in the LASR Power and Energy Lab, ready to be packaged into NRL's Ion Tiger test vehicle.

The fuel cell system appeared ready to go from bench testing, but flight tests are the true graduation exercise for UAV technology. After an unusually snowy winter, the team jumped at the chance to fly the new system on a warm day in mid-March. The team rolled into the flight range at Blossom Point, Maryland, we started up the fuel cell, Chris Bovais loaded the Ion Tiger onto the winch — and off it went. Pilot Steve Carruthers let the vehicle climb above the tree line and then flew some laps. A thumbs-up from Dan Edwards on the ground station controller. Everything worked. NRL had successfully built a fuel cell using 3-D metal printing.

The team showed that 3-D printing was definitely the right way to go toward prototyping a fuel cell concept. "The 3-D printing helped us sort out the flow field designs and verify Ravi's

CFD results, so now we are ready to commit to the more time-intensive process of developing tooling and welding for stamped titanium-foil bipolar plates," says Ben. NRL has used this experience to publish and share new information on designing bipolar plates and stacks, decreasing contact resistance in fuel cell stacks, and using CFD to design effective coolant flow fields. The resulting computational tools will allow NRL to rapidly develop future fuel cell systems in the 100 to 5000 watt range for air, undersea, and ground vehicles.

Michele Anderson, the NRL team's program manager from the Office of Naval Research, summarized the value of the effort: "3-D printing met its promise as an R&D tool to make and test complex assemblies for research prototypes without the investment of costly tooling. Clearly it is an important research tool for the Navy for rapidly demonstrating new energy system prototype technology, and identifying optimal designs prior to investment in more expensive manufacturing methods." With additional research and development, 3-D printing combined with advanced computer design tools will help to accelerate the demonstration and fielding of new Department of Defense capabilities. As NRL's LASR facility expands its 3-D printing tools, it will continue to be the home for rapid prototype development at NRL.

By **Karen Swider-Lyons**
NRL Chemistry Division

Mike Schuette, Ben Gould, Drew Rodgers, and Karen Swider-Lyons display a hydrogen fuel cell stack made with 3-D printed bipolar plates (right), a microcontroller (left), and the nose of the Ion Tiger UAV (center) which houses the fuel cell system during flight.

More LASR Projects

LABORATORY FOR AUTONOMOUS SYSTEMS RESEARCH

## Damage Control for the 21st Century (DC-21)

The DC-21 project is developing advanced technologies for shipboard damage control. The project includes the development of advanced autonomous systems to assist in discovery, control, and damage control of incipient fires. Our focus is on the human–robot interaction technology that will allow a Navy firefighter to interact peer-to-peer, shoulder-to-shoulder with a humanoid robotic firefighter. Computational cognitive models are used to create reasoning mechanisms for the robot based on required human cognitive skills. In addition, the project investigates perception, including aural, gesture, and touch, and how context helps to disambiguate perceptions. Human–robot interaction is achieved through robust parsing of human speech, integrated with human gesture and touch, all of which are important in firefighting teams.

Mobile Autonomous Navy Teams for Information Surveillance and Search

The MANTISS program is adapting techniques inspired by nature to enable advanced information gathering by multi-agent autonomous teams. Under the Office of Naval Research Science of Autonomy (SoA) program, numerous biologically inspired techniques have been developed for controlling teams or swarms of autonomous vehicles. These include foraging algorithms based on how animal herds gather food, flocking behaviors observed in birds, schooling behaviors observed in fish, and artificial physics (physicomimetics) based on how particles interact in various states of matter. We adapt these techniques to gather information (rather than food, for example), and use them to perform area coverage tasks such as search, reconnaissance, and surveillance.
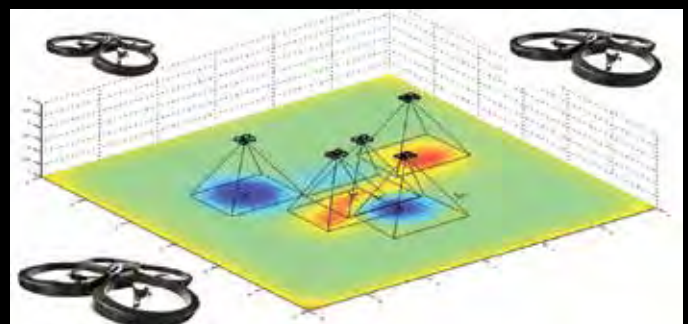
Adaptive Testing of Autonomous Systems
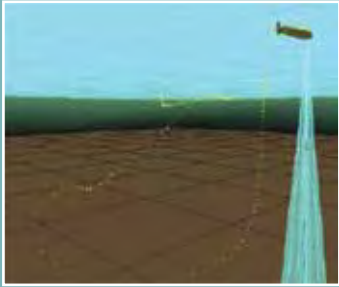
In this simulation, a UUV is performing its mission correctly.

This project is developing technologies for advanced test and evaluation of the control software for intelligent autonomous systems. Machine learning techniques in the form of evolutionary algorithms and reinforcement learning are applied to learn the minimal number of faults that cause minimal or failed behavior of an autonomous system that is under the control of autonomy software — the autonomy software is the system under test. The method uses high-fidelity simulations of the vehicle and the environment, and tests are performed in that simulation to test the robustness of the autonomous controller under various unanticipated conditions.

In this simulation, the vehicle controller has failed to deal with a limited number of faults introduced by the adaptive testing.

Characterization of Lithium-ion Batteries
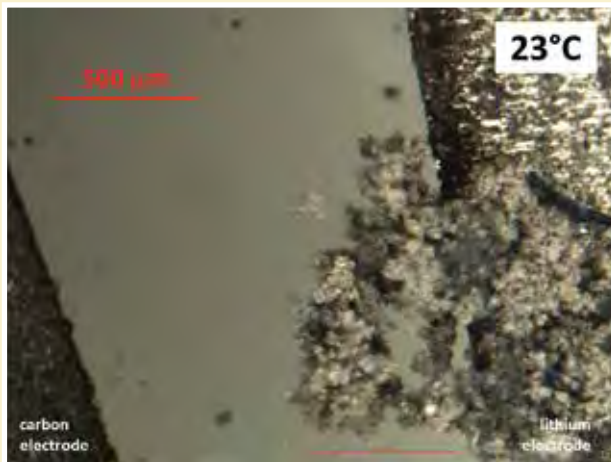
One suspect in the failure of lithium-ion batteries is the formation of metallic lithium dendrites that can puncture the cell's separator and form a short circuit between the cathode and anode. NRL research using in situ optical microscopy has identified temperature-dependent morphologies of metallic lithium dendrites: at 23 °C, spherical Li electrodeposits agglomerate to form a loosely packed structure, while at –5 °C, the Li extrudes into a continuous wire ball structure. We are examining the link between temperature, morphology, instability, and susceptibility to failure, with implications for improving lithium-ion battery safety.

Robotic Touch Sensing, Manipulation, and Fault Detection

The Robotic Touch Sensing project is developing an artificial sensate skin for robots, to extend the perceptual capabilities of robotic manipulators to include touch. The sensate skin uses an embedded array of piezoresistive sensors and an algorithm that analyzes the responses of the sensors affected by each environmental contact/impact, to detect and classify contacts (location and magnitude). The detection algorithm uses K-means clustering, rules for contact disambiguation, and 3-D trigonometric calculations.

For more research highlights, see www.nrl.navy.mil/lasr/highlights.

NAVY LAUNCHES UAV FROM
SUBMERGED SUBMARINE

By Daniel Parry, *NRL Public Affairs Office*

The U.S. Naval Research Laboratory (NRL) with funding from SwampWorks at the Office of Naval Research (ONR) and the Department of Defense Rapid Reaction Technology Office demonstrated the launch of an all-electric, fuel-cell-powered, unmanned aerial system (UAS) from a submerged submarine.

From concept to fleet demonstration, this idea took less than six years to produce results at significant cost savings when compared to traditional programs often taking decades to produce results.

"Developing disruptive technologies and quickly getting them into the hands of our sailors is what our SwampWorks program is all about," said Craig A. Hughes, Acting Director of Innovation at ONR. "This demonstration really underpins ONR's dedication and ability to address emerging fleet priorities."

The successful submerged launch of a remotely deployed UAS offers a pathway to providing mission-critical intelligence, surveillance, and reconnaissance (ISR) capabilities to the U.S. Navy's submarine force.

Operating under support of the Los Angeles class submarine USS *Providence* (SSN 719) and the Naval Undersea Warfare Center–Newport Division (NUWC-NPT), the NRL-developed XFC (eXperimental Fuel Cell) UAS was fired from the submarine's torpedo tube using a Sea Robin launch vehicle system. The Sea Robin launch system was designed to fit within an empty Tomahawk launch canister (TLC) used for launching Tomahawk cruise missiles already familiar to submarine sailors.

Once deployed from the TLC, the Sea Robin launch vehicle with integrated XFC rose to the ocean surface where it appeared as a spar buoy. Upon command of *Providence* Commanding Officer, the XFC then vertically launched from Sea Robin and flew a successful several hour mission demonstrating live video capabilities streamed back to *Providence*, surface support vessels, and Norfolk before landing at the Naval Sea Systems Command Atlantic Undersea Test and Evaluation Center (AUTEC), Andros, Bahamas.

"This six-year effort represents the best in collaboration of a Navy laboratory and industry to produce a technology that meets the needs of the special operations community," said Dr. Warren Schultz, program developer and manager, NRL. "The creativity and resourcefulness brought to this project by a unique team of scientists and engineers represents an unprecedented paradigm shift in UAV propulsion and launch systems."

The NRL Chemistry and Tactical Electronic Warfare Divisions team includes the design-builder of the Sea Robin, Oceaneering International Inc. (Hanover, MD); the fuel cell developer Protonex Technology Corp. (Southborough, MA); and NUWC-NPT's Autonomous and Defensive Systems Department for Temporary Alteration (TEMPALT) and test demonstration support.

XFC UAS launch in time-lapsed photography. Deployed from the submerged submarine USS *Providence*, the XFC vertically launched from a Sea Robin launch vehicle (bottom right). The folding wing UAS autonomously deploys its X-wing airfoil and after achieving a marginal altitude, assumes horizontal flight configuration. (Photo: NAVSEA-AUTEC)

The XFC is a fully autonomous, all-electric, fuel-cell-powered, folding wing UAS with an endurance of greater than six hours. The nonhybridized power plant supports the propulsion system and payload for a flight endurance that enables relatively low cost, low altitude, ISR missions. The XFC UAS uses an electrically assisted take-off system which lifts the plane vertically out of its container and therefore enables a very small footprint launch such as from a pickup truck or small surface vessel.

Captain Mark C. Bruington Relieves Captain Anthony J. Ferrari

Capt. Anthony Ferrari   Capt. Mark Bruington

Captain Mark C. Bruington, USN, assumed the duties as the Naval Research Laboratory's 38th Commanding Officer during a formal Change of Command ceremony in Washington, D.C. on Friday, August 1, 2014. Captain Bruington succeeds Captain Anthony J. Ferrari, USN, who retired following two years as Commanding Officer of NRL, and 28 years of Naval service.

As NRL's Commanding Officer, Capt. Bruington directs the activities of approximately 2500 scientists, engineers, and support personnel in their mission to conduct leading-edge research and provide new technological capabilities to the Navy and Marine Corps. Prior to his assumption of command of NRL, he was the Principal Director, Programs at the Defense Security Cooperation Agency where he led a team charged with Department of Defense humanitarian assistance, building partnership capacity and Foreign Military Training and Equipping U.S. partner nations.

Captain Anthony J. Ferrari Receives Legion of Merit

"For exceptionally meritorious conduct in the performance of outstanding service as Commanding Officer, Naval Research Laboratory from August 2012 to July 2014. Captain Ferrari significantly increased Untied States national security by fostering the Naval Research Laboratory's world-class research capabilities and delivery of critical advanced technologies to the Department of Defense and other national level organizations. His efforts enabled the Naval Research Laboratory to develop and transition critical science and technology programs needed to maintain overwhelming technological superiority in the dynamic global operational environment. Captain Ferrari forged the way ahead, improving business practices and methodically investing in a broad array of scientific and technological infrastructure projects such as the Marine Meteorology Center, which provides state-of-the-art research facilities for weather forecasting for the fleet. His innovative spirit, involved leadership, and ability to surge technological solutions to short-fused, mission-critical national requirements have saved lives and contributed to a plethora of operational successes. Captain Ferrari's superior performance of duties highlights the culmination of 28 years of honorable and dedicated service. By his dynamic direction, keen judgment, and loyal devotion to duty, Captain Ferrari reflected great credit upon himself and upheld the highest traditions of the United States Naval Services."

Chief of Naval Research Admiral Matthew L. Klunder presents the Legion of Merit to Captain Anthony J. Ferrari.

NRL and Aerospace Industry Host 10th Annual
CANSAT STUDENT CHALLENGE

The 2014 CanSat competition, celebrating its 10-year anniversary, required teams to develop a soda-can-size satellite-type system (CanSat) capable of harvesting energy from the environment and transmitting telemetry in real time to a station on the ground.

Created in 2004 by the American Astronautical Society (AAS) and American Institute of Aeronautics and Astronautics (AIAA), the Texas CanSat Competition is an undergraduate and graduate level design-build-launch event simulating the end-to-end life cycle of a complex engineering project.

Spanning a decade long commitment by the U.S Naval Research Laboratory (NRL) and other federal and commercial sponsors, the goal of CanSat is to foster student growth in multiple disciplines of science, technology, engineering, and mathematics (STEM). The CanSat competition has become an annual event providing a unique opportunity for university and college student teams to design, build, and launch a soda-can-size satellite-type system (CanSat) designed to meet specific mission goals selected each year by competition sponsors and co-sponsors.

This year's 10-year anniversary CanSat competition, co-sponsored by NRL in cooperation with NASA Goddard Space Flight Center, NASA Jet Propulsion Laboratory, AIAA, AAS,

Ball Aerospace Technologies, Praxis Inc., and Kratos Integral Systems International, required teams to develop a CanSat capable of harvesting energy from the environment and transmitting telemetry in real time to the team ground stations. The CanSat had to use aero-braking to slow its descent and protect a raw egg during the launch, deployment, descent, and landing. Parachutes or similar devices were not allowed.

Beginning last October and culminating in a final competition in June, teams from around the nation, as well as from South America, Europe, and Asia, entered to design and build a space-type system and then compete against each other at the end of two semesters to determine winners.

Preliminary design reviews were held in February and critical design reviews in April. Those teams able to compete attended the three-day launch event in June in Burkett, Texas. The first day was committed to safety checks and preflight briefings; on the second
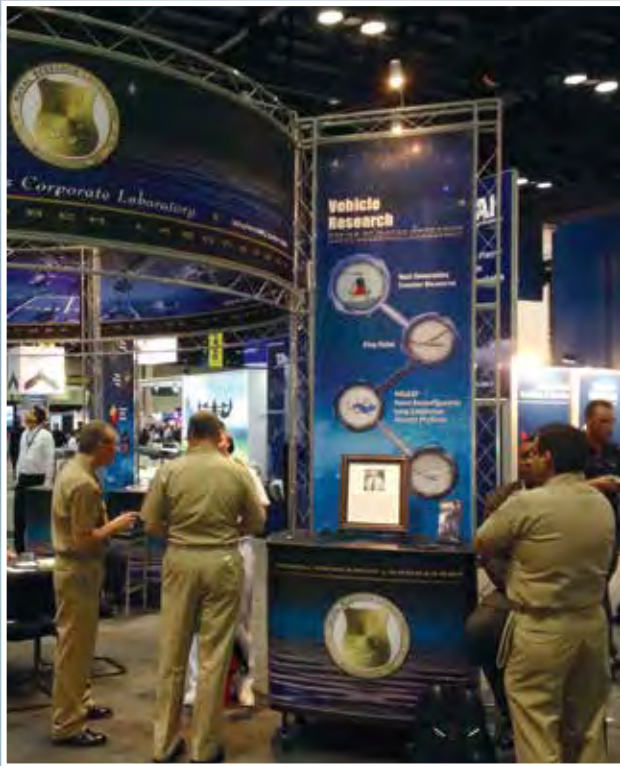
Since its start in 2004, the CanSat competition has become an annual event providing a unique opportunity for university and college student teams to design, build, and launch a soda-can-size satellite-type system designed to meet specific mission objectives. The goal of CanSat is to foster student growth in multiple disciplines of science, technology, engineering, and mathematics (STEM).

Provisions of the 2014 competition required deployed CanSats to use aero-braking to slow descent and to protect a raw egg payload during the launch, deployment, descent, and landing stages of the mission. Parachutes or similar devices were not allowed.

U.S. Naval Research Laboratory engineer and CanSat organizer Ivan Galysh was honored with the 2013 National Association of Rocketry (NAR) Howard Galloway Spacemodeling Service Award for his contributions over the last decade to educate and motivate students in the technical disciplines of aerospace engineering. As a mentor and organizer for student teams in NAR's Team America Rocketry Challenge, NASA's Student Launch Initiative, the Battle of the Rockets (of which he is a founder), and other programs, Galysh has spent hundreds of hours each year providing direct hands-on instruction and motivation to middle school, high school, and university students. In acknowledgement of these outstanding accomplishments, the NAR said, "there is no other individual in the National Association of Rocketry who is more involved across more programs in advancing our organizational goal of 'paying forward' to motivate and educate the next generation of U.S. aerospace professionals and rocketeers." Galysh has been in the NRL Space Applications Branch since 1987, where he first developed systems to test the performance of atomic frequency standards for GPS satellites, and has since worked on numerous programs developing space-based payloads. Most recently, these include a trio of experiments to demonstrate miniaturized satellite technologies for improved maritime security and measurement of space weather and the radiation environment.

day, launch competitions were held; and on day three, flight reviews were posted and final awards were announced.

Of the 54 original teams, 39 attended the launch competition, with first place won by Team Arisat from Istanbul Technical University, Turkey. Second place went to Team Wilkensat from Sri Ramaswamy Memorial (SRM) University, India; third place was Team Wind Chargers from University of Alabama Huntsville; fourth place, Team Tomahawk from Ryerson University, Canada; and fifth place was Tarleton Aerospace Club from Tarleton State University, Stephenville, Texas.

Annual CanSat Competition

Design – Build – Launch

Sharing Science
Starting Conversations

CONFERENCES

SOCIAL MEDIA

STEM FESTIVALS

New York City Tracks Firefighters to Scene with NRL Radio Tags and Automated Display

By Kyra Wiens, *NRL Public Affairs Office*

On 15 of its vehicles, Fire Department New York (FDNY) now can automatically see which firefighters are nearby from the onboard computer, and relay that information to the city's Operations Center. The system was invented by David DeRieux of the U.S. Naval Research Laboratory (NRL) Space Systems Development Department, along with Michael Manning of Manning RF, and in close partnership with FDNY.

Since the 9/11 terrorist attacks, New York City has been pursuing ways to better coordinate the 14,000 firefighters and emergency response it employs. (Prior to 9/11, the FDNY used a paper/carbon-copy ride list — Battalion Form 4 (BF4) — to account for who's present.)

NRL's system is based on an active radio frequency identifier (RFID) tag carried by each firefighter, similar to E-ZPass or how retail tracks inventory. "It's in a little sealed plastic — it looks like a little key fob, actually," says George Arthur, an NRL engineer who contributed to the project. "They're positioned over the left breast, inside the bunker coat in a little Kevlar pocket that's sewn in there. And it just sends out a little ping every five seconds: here I am, here I am, here I am."

A radio receiver on the vehicle picks up the pings and builds a table of identifiers. "It just listens and says, 'Okay, 1234, that's Jessica Smith,' so we know Jessica Smith is nearby," says DeRieux. "Periodically, a program that's running on their MDT [mobile data terminal], their onboard computer, quizzes this reader and says, 'Let me have everything.'"

The table of every firefighter on or near the vehicle is displayed on the MDT screen. "As soon as [the driver] turns the ignition on," says DeRieux, "this thing comes up. When they get on the scene, everyone takes off, they all disappear. Then eventually they come back for a roll call situation, and the captain can tell instantly everyone is within so many feet of the truck."

The MDT also sends this accounting to the FDNY Operations Center in Brooklyn, using a commercial modem. "They actually have a massive display," says DeRieux, "and on there this data gets projected. So they know what truck just showed up on scene, who was on the truck." To coordinate personnel during a city-wide disaster, this real-time information would be unimaginably valuable. "During 9/11 there were thousands of firefighters, it was a big problem," says DeRieux.

The data is also archived. "If there were a HAZMAT release," says Arthur, "they could go back and immediately see the firefighters that were on duty."

NRL received a 2014 Federal Laboratory Consortium Award for Excellence in Technology Transfer for this work. Technology transfer is very important," says Arthur. "Doing things here [at NRL] that are beneficial, not just to the warfighter, but also to the average citizen."
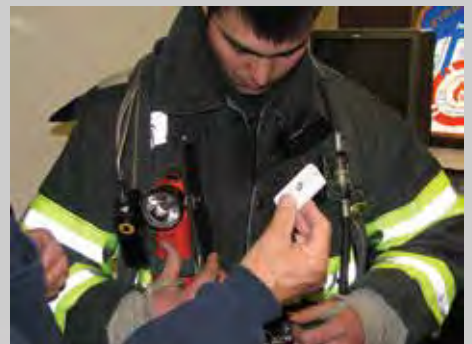
Dr. Jeremy Robinson Receives Presidential Early Career Award

"The work is a creative outlet, and that is the driver for me going to the lab."

Dr. Jeremy Robinson of the U.S. Naval Research Laboratory (NRL) is a recipient of the 2012 Presidential Early Career Award for Scientists and Engineers (PECASE).

Dr. Robinson, a materials research engineer at NRL, was recognized for his "outstanding research accomplishments in the development of graphene-based materials; dedication to community service; and mentoring work with students."

Robinson studies graphene and other carbon nanomaterials. He studies their electronic and mechanical properties and explores how the materials can be used in chemical sensors, in quantum information processing, and for nanoelectronic and radio frequency communication applications.

Robinson joined NRL as a National Research Council postdoctoral associate in 2007 after completing his Ph.D. at the University of California Berkeley; he transitioned to full-time staff in 2008. His

older brother, Dr. Josh Robinson, also did his postdoc here: "In fact, my brother sat at this desk," Robinson says with a laugh. "We are always in friendly competition. So this [Presidential award] is the latest feather in my cap."

In his research to explore the many possibilities of graphene-based materials, Robinson connects material synthesis, material properties, and applications: "Designing graphene with specific defects is an ideal way to engineer its properties and potentially improve its sensor response." He may introduce an atom of a different chemical species, like oxygen or fluorine, then test sensor capability, mechanical strength, or optical properties. And he studies the properties that emerge when layers of graphene are stacked. "We continue to be surprised about the range of interesting experiments and results," he says. Robinson has published more than 60 peer-reviewed journal articles and holds one patent.
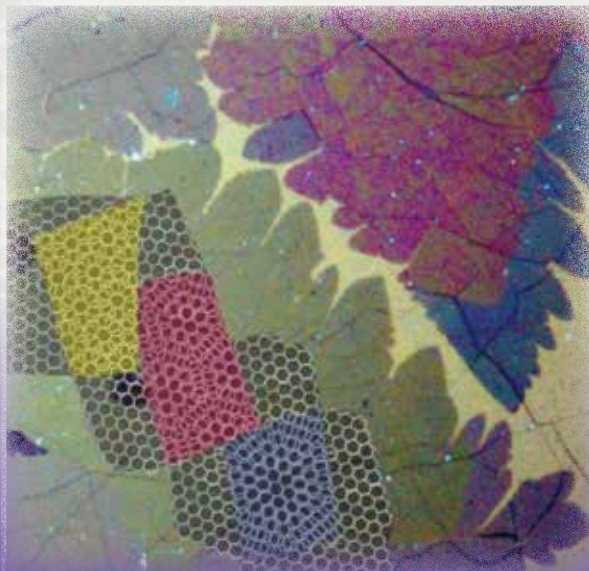
The White House announced the 102 PECASE recipients on December 23, 2013. "We are grateful for their commitment to generating the scientific and technical advancements that will ensure America's global leadership for many years to come," said President Obama.

One of Dr. Robinson's areas of research is bilayer graphene. This "stained-glass" appearance arises from the emergence of a narrow absorption band due to direct electronic coupling between the layers.

Richard J. Foch

20 March 1957 – 14 April 2014

Richard J. 'Rick' Foch was a lifelong airplane enthusiast. He built his first airplane model at the age of 7, published his first design in *American Aircraft Modeler* magazine at age 16, and soon graduated to radio-controlled models. In high school, he combined his academic and modeling skills to win a first place at the 1974 International Science and Engineering Fair. For his efforts, Rick was awarded a full tuition scholarship to the Florida Institute of Technology (FIT), a trip to attend the 1974 Nobel Prize Award Ceremony in Stockholm, Sweden, and several trips to tour government and military research laboratories. This experience cemented his desire to pursue aeronautical engineering as a career.

Upon graduation from FIT in 1979, Rick accepted a position at the Naval Research Laboratory, which was investigating the use of unmanned systems for electronic warfare missions. He earned an M.S. in aerospace engineering from the Universities of Notre Dame and Maryland in 1985. From 1980 through 1993, Rick was the chief test pilot for the NRL Vehicle Research Section's remotely piloted aircraft. He led the Vehicle Research Section from 1985 until 2005. During this period, he was responsible for the development of over 75 unmanned air vehicle projects, most of which were of his design. Their development and flight testing made significant advancements in aerodynamics, structures, propulsion, and autonomy. In February 2006, Mr. Foch was promoted to a Senior Professional (ST) position. As NRL's Senior Scientist for Expendable Vehicles, he applied his vision toward establishing effective paths for short-term and long-term Navy UAS technology development. A key research area was non-fossil-fuel propulsion and his most recent research focused on fuel cell propulsion for Navy UAVs.

Rick published over 75 research papers and journal articles on small expendable air vehicles and their technologies. In 1996, he received an NRL Special Act Award for flight testing the first biological agent detector to be successfully miniaturized and integrated into an unmanned aircraft. In 2002, he was awarded the Navy Distinguished Civilian Service Award in recognition of his career-long scientific and technical contributions to the Fleet.

In 2013, Rick completed a book detailing the achievements of the Naval Research Laboratory in unmanned aviation over the past thirty years: *Unmanned Aircraft Systems Innovation at the Naval Research Laboratory*, published by the American Institute of Aeronautics and Astronautics.

Rick Foch with the Dragon Warrior unmanned air vehicle.

When Rick was four years old, his father let him sit in the cockpit of a Cessna T-37.
"At that instant, I fell in love with anything and everything involving airplanes."

Dr. Glen Henshaw (left), NRL space roboticist, describes his research to George Zaidan, the host of the Pentagon Channel's 'Armed with Science' program that aired in March 2014. Henshaw and colleagues in NRL's Spacecraft Engineering Department are developing robotic technology that can help repair, reposition, or update satellites on-orbit. The video can be viewed at http://www.nrl.navy.mil/media/news-releases/2014/pentagon-channel-defense-laboratories-team-up-for-new-science-tv-show.

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