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SOFT COATINGS FOR ARMOR ENHANCEMENT

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MESSAGE FROM THE EDITOR

By Brian Benesch

Each issue of the *DSIAC Journal* has its own set of uniquenesses that makes it a featured product for the defense community. This winter issue is no exception. The twist in this journal is the inclusion of what we are dubbing Technology Spotlights. The Technology Spotlight articles are designed to succinctly review the need for and development of cutting-edge technologies for defense applications.

The Technology Spotlight articles are designed to succinctly review the need for and development of cutting-edge technologies for defense applications.

This issue includes three Technology Spotlights—one on dual-arm robotic systems, a second on a new case for the BLU-122 penetrator, and a third on grease for marine applications. The article "Two Arms Are Better Than One," written by RE2 CEO Jorgen Pedersen, showcases the benefits of a dual-arm robotic system for, in one application, investigating and defusing improvised explosive devices. In "A New Design for A Better Bunker Buster," Gregory Vartanov of Advanced Material Development Corporation describes the materials-based improvements to the BLU-122 bomb—specifically, to its case—which will allow for deeper penetration effects. Finally, the article "Grease is the Word" by Sarah Peckham of Texas Research Institute/Austin presents a survey of greases based on their ability to lubricate parts in a marine environment, keep the sailor safe, and reduce environmental effects.

Beyond the Technology Spotlights, the remaining four articles come from the Navy Research Laboratory (NRL), the Army Research Laboratory (ARL), industry, and the Navy's Program Executive Office (PEO) for Littoral Combat Ships (LCS).

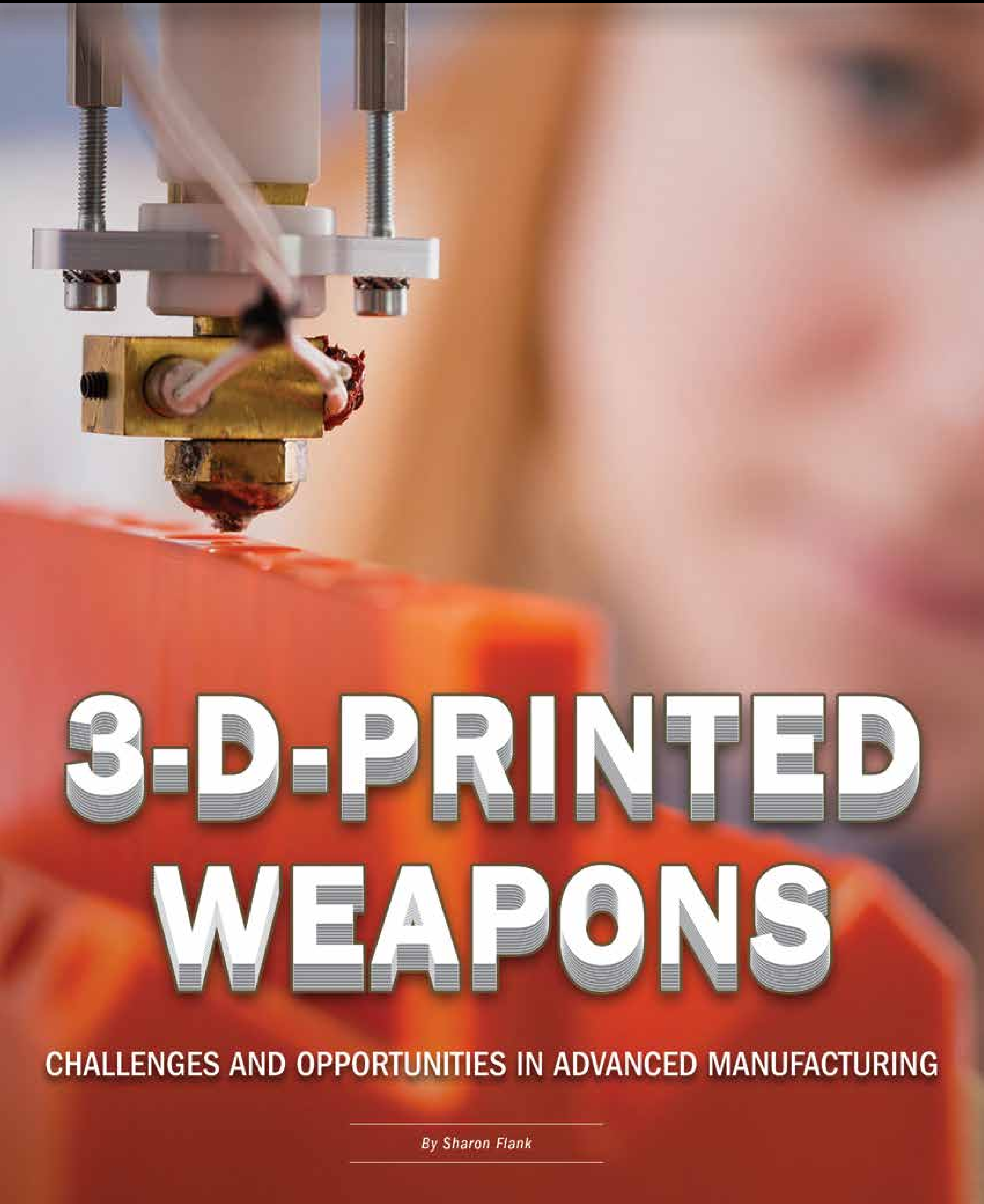
The feature article, written by NRL's Michael Roland, provides an overview of the latest in "Soft Coatings for Armor Enhancement." This research advances ballistic protection capabilities that also offer tactical advantages through lighter-weight armor. The work even shows promise of repairable, transparent, wearable armor!

Not to be outdone in the area of survivability, ARL has contributed the "Underbody Blast Methodology" article, which describes the Army's modeling methodology to simulate buried blast attacks against ground vehicles. Ultimately, the methodology is used to understand underbody blast phenomena and thus better protect the Warfighter.

InfraTrac's Sharon Flank writes from the perspective of enhancing and protecting U.S. weapon systems in her article "3-D-Printed Weapons: Challenges and Opportunities in Advanced Manufacturing." In this article, recent achievements in 3-D printing weapons are reviewed to highlight the value of the technology and importance of certain considerations, such as part qualification and authentication.

Finally, in "Expanding the Navy's Unmanned Systems Portfolio," Howard Berkoff of the Navy's PEO LCS gives a wide-angle overview of the Navy's ever-growing surface and underwater vehicles of the unmanned variety. This article provides a unique one-stop-shop for informing the reader of the latest in programmatics of the Navy's unmanned systems.

With these seven distinctive articles, including the new Technology Spotlights, I hope you enjoy all the features provided in this latest issue. ■



3-D-PRINTED WEAPONS

CHALLENGES AND OPPORTUNITIES IN ADVANCED MANUFACTURING

By Sharon Flank

INTRODUCTION

Three-dimensional (3-D) printing—or “additive manufacturing,” the preferred production-focused term for industrial-quality 3-D printing—is expected to revolutionize manufacturing processes as the technology moves from prototyping and into production. Moreover, this rapid technology development, combined with the ongoing decrease in cost and increase in popularity, has enabled a wide range of defense applications.

The 3-D-printing revolution brings with it two major advantages: (1) lightweighting, and (2) on-demand parts production for complex systems. For the Warfighter, 3-D lightweighting will impact weapons manufacturing directly. Highly publicized activity by hobbyists and leading-edge manufacturers portends a future that likely includes 3-D-printed guns and ammunition.

Likewise, 3-D printing promises many new opportunities for manufacturing spare parts for complex operational systems. If a part can be generated from materials as needed (and where needed) rather than be stockpiled for a need that may never arise, complex logistical tails can be greatly shortened or eliminated and field inventory can be reduced to as little as raw materials and design files. Better yet, a 3-D scanner could simplify the process of creating a design to fit a problem, even without a pre-existing design file.

The range of materials available for 3-D-printing applications is also expanding at a rapid pace. These materials now include high-performance polymers, flexible silicones, and heat-tolerant metals and ceramics, along with composites and combinations, such as printed circuit boards.

Not surprisingly, the significant advantages and opportunities in 3-D printing for military application also bring considerable safety and security challenges/risks (including the exploitation of these technologies by real and potential adversaries). Thus, the U.S. defense community must stay aware of, and engaged in, technological developments across the advanced manufacturing industry.

HYPE AND REALITY

Much attention has been devoted recently to the 3-D printing of weapons. In fact, it has been feasible to 3-D-print a gun for several years now. For example, Cody Wilson gained notoriety with the printing of the plastic Liberator in 2013 [1]. Wilson’s accomplishment was in some ways a stunt focused on the legal aspects of the effort as much as on its technical achievability.

The 3-D printing of AR-15 components was successfully demonstrated that same year by Michigan-based Sintercore, which later announced the availability of a 3-D-printed magazine extension for the Glock 43 [2]. Manufacturing efforts such as these continue on AR-15’s and other weapons, as well as a wide range of related personal accessories (such as clips, brackets, and carriers), by various hobbyists and others.

An arguably more significant achievement, at least from a technical standpoint, was the metal Reason gun created in 2014 by Solid Concepts. The Reason was a 3-D-printed 10-mm Auto 1911 pistol said to cost $11,000 [3, 4]. More recently, the Army succeeded in printing all the parts (except the springs and fasteners) of a grenade launcher named R.A.M.B.O. (which stands for Rapid Additively Manufactured Ballistics Ordnance) [5]. Billed as functional, accurate, and cost-effective, R.A.M.B.O. (shown in Figures 1 and 2) represents another significant step forward in the 3-D printing of weapons.

It must be remembered, of course, that real dangers to personnel safety can and do exist whenever a weapon (especially a plastic weapon) is manufactured and used. Not the least of these dangers are the violent physical and chemical reactions associated with the functioning of firearms. The high explosive pressures resulting from igniting propellant inside a gun barrel

Figure 1: The Army’s R.A.M.B.O. Grenade Launcher *(Credit: U.S. Army ARDEC, Source: http://asc.army.mil/web/news-alt-amj17-rambos-premiere/).*

can cause catastrophic failures to a weapon (and potentially lethal injury to a user) if the weapon is not manufactured with the proper material strengths, engineering tolerances, and quality controls.

PRIMARY ADVANTAGES OF 3-D PRINTING

As noted, one of the major advantages of 3-D printing is lightweighting. Additively manufactured parts can be made of lighter materials, and high-performance polymers can sometimes substitute for metal, especially when reinforced by carbon fiber or Kevlar. And even if traditional materials are used, the geometry of 3-D printing is seldom a solid block of material. Open weave areas, honeycomb designs, and even completely redesigned shapes can be optimized within the digital design files to create strong but much lighter parts.

Understandably, this lightweighting advantage is particularly attractive in flight and transportation because it lessens fuel use and leaves more room for cargo, whether in an aircraft, truck, or drone. For weapons, lightweighting can also enhance portability. And even if the actual weapon is not redesigned, 3-D printing can bring weight advantages to clips, brackets, carriers, and other accessories. In addition, drones and microdrones provide considerable opportunity, as every gram saved in drone weight can be used for payload.

The other clear advantage of 3-D printing is the ability to generate objects (including relatively complex objects) in small batches and close to where they are needed. This aspect not only addresses the need in the field to supply on-demand parts, but it has broader implications for the supply chain as well. In short, if one can create a part on demand, one does not need to maintain, supply, or protect a warehouse of parts in the field.

If one can create a part on demand, one does not need to maintain, supply, or protect a warehouse of parts in the field.

Figure 2: R.A.M.B.O.'s 3-D-Printed Parts (Minus the Receiver and Barrel) *(Credit: U.S. Army ARDEC, Source: http://asc.army.mil/web/news-alt-amj17-rambos-premiere/).*

3-D PRINTING AND THE SUPPLY CHAIN

The supply chain model of the future is expected to incorporate 3-D printing. The model relies on stockpiling material and then creating the needed part on demand. In 2014, NASA demonstrated an excellent example of applying this model in space. Astronauts on the International Space Station, who had a 3-D printer (modified to overcome the gravity-based layering model), needed a ratchet wrench to fix a particular problem. As the closest hardware store was, to say the least, not easily accessible, they requested software with the given dimensional measurements, got everything validated and approved, printed the wrench, and successfully fixed their problem [6].

If 3-D printing and the supply chain model can be successfully applied in space, the possibilities for what might be done on Earth are virtually endless. As for space, 3-D printing is part of the shelter concept for a possible Mars mission, including a plan to use a 3-D printer to potentially create objects, including buildings, using Mars soil. Likewise, in a military context, Special Forces or other forces deployed in remote areas around the world could have the ability to quickly create whatever equipment they need whenever and wherever they need it.

Furthermore, incorporating artificial intelligence into the process could provide even greater opportunities and applications for 3-D printing. With a 3-D scanner, it is possible to scan a problem part (e.g., a cracked bracket) as well as a baseline part (e.g., an intact bracket) for comparison. Intelligent software could then potentially "propose" both a geometry and a material fix (e.g., "Heat-resistant to 60 °C, light-resistant, slightly flexible, carbon fiber reinforcement advisable: Use material 96N.").

Special Forces or other forces deployed in remote areas around the world could have the ability to quickly create whatever equipment they need whenever and wherever they need it.

It should be noted here, however, that the "print-anywhere" model can be a little misleading. There are many printer versions that are optimized for many different materials and tasks. It is thus likely that many types of printers will be needed to replace our supply depots. The supply chain will also still include handoffs, because not every need will be fulfilled by a single printer one can monitor personally. Additionally, that supply chain, with its handoffs, will include all the usual vulnerabilities to fraud and sabotage, further complicated by the counterfeiters' ability to produce excellent copies, potentially with hidden flaws. Digital files and models must thus be protected via cybersecurity, coupled with an approach for cyber-physical security.

Likewise, as reverse engineering of weapons increasingly becomes a matter of 3-D scanning and replication, counterfeiters and adversaries will increasingly be able to make their own versions, thus magnifying the importance of validation. Thus, the easier it is for rogue players to insert fakes into the supply chain, the more important it is to enshrine authentication into the process.

AUTHENTICATION PROTECTIONS FOR 3-D PRINTING

Other types of authentication controls are appropriate in the context of weapons. It may be necessary to incorporate "do-not-copy" provisions into scanners and printers, limiting replication in the same way that color copiers in the United States thwart copying of currency. It may also make sense to incorporate authentication and tracking into 3-D-printed weapons and ammunition.

Current protection options in the 3-D printing arena fall into two general categories. First, cybersecurity protections manage the use and reuse of the digital file. Part of the protection scheme incorporates digital rights management, dealing with questions such as "Does a particular individual have the right to use this file, and if so, are there restrictions on how many times he/she can use it (and with which printers and materials)?" Other cybersecurity concerns include access to the printer's industrial controls, dealing with questions such as "Is the printer protected from sabotage to its cooling systems, laser safety, and print quality controls?"

Figure 3: Example of a COTS Pocket-Sized Spectrometer for Authentication *(Source: InfraTrac).*

The second area of protection addresses the printed object. Conventionally, objects are protected with some sort of covert marking (on the product or label), conveying authenticity. Such covert indicators, however, are often easy to spoof. For example, if a product conveys authenticity with a hologram, it is not that difficult for a counterfeiter/adversary to put a hologram on the fake product as well. In fact, the advent of 3-D scanning and replication can further exacerbate the problem. Whatever the mark on the product, a 3-D scanner can see it and make it appear, as a kind of hijacked mark of authenticity, on the copy.

For this reason, chemical tagging schemes should be preferred over visual marks. Options include quantum dots, which may eventually emerge as a solution but currently have scale-up and supply chain issues (not to mention toxicity concerns regarding cadmium and lead). DNA taggants have also been employed in the supply chain, but full verification requires sequencing (which is not yet field-friendly) and most 3-D printing processes involve temperatures that are too high for DNA to be usable.

Chemical fingerprinting with spectroscopic taggants, hidden in an invisible layer within the print, has been called the most promising technique for authentication protection [7]. This technique, which uses chemical taggants controlled by the print process, could be likened to one hiding a spot of peanut butter and jelly in the “sandwich” of the many 3-D print layers [8]. The chemical “fingerprint” can then be validated quickly and nondestructively with a commercial off-the-shelf (COTS) light-based hand-held spectrometer (such as the one shown in Figure 3).

CONCLUSION

Overall, emerging 3-D printing/additive manufacturing technologies are poised to transform standard manufacturing and supply chain practices, and weapons and the DoD community are certain to be part of this transformation. As mentioned, the advantages this transformation promises include lightweighting products and on-demand production capabilities. But with these advantages come challenges as well—including critical safety and security issues—that military planners and developers will have to address as they move forward and find new ideas and applications for this exciting emerging technology. ■

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BIOGRAPHY

SHARON FLANK is the founder and CEO of InfraTrac, a company specializing in the development of product protection solutions based on spectroscopy. Dr. Flank is a recognized expert in intellectual property protection for additive manufacturing and has worked with defense contractor SRA (now CSRA) to spin out its first technologies and create companies acquired by AOL (Navisoft), the Chicago Tribune (Picture Network International), Kodak (eMotion), and CA (Assentor). She has also authored numerous journal articles—including refereed publications on anticounterfeiting, artificial intelligence, and 3-D printing—and holds 10 patents. Dr. Flank earned an A.B. from Cornell University and a Ph.D. from Harvard University.

TWO ARMS ARE BETTER THAN ONE

BENEFITS OF A DUAL-ARM ROBOTIC SYSTEM

By Jorgen Pedersen

INTRODUCTION

Already one of the most dangerous jobs in the military, the role of explosive ordnance technician has become even riskier in recent years due to a marked increase in the use of improvised explosive devices (IEDs) in theater. The military has long relied on the use of unmanned vehicles (including ones with robotic arms) to alleviate some of these risks, but ongoing advances in dual-arm robotic technology are offering significant advantages over single-arm applications for the way military operators inspect, detect, and dispose of IED threats. In addition, military planners and developers continue to consider dual-arm technologies for other applications and missions that call for human-like dexterity and control.

THE EVOLUTION OF ROBOTIC ARMS

Historically, unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) have provided military personnel with basic reconnaissance and surveillance capabilities. In fact, as far back as the 19th century, Thomas Edison and Nikola Tesla were espousing the benefits of using robots on the battlefield via experiments with radio-controlled devices [1].

In the 1960s, UGVs began to be tested to help with basic navigation and exploration tasks on the battlefield [2]. These early units could motor through and over rough terrain, deliver payloads, and capture still images. As time progressed, robotic platform capabilities continued to grow to include a variety of sensing capabilities, including video, audio, and heat-sensing technologies. While these fundamental capabilities provided a certain degree of risk reduction, the completion of dangerous tasks, such as the actual dismantling and disposal of an IED, still required the dexterity of human hands.

The effectiveness of unmanned vehicles was further enhanced by the eventual incorporation and use of single robotic arms. With the addition of manipulator arms, mobile platforms now had the capability to interact with and manipulate their surroundings: they could pick up explosives or other hazards and even neutralize such objects via teleoperated control. Despite these capabilities and advantages in certain circumstances, however, single-arm robotic systems have remained limited in their dexterity, reach, and lifting capacity. For instance, if an explosive ordnance disposal (EOD) team encounters an IED inside a bag, a single-arm robot would need to use force to open the bag and explore its contents. This action could damage or destroy the evidence and/or endanger lives.

Single-arm robotic systems have remained limited in their dexterity, reach, and lifting capacity.

Accordingly, dual-arm robots can greatly improve a mission's effectiveness by providing users with more human-like control over their environments. The direct benefit of such technology to military personnel is significantly increased performance and capability over currently fielded manipulators for both teleoperated and semi-autonomous use on mobile robot platforms.

PRECISION PLACEMENT

With dual-arm robotic systems, the dexterous manipulation and precision placement of objects are possible, as the robot essentially serves as an extension of the human controlling it. Should the dual-arm robot encounter an IED inside of a locked container, for example, the robot would be able to use both end effectors to open the lock and gently remove its contents without damaging any of the items, making accidental detonation less likely.

A dual-arm robotic manipulation system provides the capability to stabilize an object with one arm while allowing the other arm to manipulate the object. According to Hau Do, Robotics Team Lead, EOD Technology Division, at the U.S. Army's Armament Research, Development and Engineering Center at Picatinny Arsenal, NJ, this capability would help with tasks that are particularly challenging and time-consuming for one-arm systems, such as unscrewing bottle caps, opening packages, unzipping backpacks, and pulling items apart.

Additionally, technicians conducting EOD missions typically wear blast suits that weigh nearly 100 lbs. These suits are difficult to move in and may even induce heat stress. Thus, a dual-arm robotic system that can mimic the movements of a robot operator can reduce these concerns by allowing Warfighters to execute dangerous missions and neutralize threats from a safe distance, while preserving the evidence.

The Army has begun testing early prototypes of these dual-arm manipulators in Limited Objective Experiments to better inform upcoming Army acquisition programs that look to adopt human-like capability.

IMITATIVE CONTROL

Note that dual-arm robots are ultimately only as useful as their control devices. As robotic systems grow more complex, so does the need for a controller that can keep pace with ever-evolving technology. Traditionally, manipulator arms are controlled using modified versions of today's most popular gaming-system controllers, which are relatively limited in their use [3]. Recognizing this limitation, RE2 Robotics researched a new control device, called the Imitative Controller, which allows users to move a scaled model of the robot's manipulators.

Traditional methods that control each joint of a manipulator independently, such as dial and switch controllers or gaming controllers, are not practical for effectively and efficiently controlling highly dexterous manipulators. Furthermore, once a second arm is added, traditional control methods become obsolete.

Essentially a high-tech "puppet master," Imitative Controller technology provides highly intuitive command of dual-arm manipulation systems. The joints contain encoders that determine the position and orientation of the device [3]. This technology, which features one-to-one-mapping and optionally haptic feedback, has been shown to be the most useful feedback type when manipulating objects because it provides the user with immediate sensory feedback and physical confirmation of the robot's specific positions and orientations [3]. In addition, the controller gives users specific control over all of the robot's joints, and the curved-handle design reduces cognitive and physical fatigue.

And when it comes to controlling a two-arm system, the value of intuitiveness cannot be underestimated. Intuitiveness is measured in two ways: (1) training time, and (2) time to proficiency. Numerous demonstrations and training exercises have shown that an operator of the Imitative Controller can become proficient at controlling a highly dexterous two-arm system with as little as 1 minute of training. Likewise, time to proficiency is typically achieved within 1 hour.

MOVING FORWARD

The military's ultimate goal for this technology is to improve the manipulation capabilities of existing EOD robots. A proponent of the Army's Interoperability Profiles (IOP), RE2 Robotics has integrated its dual-arm robotic system onto a variety of third-party platforms, proving interoperability and extending the usefulness of legacy systems. Interoperability among platforms is essential during active engagements, as a system's ability to be rapidly configured through hot-swappable payloads can reduce the time it takes to perform missions.

Dual-arm robots can also be used for various non-EOD defense mission areas, such as combat engineering and infantry. This technology can significantly enhance performance and capability over currently fielded manipulators for both teleoperated and semi-autonomous use on mobile robot platforms. These manipulation improvements directly correlate to a reduction in time-on-target and overall mission time, resulting in increased safety for all mission personnel.

Dual-arm robotic technology also adds flexibility and maneuverability to industrial settings. For instance, companies such as Kawasaki and ABB Robotics have designed dual-arm collaborative robots that assist with the fine assembly of small parts—applications that would be virtually impossible to conduct with a single-arm robot. Moreover, there is potential for dual-arm robotic systems to be used in commercial industries that require remote operation for dangerous tasks, such as hazardous materials handling or offshore and surface oil and gas inspection.

In conclusion, ongoing innovation and advancements in manipulation technologies and intuitive control are expected to help meet the ever-changing demands of the military, enabling users to successfully perform a variety of dangerous missions from safe distances. And any mission—whether military or not—that requires human-like dexterity and control is a potential recipient for the significant benefits that dual-arm robotic technologies increasingly offer. ■

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A NEW DESIGN FOR A BETTER

BUNKER BUSTER

By Gregory Vartanov

TECHNOLOGY SPOTLIGHT

INTRODUCTION

The 5,000-lb class BLU-113 "Bunker Buster" bomb was designed to hit multilayered, hardened underground targets during Operation Desert Storm. During testing, the weapon was shown to penetrate more than 100 ft of earth and 20 ft of solid concrete. Recognizing the need to penetrate not only concrete but also rock, however, the Air Force in 2003 directed the development of the BLU-122 to enable greater hard-target penetration. Unfortunately, while the BLU-122 incorporates more energetic explosive fill, higher-strength case material, and a modified nose shape, it possesses only 18–20 ft of penetrability in 5,000-psi-strength reinforced concrete.

This article briefly highlights a cost-effective new case design for the BLU-122 that incorporates a new high-strength steel (or M-steel) and demonstrates a >50% projected increase in penetrability in 5,000-psi-strength reinforced concrete compared to the standard case, which uses the well-known Eglin steel (or ES-1) [1].

MATERIAL AND COST COMPARISON

Table 1 provides a comparison of quasi-static tensile test results at room temperature, as well as of Charpy v-notch (CVN) test results at room temperature and at -40 °F, for the air-melted quenched and tempered M-steel and ES-1 [2]. As shown, M-steel is stronger than ES-1 (as evidenced by the yield strength [YS] and ultimate tensile strength [UTS] values) while having the same level of ductility and toughness (as evidenced by the elongation [El], reduction area [RA], and CVN values) [3]. In addition, M-steel has a reduction in raw material cost of 50% or more compared to the ES-1, while the cost of manufacturing, including melting, forging, machining, and heat treatment of the two cases is similar. This steel also possesses better formability at hot forging and better machinability at rough machining of cases.

PENETRATION PARAMETERS AND CALCULATIONS

One reason a bomb's material is so important is that the nose of the penetrator plays a crucial role in its strength and durability. If a penetrator material does not have enough strength, large deformation of the nose and wall can occur. As a result, the nose can be flattened and the wall can be warped. On the other hand, if a material (even a high-strength material) does not have enough impact toughness, a fracture of the nose and wall can occur. Both scenarios can lead to a reduction of penetration distance and a failure to meet the strict requirements for the penetrators.

The main parameters that affect penetration distance are:

- Strength and toughness of the case material
- Shape and length of the nose
- Length of the penetrator
- Thickness of the wall
- Diameter of the case

The penetration distance of the penetrator for the proposed new case design was calculated using equation 3.2 of Young's "Penetration Equations" for soil, rock, and concrete targets [4]. In addition, the penetrability of the conic nose and tangent ogive nose shapes (N-factor) was calculated using equations 3.7 and 3.9, and the penetrability of target (S-factor) was calculated using equation 4.2 of the same source.

Table 2 shows a comparison of penetrability of a new designed case (Design1) with M-steel and the standard BLU-122 with ES-1. Note the cases have the same material density, penetrator weight, explosive material weight, case diameter, wall thickness, and impact velocity. This velocity corresponds to dropping the projectile from a height of 41,500 ft with negligible air drag.

Table 1: Comparison of Tensile and CVN Test Results for M-Steel and ES-1 *(Source: Advanced Materials Development Corporation).*

	Rockwell Hardness (HRC)	Yield Strength (YS) (ksi)	Ultimate Tensile Strength (UTS) (ksi)	Elongation (El) (%)	Reduction in Area (RA) (%)	Charpy V-Notch (CVN) (ft-lbs)	
M-Steel	52 – 53	220 – 230[a]	280 – 285[a]	12 – 14	44 – 48	26–32 @ room temp.	14 – 16 @-40 °F
ES-1	48 – 49	200 – 210[a]	250 – 260[a]	12 – 14	44 – 48	26–32 @ room temp.	11.5 – 15.5 @-40 °F

[a] *M-steel and ES-1 exhibit a ~10% increase in YS and UTS at a strain rate of ~200 1/s.*

Table 2: Penetrability Comparison of Design1 and Standard Cases *(Source: Advanced Materials Development Corporation).*

Parameter	Case	
	Design1	Standard
Material of case	M-steel	ES-1
ρ, density of material (lb/in^3)	0.285	0.285
W, weight of penetrator (lb)	4,450	4,450
W_{exp}, weight of explosive material (lb)	780	780
d, diameter of case (in)	15.3	15.3
Δ, wall thickness (in)	1.75	1.75
V, impact velocity (ft/s)	1,650	1,650
D, penetration distance (ft)	27.5	18
Increment penetrability (%)	53	–

The calculation of the S-factor for concrete assumes that a target is 5,000-psi-strength reinforced concrete with the following properties: volumetric % rebar, P = 2; cure time, tc = 1; thickness of the target, in penetrator diameters, Tc = 6; unconfined compressive strength, fc = 5,000 psi; target width, in penetrator diameter, WID > 20, and Ke = 1. In addition, calculation of the N-factors for both cases assumes that both cases have modified nose shapes.

As shown by the calculated penetration distances in Table 2, the penetration of the BLU-122 with the standard case in 5,000-psi strength reinforced concrete is ~18 ft, which closely approximates the actual test data [5]. The new case with the M-steel has a projected penetration of ~27 ft, which is an increase of more than 50%.

SUMMARY

With a >50% increased penetrability in reinforced concrete, a 50% or more reduction in raw material cost, and a comparable manufacturing cost, the new M-steel bomb design offers a promising enhancement to the standard ES-1 BLU-122 design. This design change allows for the penetration of targets currently unreachable by the BLU-122 and may prove to be crucial in continued defense efforts. ■

With a >50% increased penetrability in reinforced concrete, a 50% or more reduction in raw material cost, and a comparable manufacturing cost, the new M-steel bomb design offers a promising enhancement to the standard ES-1 BLU-122 design.

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BIOGRAPHY

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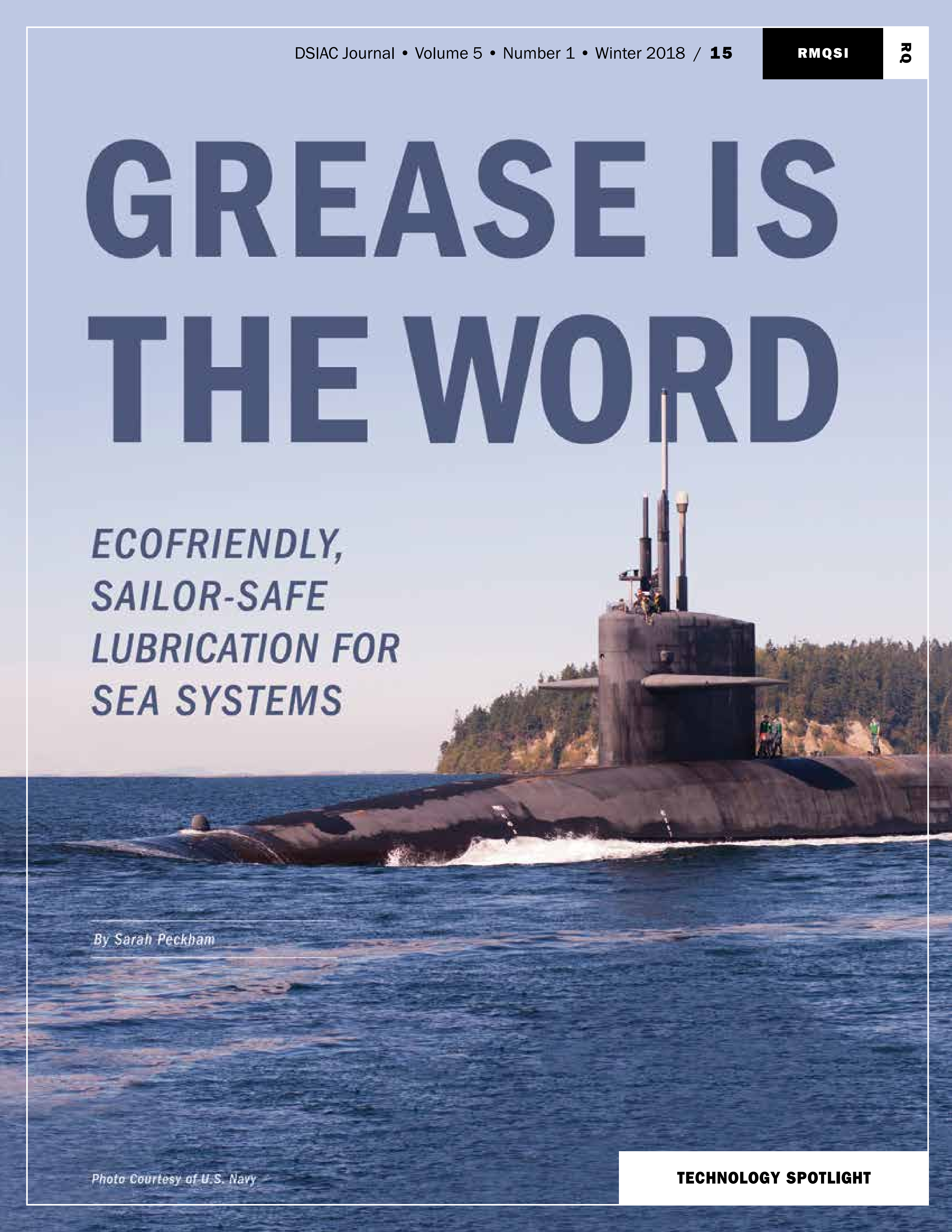

GREASE IS THE WORD

ECOFRIENDLY, SAILOR-SAFE LUBRICATION FOR SEA SYSTEMS

By Sarah Peckham

Photo Courtesy of U.S. Navy

TECHNOLOGY SPOTLIGHT

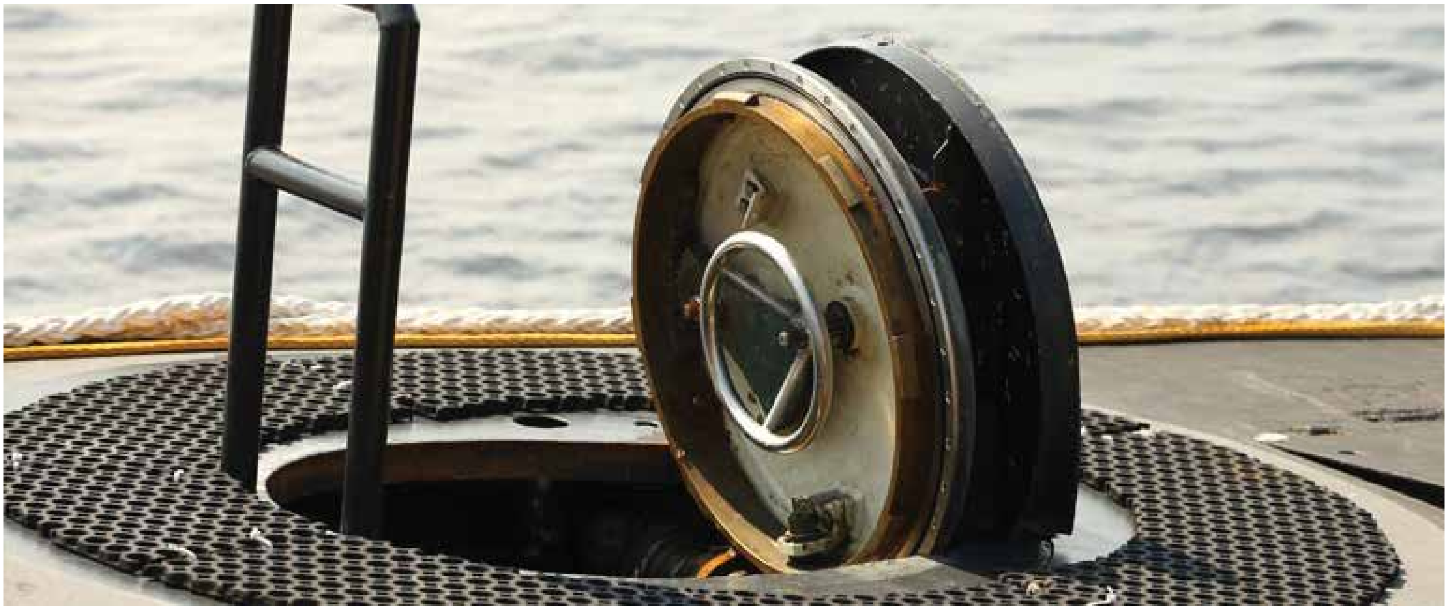

Figure 1: An Actuated Part Subjected to Extreme Seawater Environments, Requiring High-Performance Lubricants That Are Also Sailor-Safe *(Source: © mrivserg-stock.adobe.com).*

INTRODUCTION

Seawater is an extremely persistent, surprisingly corrosive force that causes a multitude of complex problems when it comes to use and maintenance of maritime vessels. Any equipment that is exposed to seawater on a regular basis is especially vulnerable and must be rigorously maintained if it is to function reliably. At the same time, any lubricants that come into contact with seawater need to be specially formulated to minimize their environmental impact as well as to avoid exposing sailors to hazardous volatile organic compounds (VOCs). This article highlights several environmentally friendly and sailor-safe grease solutions for potential use on submarines and other military (and nonmilitary) sea systems.

THE CHALLENGE TO KEEP MOVING PARTS MOVING

Keeping all of the moving parts of seafaring vessels adequately lubricated is an especially complex problem, particularly when the vessel is a submarine. Properly greasing actuated parts (such as the hatch shown in Figure 1) can greatly lengthen service life and ensure equipment reliability, but finding an environmentally friendly grease that is reliable when submerged in salt water, does not off-gas (i.e., emit harmful fumes), and is not prohibitively expensive is a difficult task.

Aquatic ecosystems are delicate and especially susceptible to pollutants, but ships of all kinds require lubricant on a variety of submerged parts to function properly. The Environmental Protection Agency (EPA) issues any vessel over 79 ft long a Vessel General Permit (VGP) to regulate the amount of pollution produced by ships. These permits allow incidental discharge of wastewater and lubricants through the course of normal operation, while imposing limits on this discharge and having specific standards that must be met for any lubricant that comes in contact with the water. To qualify for a VGP, commercial vessels must use

Keeping all of the moving parts of seafaring vessels adequately lubricated is an especially complex problem, particularly when the vessel is a submarine.

Environmentally Acceptable Lubricants (EAL). According to the EPA website, EALs are biodegradable, minimally toxic, and nonbioaccumulative (i.e., fish and other ocean organisms will not absorb pollutants from the lubricant at a faster rate than they can excrete them). Accordingly, many of the most common types of lubricants, such as petroleum-based oils and mineral oil, are excluded under these regulations.

HYDROCARBON, FLUOROCARBON, AND HYBRID GREASES

Hydrocarbon-based greases such as Termalene are frequently used by the U.S. Navy on submarines. These greases are fairly inexpensive, are hydrophobic (i.e., they are resistant to "washout"—the likelihood or potential for being washed away by seawater), have a long service life, and have minimal environmental impact. They do, however, have some drawbacks. Hydrocarbon greases are essentially soaps. They are generally made of fats that are "saponified" by having an alkoxide-salt-like lithium isopropoxide added to them. This process produces a thickened surfactant, the grease, and an alcohol, such as isopropanol. The isopropanol remains trapped in the grease, and off-gasses over time.

On some parts of the submarine that are completely external, the off-gassing is not a problem. However, the off-gassing does pose an issue on parts that are exposed to the interior of the submarine, such as hatches. During diving operations, the submarine is a sealed environment, and the isopropanol gas has nowhere to escape. Thus, the gas could accumulate and become harmful to the sailors inside.

Table 1: Comparison of Hydrocarbon-Based, Fluorocarbon-Based, and Hybrid Greases *(Source: Texas Research Institute Austin).*

Grease Type	Characteristic			
	Ecofriendly	Washout-Resistant	Sailor-Safe	Inexpensive
Hydrocarbon-Based	✓	✓		✓
Fluorocarbon-Based	✓		✓	
Hybrid	✓	✓	✓	

To mitigate the off-gassing problem, the Navy uses fluorocarbon-based greases, such as Krytox 240AC, on areas that are exposed to the interior of the submarine. Fluorocarbon-based greases use perfluoropolyether oil combined with a solid particle thickener, such as polytetrafluoroethylene (PTFE) powder, rather than conventional soap thickeners. By avoiding the saponification process, no volatile substances that could later off-gas and endanger sailors are produced.

> Off-gassing poses an issue on parts that are exposed to the interior of the submarine, such as hatches.

Fluorocarbon-based greases also have superior lubricating qualities to their hydrocarbon-based counterparts. Unfortunately, this superiority comes at a price. Fluorocarbon greases are polar, making them more soluble than hydrocarbon greases and thus far more susceptible to seawater washout.

Therefore, the comparatively high price of fluorocarbon greases themselves is exacerbated by the need to constantly reapply them to maintain any sort of efficacy, the accompanying labor cost, and the loss of service as the submarines are frequently taken out of commission to be regreased.

Another option currently on the market is hydrocarbon-fluorocarbon hybrid grease. TRI marine grease (NSN #9150-01-651-7256 07), which is an example of such a hybrid, is thickened with solid particles such as fluorocarbon greases, thus eliminating the isopropanol off-gassing danger. This combined molecular structure makes this grease hydrophobic enough to be resistant to seawater washout. Hybrid greases are a relative newcomer to the market, however. They are also more expensive than traditional grease options (albeit less expensive than the currently used fluorocarbon greases). That said, the higher cost of hybrid greases is offset by the increased service life and reduction in required maintenance time for regreasing. In addition, the cost of hybrid greases is dropping significantly, with newer versions now half the cost of some of the older products.

Table 1 provides a basic comparison of the three previously mentioned grease types, in terms of their environmental friendliness, washout resistance, personnel safety, and cost.

Figure 2: Navy SEAL in a Dry Deck Shelter on the Back of a Los Angeles-Class Submarine. Lubrication of Actuated Parts in the Shelter Is Critical to Personnel Safety *(Source: U.S. Navy Photo, Chief Photographer's Mate Andrew Mckaskle).*

CONCLUSION

With current technology, there is no perfect solution to the seawater-lubricant interface problem. From an environmental standpoint, hydrophobic greases that minimize grease contamination are certainly preferable, but there are many other angles to consider when selecting the right marine grease. The safety of personnel (such as those shown in Figure 2) is of paramount concern, with overall cost (both purchase and labor costs), the ability to lubricate, the ability to protect parts from salt water, and the ability to protect the environment being other important considerations. As technology advances, the safest options will become more affordable in initial purchase cost as well in the ability to substantially reduce life-cycle costs. ■

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BIOGRAPHY

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SOFT COATINGS FOR ARMOR ENHANCEMENT

BY C. MICHAEL ROLAND

INTRODUCTION

Conflict dates to the beginning of mankind, and along with it has come the need for protective systems. Archeological records show that, from the start, humans have been trying to enhance armor for personnel, structures, and vehicles, with two seemingly opposing goals—better protection, while still being as light and unrestrictive as possible. Traditionally, better armor has often come via thicker, heavier designs and materials. But armor can become so heavy to be practically unusable. (For example, David, in his biblical battle with Goliath, eschewed the protection of heavier armor due to weight and mobility concerns.) In addition, armor materials and enhancements must be accessible and affordable. Thus, modern-day armor developers are constantly challenged to address often-competing demands of performance, cost, weight, and space.

This article briefly summarizes work over the past decade at the Naval Research Laboratory to incorporate soft polymers in military armor and systems for civilian infrastructure protection. Because polymers are an order of magnitude less dense than steel, they are an attractive route to lighter armor. Of course, performance must also be maintained, which (as described herein) is possible by exploiting a mechanism unique to certain elastomers. In addition, cost considerations have restricted the component selection to commercially available "off-the-shelf" materials, which also expedites technical readiness.

BACKGROUND

The genesis for these efforts was a program started two decades ago by the U.S. Air Force to suppress fragmentation from buildings and similar structures when bombed. Although the foundation of a building is the primary source of its strength, fragmentation (concrete and wood fragments propelled by the blast) is the second leading cause of injury when a structure is bombed. Thus, the Air Force studied how to suppress this fragmentation by applying a rubbery polymer to the walls and foundation. The coating adheres to the structure, remains intact during an explosion, and thereby suppresses flying debris. In addition to reducing fragmentation, the coating was also found (unexpectedly) to attenuate the shock wave, requiring a blast to be closer to the building to effect damage.

The material selected by the Air Force for this application was a polyurea elastomer. Polyurea coatings have been used commercially since the early 1990s, with applications including concrete coatings; repair of roofs and parking decks; and liners for storage tanks, freight ships, and truck beds. Some prominent uses of polyurea include the Boston Tunnel Project; the Incheon International airport; and the San Mateo, CA, bridge.

Subsequently, the Navy undertook a program to explore the use of polyurea coatings to protect its High-Mobility Multipurpose Wheeled Vehicles (HMMWVs) and other light vehicles from gunfire and fragmenting explosives. Although it is counterintuitive that a soft elastomer would significantly affect projectile penetration of steel, the Navy was inspired by the work of the Air Force, and polyurea coatings were sprayed onto the outer surface of armor plates attached to the vehicle's exterior. This technology, known as "Dragon Shield," was used to up-armor light vehicles during Operation Iraqi Freedom.

ELASTOMERIC COATINGS

A fundamental study of elastomer coatings for armor, funded by the Defense Advanced Research Projects Agency (DARPA), was initiated at the Naval Research Laboratory (NRL) in 2004. Much of the work was performed in collaboration with the developer of Dragon Shield, Dr. Raymond Gamache, then at the Naval Surface Warfare Center – Dahlgren. To understand the origin of the ballistic and shock wave mitigation, researchers tested various soft, organic polymers as coatings on the strike face of rolled homogeneous armor (RHA) or high-hard steel (HHS) substrates. The emphasis was the connection between coating performance and either the glass transition temperature of the polymer (which is a measure of the rapidity of the polymer chain dynamics) or conventional compound properties, such as hardness and strength.

The Navy carried out both blast and ballistic tests, and found that only a particular type of polymer worked well, which limited the options to a few of the hundreds of available elastomers. The key requirement was that the elastomer have segmental dynamics (the rate at which small sections of the polymer chains move) occurring in the high kilohertz to megahertz range of frequencies. This range corresponds to the impact frequency for ballistics (estimated as the projectile velocity divided by the coating thickness), so that a resonance exists between the rate at which the armor is perturbed and the rate of motion of the molecules composing the polymer coating [1].

This resonance condition, which can be referred to as an impact-induced transition of the rubbery polymer to a glassy state, increases the hardness of the coating by three orders of magnitude and converts kinetic energy of the projectile into thermal energy (heat). The change in properties is transient; after the perturbation, the coating returns to a soft elastomeric state. The same effect is exploited generally for energy dissipation, with examples including the reduction of wet-skidding of automobile tires, the attenuation of sonar by submarine acoustic tiles, and the suppression of turbulent blood flow around arterial plaque [2].

> Because polymers are an order of magnitude less dense than steel, they are an attractive route to lighter armor.

Because ballistic impacts and blast waves are extremely different in amplitude and frequency, an elastomer functioning well to defeat one threat would not necessarily be effective against another. However, the dispersion (range of frequencies of the polymer segmental dynamics) is extremely broad for the elastomers used for these applications. Thus, while the polymer is chosen so that its dispersion maximum roughly coincides with ballistic frequencies, there is still substantial energy absorption at lower frequencies corresponding to blast waves.

The breadth of the dispersion also imparts an insensitivity to temperature, at least over the range of service temperatures. At extremely high temperatures (>60 °C), the segmental dynamics are too fast, and the resonance condition is lost. At low temperatures (below the glass transition temperature of the coating, which is approximately -50 °C), the polymer is already a glass, and thus the large energy absorption associated with transition of the rubber is absent.

The armor designs typically consist of a surface layer of polymer (a couple of millimeters thick) over a hard substrate; the hardness of the substrate enhances the energy conversion of the coating [3].

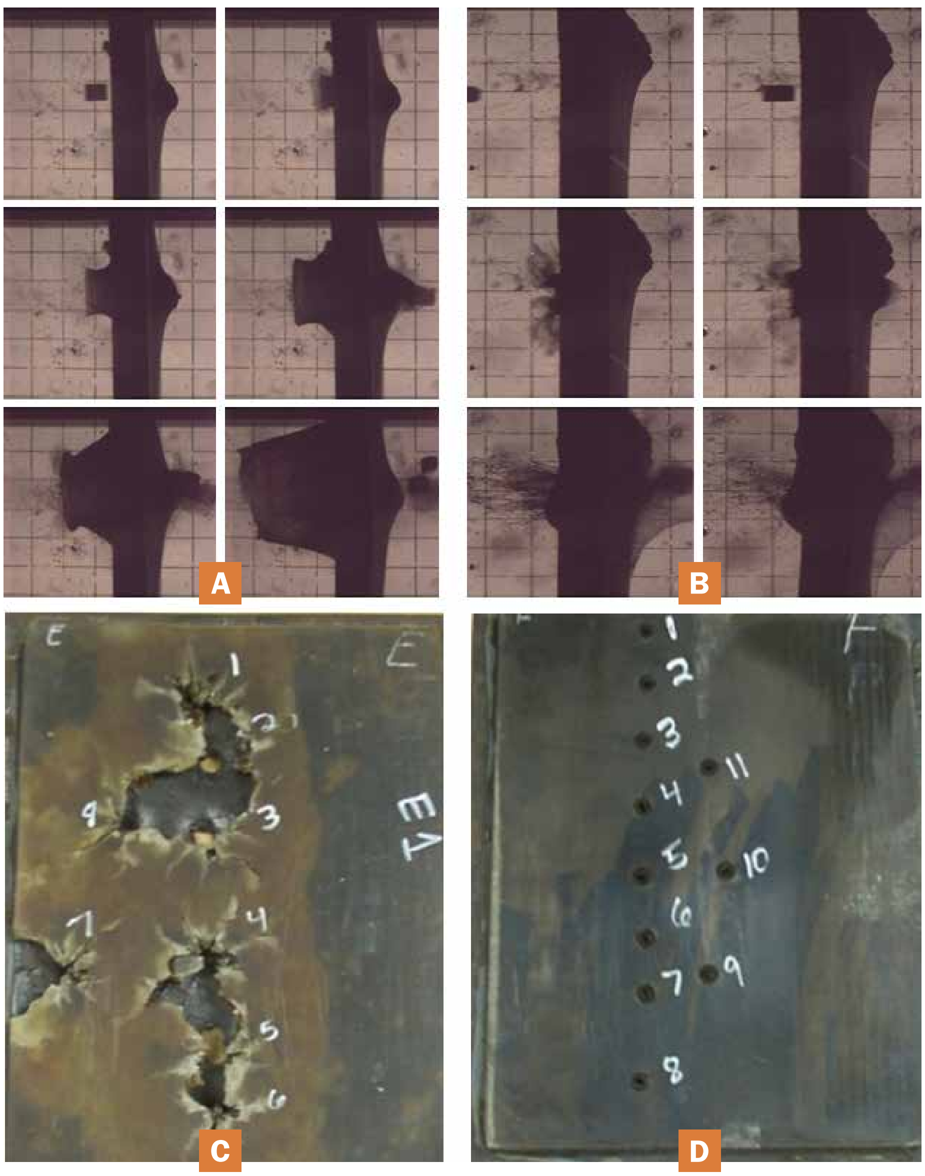

Figure 1: Elastomer-Coated Steel Substrate Impacted by a .50-cal. FSP: Conventional Rubber Stretching and Tearing (Left, i.e., images A and C); Resonating Rubber Coating Shattering Into Small Pieces on Impact (Right, i.e., images B and D); Post-Impact View of Coatings (Lower Left and Right, i.e., images C and D) *(Source: NRL).*

When exposed to ballistic impact, the coatings give rise to a unique mode of failure and a limited damage zone (Figure 1). The latter makes armor designs incorporating the coatings inherently capable of stopping multiple hits. And since the polymers are nine times less dense than steel, armor can be significantly lighter while maintaining ballistic protection (Figure 2).

ENHANCEMENT OF BILAYER DESIGN

The simple arrangement of a polymer coating over a hard substrate works well. However, protection from higher-severity threats can benefit from certain modifications. For example, if the projectile mass and/or velocity are extremely high (e.g., the STANAG 4496 Fragment Impact Test), equivalent ballistic performance can be achieved with lower areal densities by replacing the homogeneous coating with multiple layers of rubber on thin metal sheets [4]. This laminate construction can be used in a multiple-ply design in combination with more than one coating/steel layer.

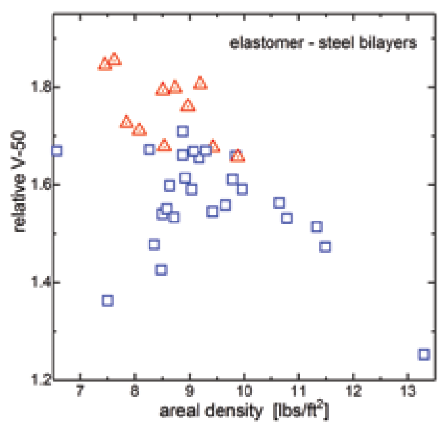

Figure 2: Projectile Velocity (.50-cal. FSP) for Which There Is a 50% Probability of Complete Target Penetration (Normalized by the Values for Conventional Steel Armor) vs. Mass Per Unit Area of the Armor: Elastomeric Polymer Coating on HHS (Squares) and Ultra-HHS (Circles) *(Source: NRL).*

The elastomer coating functions by being rapidly compressed, but this mechanism is effective primarily against blunt projectiles (e.g., fragments and ball ammunition). Projectiles having sharp ogives (e.g., armor-piercing [AP] bullets) cut the coating, reducing its ability to absorb energy. Thus, for defeat of such projectiles, it is necessary to rotate or blunt the tip. This rotation/blunting can be accomplished by incorporating ceramic spheres within the coating. The spheres rotate the incoming projectile, which is simultaneously eroded by the ceramic [5, 6].

The usual limitation in the use of ceramics is their weakness in tension. This weakness causes the tensile wave reflecting from the back surface of the armor to shatter the ceramic, requiring use of thicker ceramic layers to achieve sufficient erosion of the round. However, because the resonating polymer maintains its mechanical integrity, it contains the (now granulated) ceramic. Ceramic powder is effective in eroding metal, and thus subsequent incoming bullets can be defeated. Figure 3 shows a thin sheet of Kevlar added to the front surface to help maintain the granulated ceramic in place. The construction was able to pass the STANAG 4241 Bullet Impact Test, which involves three closely spaced .50-cal. AP rounds at an 850-m/s strike velocity. Note that the dimensions of the armor can be much smaller than designs relying on perforated plates to rotate projectiles.

INFRASTRUCTURE PROTECTION

A self-sealing coating can be used to prevent leakage after ballistic penetration of tanks and vessels used for gas storage. Conventional elastomers seal by virtue of their high elasticity—the ability to completely recover their original shape after large deformation. However, such materials tend to fail with widespread cracking and tearing (Figure 1), so there would be no sealing of the hole from bullet penetration. This problem is avoided using elastomers that are in resonance with the ballistic impact, as they have negligible damage (Figure 1).

Self-sealing coating might be used to protect storage tanks holding gases after .50-cal. AP bullet penetration. For this application, the coating was not intended to prevent penetration of the projectile, so that the elastomer was compounded with sufficient elasticity to completely close after passage of the bullet (Figure 4). Other applications that take advantage of the coating's combination of ballistic penetration resistance and capacity for self-sealing are currently being explored.

HELMETS

The high incidence of traumatic brain injury (TBI) has spurred significant efforts to modify combat helmets to more effectively mitigate the effects of a blast wave. Although the fragments of a bomb casing represent a threat similar to that from bullets, the blast wave perturbation is slower (in the kilohertz range). Consequently, there is less resonance with the elastomer and attenuated energy absorption

Figure 3: Ceramic Spheres Embedded in Elastomer (Left); Front-Side After Penetration by Three 0.50-cal. AP Rounds Falling Within 2-inch Circle (Stanag 4241 Bullet Impact Test), Showing Small Holes in Kevlar Top Layer (Right). The Damage Zone Is Less Than the Bullet Diameter Because the Elastomer Contains the Ceramic Granulated by the Projectile *(Source: NRL).*

Figure 4: Elastomer Coating on Front of Steel Tank After Penetration by .50-cal. AP Round (Left); Hole in Center Has Completely Closed; Backside of Steel Vessel, With Hole Approximately 50% Larger Than Bullet Diameter (Right) *(Source: NRL).*

Figure 5: Advanced Combat Helmet Core With Added Layer of Resonating Elastomer Containing 33% Hollow Spheres. The Latter Have the Same Density as the Polymer, So the Helmet Weight Is Independent of Sphere Content *(Source: NRL).*

Figure 6: Transparent Elastomer Used for Coating *(Source: NRL).*

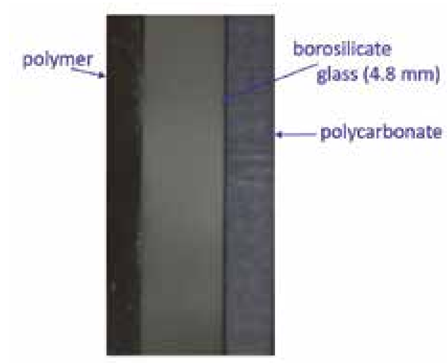

Figure 7: Representative Transparent Armor Design Used for Testing *(Source: NRL).*

by the coating. To enhance blast resistance, small hollow particles can be embedded within the coating to introduce another energy dissipation mechanism (Figure 5) [7, 8]. The energy lost in crushing the particles reduces the amplitude of the blast wave, which, in combination with energy absorption by the coating and partial reflection from the impedance mismatch at the helmet surface, reduces the wave reaching the interior of the helmet. Blast tests have also shown reduced displacement, velocity, and acceleration of the helmet interior (as compared to the standard Advanced Combat Helmet), along with equivalent ballistic performance and a 10% weight reduction.

TRANSPARENT ARMOR

Because the glass transition temperature of polymer coating is high for a rubber, its segmental dynamics are in resonance with bullet impact frequencies. Consequently, superior ballistics can be obtained with even thin coatings. For example, the V_{50} of HHS for a 0.50-cal. fragment-simulating projectile (FSP) increased 40% by adding a coating of soft polymer that was just a couple of millimeters thick. Because the polymer has low crystallinity, with any crystalline domains smaller than the wavelength of light, it is transparent (Figure 6). This effect suggests the feasibility of transparent armor applications, a representative configuration of which is shown in Figure 7 [9].

The particular polymer used here offers another important advantage. It is a thermoplastic elastomer, whereby its crosslinking to form a solid network is via a physical process, rather than chemical reaction. Consequently, the solidification is reversible; by heating the polymer above its softening point of 100 °C, fracture surfaces meld together and reform. Damage can thus be repaired "on-the-fly" in the field, using a heated plate to form a new surface that is smooth and has the mechanical integrity of the original specimen. This repair capability is made possible by the coating's ability to sustain only limited damage when impacted by a projectile (Figure 8).

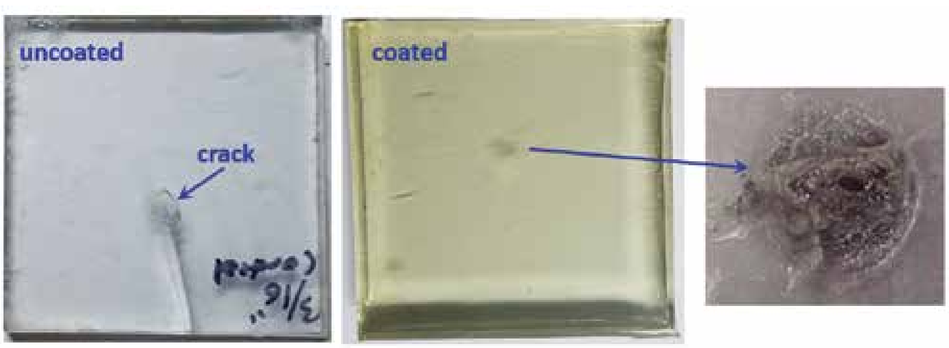

Figure 8: Comparison of Borosilicate Assembly in Figure 7: Without Front-Side Coating, Showing Crack Propagation From Impact Locus (Left); With Polymer Coating, Showing Small Damaged Region (Center); and Magnification of the Coated Target Damage (Right). The Projectile Was a Full Metal Jacket Flat Nose 9-mm + P at 1,250 ft/s *(Source: NRL).*

Polymer coating damage can be repaired "on-the-fly" in the field, using a heated plate to form a new surface that is smooth and has the mechanical integrity of the original specimen.

SUMMARY

As discussed, certain elastomers are able to increase the effectiveness of systems intended to mitigate ballistic and blast events. Some applications of the technology, to protect against specific threats, require custom features and are under active development. Common to these efforts (and to armor development in general) is a focus on increasing the protection level while reducing the weight. What is unique to the approach described herein is the complexity of the material response, involving not only the usual mechanical nonlinearities but also extreme rate-sensitivity of the response of polymers undergoing a transient phase transition. For these reasons, modeling has proved to be of limited value, and advancement of the technology has relied largely on testing and evaluation. ■

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BIOGRAPHY

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UNDERBODY BLAST METHODOLOGY

A Modular Approach to Simulating Buried Blast Effects

By Christopher Coward, Douglas Howle, Matthew Schulz, Brian Benesch, Raquel Ciappi, and Virginia Williams

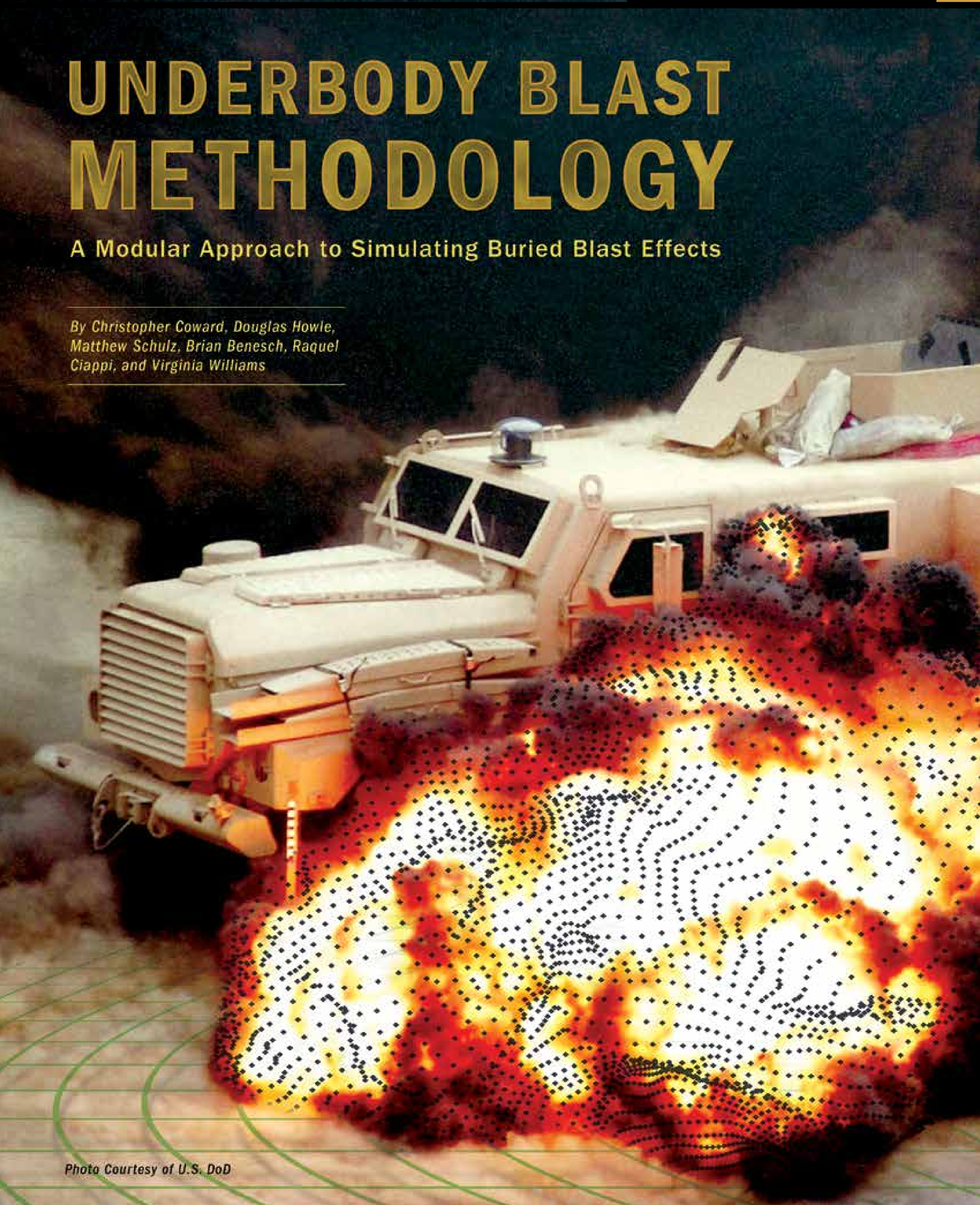

Photo Courtesy of U.S. DoD

INTRODUCTION

With the proliferation of improvised explosive devices (IEDs) and other buried mines and threats in and around today's combat zones, underbody blast (UBB) is a research area that continues to demand much attention from military planners, analysts, and others interested in protecting our military ground vehicles and the operators and occupants within them. This article provides an overview of the Underbody Blast Methodology (UBM) development program, which is led by the U.S. Army Research Laboratory (ARL) and leverages expertise from the U.S. Army Test and Evaluation Command (ATEC), the U.S. Army Materiel Systems Analysis Activity (AMSAA), and the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC). The overarching goal of the program is the development; verification, validation, and accreditation (VV&A); implementation; as well as utilization of a toolset and modeling methodology for simulation of UBB against armored ground vehicles and prediction of resultant occupant injury modes.

UBM APPLICATIONS THROUGHOUT THE ACQUISITION LIFE CYCLE

UBM comprises a collection of modular tools, which enables a hybrid approach (using both high-fidelity finite element modeling and reduced-order or semi-empirical modeling) to investigate the complicated phenomenon of UBB. The problem is divided into four basic phases: loading a vehicle, capturing the vehicle response, capturing the occupant response, and evaluating injury.

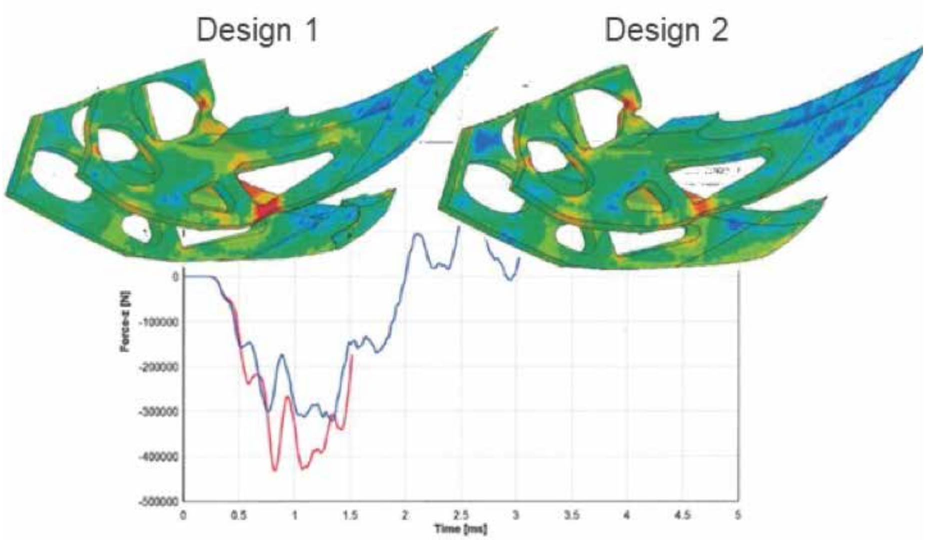

Figure 1: Notional Example of a Structure Evaluated via UBM Simulation to Consider Two Different Material Types *(Source: ARL).*

UBM is flexible enough to provide impact across the entire acquisition life cycle. Several examples of potential impact areas are discussed herein, including support for analyses of alternatives (AoAs), design recommendations, developmental testing analysis, test planning, and supplementation of live fire test and evaluation (LFT&E), etc. In parallel, despite their differing challenges and needs, a wide range of customers can benefit from UBM, including evaluators, system designers, manufacturers, program managers, testers, Warfighters, and analysts.

Early in the acquisition life cycle, decision-makers typically conduct a formal AoA to compare existing and proposed future systems. AoA's tend to be high-volume, short-suspense tasks involving a top-level comparison of systems described by varying—and oftentimes coarse—levels of characterization detail. UBM reduced-order tools are well-suited to inform AoAs because they can produce a physics-based analysis with little vehicle description and are fast-running enough to support aggressive turn-around goals. Consequently, UBM enhances confidence in the AoA comparisons that are used to make high-level program decisions.

In addition, when used early in the system design process, UBM can also provide analysis and recommendations on design alternatives (as nominally illustrated in Figure 1, showing a simulation-based comparison of two design choices distinguished by their material type). Questions regarding material choices, geometry specifics, estimated performance specifications, etc., are all questions that are well-suited to UBM's capabilities. This area is one in which the collaborative nature of the program particularly shines; by leveraging TARDEC's expertise in performing design analyses, UBM tools and practices are increasingly useful for this application.

Later in the acquisition life cycle, when the system is mostly finalized but still requires evaluation and fine-tuning, testing may be conducted to more concretely determine the quality of a system. This sort of developmental testing is typically reduced in nature — the system may only consist of a floor, hull, etc. Additionally, tests may preclude anthropomorphic test devices

(ATDs) (otherwise known as crash test dummies) due to the risk of loss or damage.

In cases where ATDs are omitted, an evaluator may still want to know what would have happened to an occupant. UBM, due to its modular nature, can produce injury estimates for a hypothetical occupant given measurements from accelerometers mounted in appropriate structural locations, such as the floor or wall. Essentially, UBM translates structural response data into injury predictions without an ATD expressly present in the test or simulation. This capability does not entirely obviate the benefit of using actual ATDs in testing, but it does augment otherwise limited test data under programmatic testing constraints.

As a system begins to undergo additional testing, stakeholders (program managers, evaluators, engineers, testers, etc.) determine the range of test parameters, including threat size and location, and the number of tests feasible within allotted resources. UBM can be employed to considerably optimize those limited resources by simulating tests throughout the experimental space, then identifying the most advantageous conditions or suspected vulnerable areas to look out for during testing.

Finally, once a system reaches formal LFT&E, UBM modeling can aid evaluators, engineers, and designers by exploring system response against untested conditions. Because live-fire testing is resource-intensive, modeling support is often required for answering questions unaddressed by the test matrix. Examples are often along the lines of the following:

- "What would have happened if the blast was of a greater magnitude?"
- "At what point does the hull rupture?"
- "What is the actual cutoff for our protection level?"
- "What if our underbody kit had been a little thicker?"

Once UBM receives accreditation to provide modeling and simulation (M&S) support for a given system, simulations can be performed to expand the experimental space considerably.

In summary, UBM can provide impact to programs across a system's acquisition life cycle by leveraging a flexible, hybrid approach to UBB M&S.

UBM can provide impact to programs across a system's acquisition life cycle by leveraging a flexible, hybrid approach to UBB M&S.

UBM PROCESS AND TOOLSET OVERVIEWS

Figure 2 illustrates the UBM process. The boxes and images surrounding the flow chart in the center illustrate the suite of tools available to accomplish the functions to which they are linked. The modeling process begins with blast loading (the red-shaded boxes) and vehicle response (the green-shaded boxes) as a coupled event, meaning that they occur simultaneously and each phenomenon influences the other. The vehicle response produces outputs such as local floor and seat-mount motion that are fed to independent subsystem models. These subsystem models, or submodels, generate simulated occupant responses (the orange-shaded boxes). The lower-leg methodology uses floor motion to predict response of an occupant's lower legs (left branch), and the seat and occupant upper-body methodology uses the seat-mount motion to predict an occupant's upper-body response (right branch). These specific modes of occupant response are then passed to the injury assessment tool, which predicts occupant injury/injuries due to the blast loading event.

Furthermore, the modular nature of the modeling process allows for significant input from subject-matter experts (SMEs). This expertise can be internal or external to the original set of modeling personnel. It should also be noted that each process has several options associated with it in Figure 2, showing that there are numerous modeling options available to accomplish that process, depending on the fidelity required and resources available. Generally, there is a fast-running low-fidelity tool that is complemented with a slower, higher-fidelity option for situations where the additional complexity is necessary.

Regarding blast loading, there are the high-fidelity Arbitrary Lagrangian-Eulerian (ALE) algorithm and the fast-running Momentum Impulse Numerical Estimator (MINE) Suite of Codes (MSOC).

ALE is a loading technique that explicitly couples the soil, explosive, and vehicle elements within the finite element

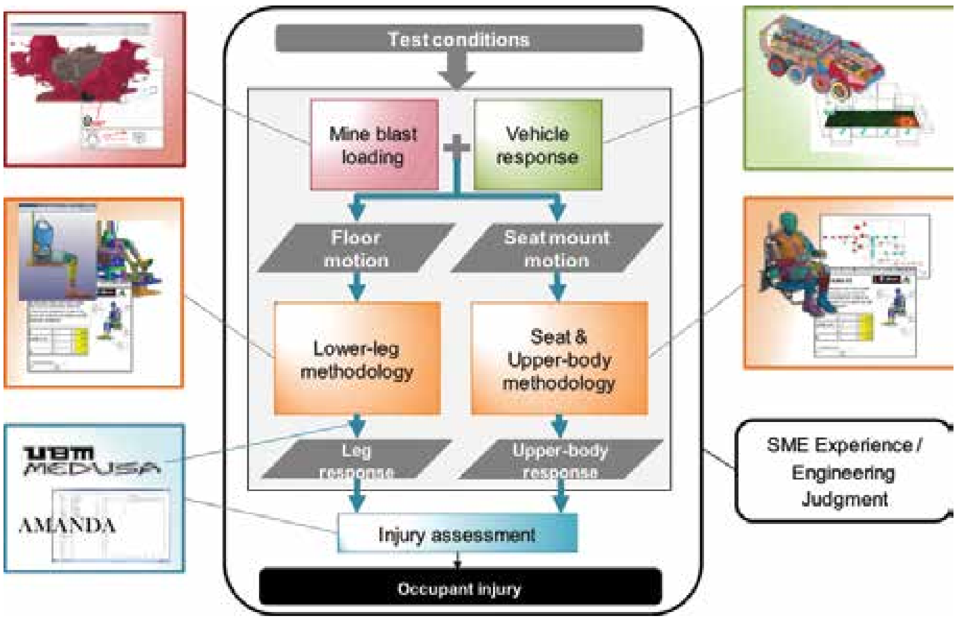

Figure 2: UBM Flowchart *(Source: ARL).*

Figure 3: High-Fidelity Finite Element Model of an Example Vehicle *(Source: ARL).*

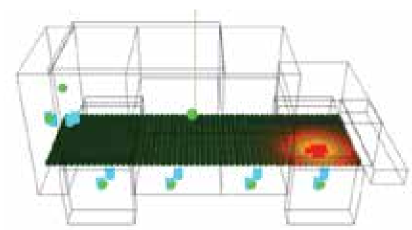

Figure 4: Screenshot From the TRUCK Model *(Source: ARL).*

analysis (FEA) (in this case, an LS-DYNA execution). It tends to produce more accurate results but also requires a greater degree of modeler knowledge and significant computational resources.

MINE, on the other hand, is a numerical approximation of blast loading that is used to generate an impulse profile against an arbitrary target geometry. The finite element target vehicle is then run using the MINE-generated loading profile but without any of the Eulerian elements associated with ALE. The primary advantages of MINE are its government ownership, extremely fast run-time, and easy implementation as a stand-alone code. However, effectively using it in some scenarios can be difficult, as it requires familiarity with its numerical methodology to appropriately set up loading profiles.

Vehicle response, which is calculated concurrently with blast in the coupled methodology, also has high-fidelity (explicit finite element) and low-fidelity modeling options. The finite element approach (illustrated in Figure 3) is typically desired; however, it can have longer lead times due to the level of effort that must be put into it and the requirement of detailed target geometries.

The low-fidelity option for vehicle response is called TRUCK, a mass-spring-damper representation of an otherwise rigid vehicle (Figure 4). Because of the simplification of the vehicle structure, this technique is exceedingly fast, but accurate output is limited to rigid-body motion.

For upper-body occupant-response methodologies, two options are again available: the high-fidelity Seat and Occupant Subsystem Model (SOSM) and the low-fidelity One-Dimensional Seat and Occupant Model (1D Model). SOSM is the occupant-only analogue to explicit vehicle modeling—every effort is made to accurately capture the seat geometry, materials, and behavior by carefully capturing as many details as possible. The 1D Model is somewhat akin to TRUCK, as it is a one-dimensional mass-spring-damper representation of the seat and the occupant's upper body. As with TRUCK, the 1D Model is exceedingly fast, albeit somewhat limited in what it may accurately predict (e.g., lumbar spine forces are a known problem).

Additional occupant-response tools include the Lower-Leg Subsystem Model (LSM) and the Heel-Strike Subsystem Model (HSM), both of which model lower-leg response. Both are laboratory designed and optimized to focus exclusively on their respective injury metrics for minimum computation time without sacrificing accuracy. They are considered medium-fidelity because the occupant's upper body has been removed to save computational time. Both are explicitly modeled portions of the ATD and seat models they would represent.

The Injury Predictor Tool (IPT) is the final response option. This is a meta-model (effectively a look-up table) of results from simulations of parameterized SOSM runs. This tool is unique in that it can produce both lower-leg and upper-body responses.

For injury assessment, AMANDA, or Analysis of Manikin Data, is the Army's validated method for evaluating injury from time-series data. This tool is used exclusively as a library for a more comprehensive tool, the Modular Engine for Development of Underbody Blast System Analyses (MEDUSA).

Internally, MEDUSA is used to handle data flow from process to process. MEDUSA's functions are illustrated by the blue arrows in the flowchart in the upper-left corner of the previous figures, and described in Figure 2. Besides handling data flow, MEDUSA is also capable of a wide variety of utility tasks, such as generating meshes, error-checking model decks, post-processing data, and generating documentation.

CURRENT STATUS AND NEXT STEPS

Currently, UBM is undergoing VV&A in accordance with relevant Army standards to support the live-fire testing of ground vehicle systems. A more detailed discussion of VV&A efforts is found in the following section.

Note that these tools and capabilities are not set in stone; UBM is an evolving capability that continues to adapt to suit the needs of the live-fire community. The development effort is proactively moving toward enhancing UBM's capabilities by adding various injury metrics, investigating human body modeling to replace ATD submodels, modeling shock and fragmentation effects, and other features.

VERIFICATION AND VALIDATION (V&V) OF THE UBM TOOLS

The V&V of UBM is focused on tools to be used in support of ground vehicle LFT&E programs. Tools that offer the highest fidelity were selected for this application: ALE's loading methodology paired with an explicit finite element target model; LSM and SOSM for lower-leg and upper-body response, respectively; and MEDUSA/AMANDA for injury assessments. Injury assessments will be based on tibia compressive force and dynamic response index (DRI), a metric related to spinal injury derived from pelvis acceleration.

The first step in V&V is verification—demonstrating that the tools do what they are supposed to be doing. The operative approach to UBM verification was to verify each of the tools individually and then to verify the methodology as a whole. This strategy, sometimes called verification by incorporation, is particularly well-suited to a modular process such as this one.

Verification entails checking that modeling parameters match those from the test (e.g., verifying the correct charge mass and dimensions, vehicle geometry and mass, soil properties, and ATD boundary conditions). It also consists of verifying that appropriate mesh size and element densities are used in the model and that the simulation is set up according to published standard operating procedures.

Verifying such a complex methodology can present many challenges. For example:

- Schedule and other resource limitations mean that every aspect of UBM-constituent models cannot be verified. However, numerous variables were selected for output sensitivity as a way to focus available resources.
- LS-DYNA is "black box" software, meaning that the source code is inaccessible. Therefore, specific equations and processes cannot be verified for correct implementation. Instead, a number of simple test cases with varying parameters were tested for the reasonableness of their results and the correspondence between parameter variation and output trends.
- Proprietary material properties pose a challenge because they cannot be interrogated to confirm their constituent properties. Many vendors incorporate such materials in the models that they create and provide. To help mitigate this risk, test data and development documentation are requested to enhance confidence in the material models as implemented.
- Continuing improvement and refinement of tools and techniques, as well as working to develop new ones, create a "moving target" for the verification task. To perform the on-record VV&A, the tools and methodologies to be used for a specific program are frozen in their state for VV&A while development continues for other applications.

While verification aims to determine that the tools are working as they are intended to work, validation goes further to then determine whether they are doing so accurately from the perspective of the intended use. UBM applications often involve some tie-in to real-world events. Therefore, validation leans heavily on comparing test results to simulation predictions.

The overarching validation philosophy for UBM is to compare simulations with UBB tests of increasing complexity and/or realism. For example, simulated targets include a rigid flat plate, a small-scale V-hull, a generic vehicle hull, a modified ground vehicle, and full-up system-level test assets. This validation methodology helps to reveal changes in accuracy as a function of test complexity and thus increases knowledge and confidence in the application of UBM tools.

A three-pronged approach for validation of UBM was undertaken. First, the ALE loading on a structure was validated. Second, the occupant subsystem models were validated. Third, the integrated, end-to-end UBM process was validated on a complex event.

ALE loading and finite element structural response are validated together because loading by itself cannot be measured directly. Therefore, the most straightforward way of measuring blast loading is applying it to a structure with predictable response patterns and

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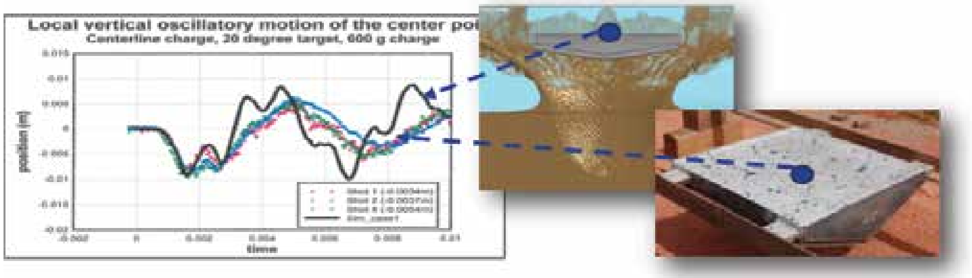

Figure 5: Notional Example Comparing SDIC Test Measurements to Simulation Results for UBM Validation *(Source: ARL).*

measuring the loading's effect on the structure. To this end, simulation results are compared to testing via metrics of the structure's response that can be measured directly. Tests against simple, small-scale targets allow for high-quality local response data. For instance, the stereo digital-image correlation (SDIC) measurement technique was used to gather displacement data during the small-scale V-hull test series (Figure 5).

As the targets become more complex and realistic, up to a full-size vehicle, validation of the loading and structural response becomes difficult. Full-scale tests are exponentially more expensive, and thus the quantity of available data can be extremely limited.

One common comparison metric is the jump height of the vehicle as measured from high-speed video. Another metric might be plastic hull deformation. Three-dimensional laser scans of the vehicle hull after the underbody test can be compared to contour plots of the deformed hull taken from the simulation. Structure or component damage is also a useful metric. Damage observations from test cases can be used to interrogate the simulation to see if regions of high strain or failure at or near that component were predicted.

The second prong in the three-pronged validation approach is validation of the occupant subsystem models. These models are independent of the vehicle structural model so they can be evaluated separately. They produce a prediction of occupant response given a prescribed excitation (loading) dictated by the local structural response.

As with the overall vehicle model, these models are validated by comparing simulation results to tests of increasing complexity. In this case, the simplest tests include controlled, laboratory tests. A second tier of complexity uses an accelerative loading fixture, where the structure is simplified and its response is tightly measured, but the loading is produced from an actual UBB to increase realism. The most realistic tests are from full-scale vehicle testing in which occupants are seated in a vehicle that is subject to an actual UBB event.

The third prong of the validation approach is to compare simulation results from the entire integrated, end-to-end UBM methodology to live-fire tests. This comparison involves repeating the type of work described in the first two prongs of the validation approach but in a single exercise. The key difference is that errors from the loading and vehicle response simulations might exacerbate, mitigate, or have no effect on errors from the occupant response and injury phases. Metrics for validation might include the entire set previously mentioned: jump height, hull deformation, occupant response time histories, and injury assessments. A full "walkthrough" example case, notionally done to support a live-fire pre-shot prediction, is discussed in detail in the following section.

SIMULATING A TEST (UBM WALKTHROUGH)

The final part of this article discusses a demonstration of how UBM is typically applied to live-fire support—specifically, how it will be applied to advance its case for accreditation. This LFT&E support process is a necessary extension of the V&V process. As discussed previously, once accreditation is achieved, UBM can be applied in additional ways, including supplementing physical testing with simulations of additional conditions.

Before M&S can be conducted, the models need to be prepared. A finite element model of the vehicle must be built, or received and edited, along with an ALE mesh. The model and mesh are built according to published standard operating procedures.

Additionally, the occupant submodels must be built. SOSM represents a specific seat, so a finite element model of an ATD in the system-specific seat must be constructed. A library of standards-compliant SOSMs is being populated to reduce production time in the future. It should also be noted that laboratory-scale testing is performed on the seat to be used to validate the SOSM characterization parameters.

LSM features a representation of floor blast mats that must be characterized from laboratory testing, along with the SOSM seat. As with SOSM, a library of blast mat characteristics is being collected so that the appropriate mat properties can be simply pulled from the library if they are already available.

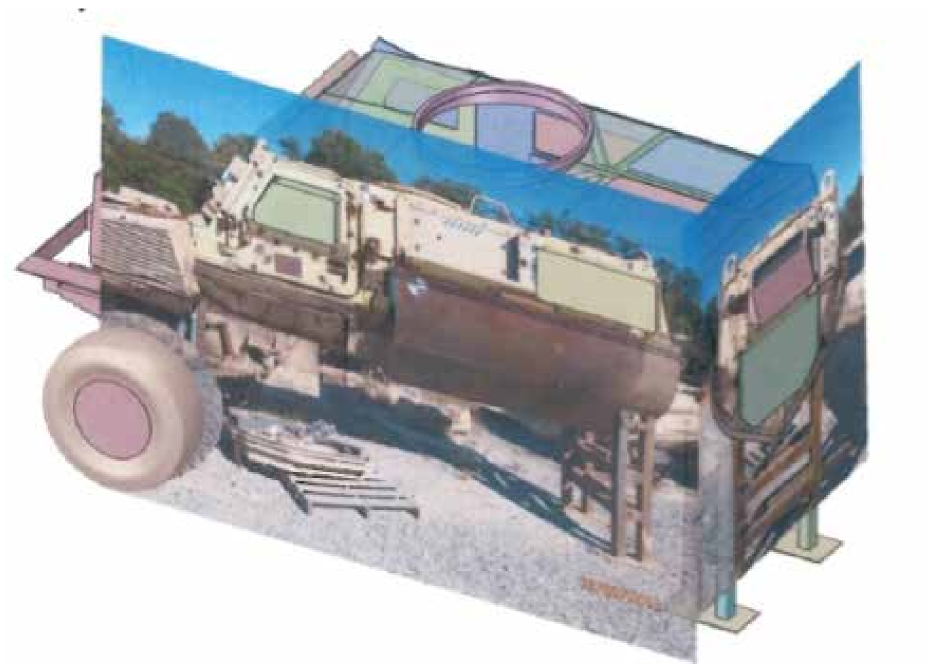

Figure 6: Notional Example of Comparing a Simulation to Test Photographs to Verify Vehicle Model's Geometry *(Source: ARL).*

As the simulation is being constructed, a checklist is followed to verify that the correct parameters are being used; for example, test photographs of the vehicle can be overlaid on the vehicle model to verify corresponding geometries (Figure 6).

The measured test results are compared to the simulation predictions across numerous metrics (many of which have been mentioned previously), including gross vehicle motion, local structural response, injury assessment, and occupant response.

High-speed video of the vehicle's gross (approximately rigid-body) motion during testing is compared to similar displacements calculated in the simulation. A comparison of the local plastic structural response aids in showing that the load is correctly applied spatially to a well-behaved vehicle model. Additionally, the simulation is evaluated by comparing predicted component damage and other dynamic events (e.g., a battery box striking a wall or a floor rising up and impacting a seat).

Faithful comparisons of the vehicle's gross motion, hull deformation, component damage, and dynamic events give good confidence that the loading and vehicle models are accurate. Assuming sufficient success, the next step is to compare occupant injuries.

A top-level comparison of the assessed injuries is the first one performed. The injury predictions for each metric per occupant are compared to those observed in the test results. These comparisons form a tally of agreement/disagreement between modeling and testing. Currently, UBM focuses specifically on lower tibia and DRI injuries, so injury assessments for these metrics for each occupant are the relevant comparisons.

Beyond the top-level comparison of injury predictions is a comparison of response time histories of the occupants (Figure 7). This consists of a comparison of tibia force time histories (for LSM) and DRI time histories (for SOSM). The comparisons provide information about the difference between relative indices (the percentage of an injury metric as compared to its injury threshold) as well as the quality of the agreement in shape and timing of the responses.

The accreditation decision will proceed based on the results of these comparison exercises. Generally "good" comparisons yield accreditation, and then UBM will be used to generate additional predictions as required to enhance the vehicle evaluation. There may be cases in which the model does not match the test well, but it is possible to still receive limited accreditation for, say, predicting qualitative trends or for certain subsets of the evaluation space.

If the model does not generally match the test well, then investigation will yield possible explanations, updates for the model or modeling techniques (where applicable), and a rerun of the test scenarios. Potential sources of error include the possibility that the model was not set up in the same way as the test was conducted, the vehicle model differed from the actual tested vehicle, and/or of the occupant models did not represent how they were actually tested. Nevertheless, the improvement cycle exists so that the model can be improved for future accreditation. Ultimately, the goal remains to show good model-to-test comparisons across all the criteria, thus building the cumulative case that the model is predicting the right results (injuries) for the right reasons.

SUMMARY

UBM, in its current state, can be used for (1) live-fire test planning and shot prioritization, (2) design trade-offs and recommendations, (3) AoAs, and (4) live-fire pre-shot predictions. The specific use of UBM for official live-fire pre-shot predictions will ultimately inform a model accreditation decision. Accreditation is based on successful verification of the methodology and model inputs, as well as validation of model results. Validation is achieved by comparison of model predictions to measured test results using the following metrics: gross vehicle motion, local structural response, injury assessment, and occupant response. Successful accreditation allows UBM results to be used for expansion of test data to a broader set of threats, systems, and contexts that would otherwise be limited due to resource constraints. UBM will result in enhanced ground vehicle evaluations and, ultimately, improved vehicle and occupant survivability against buried blast threats. ■

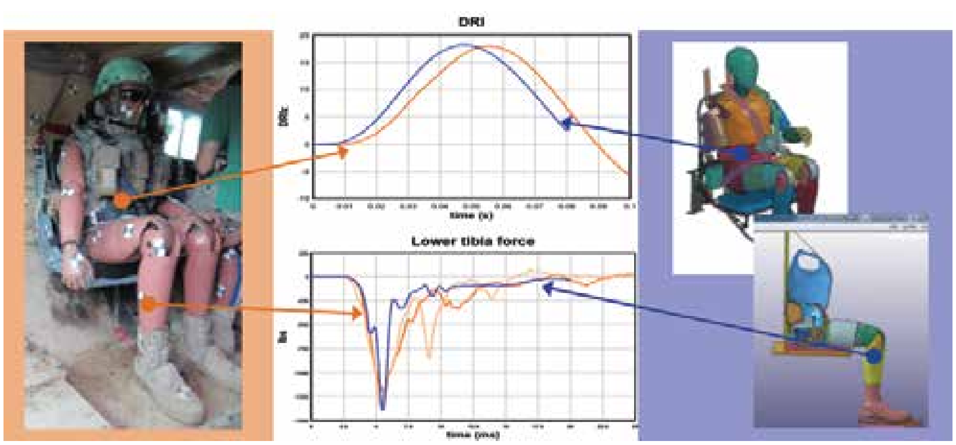

Figure 7: Notional Example of a Comparison Between Occupant Injury Test Measurements and UBM Results *(Source: ARL).*

BIOGRAPHIES

CHRISTOPHER COWARD is a mechanical engineer at the U.S. Army Research Laboratory (ARL), working on the Survivability/Lethality Analysis Directorate (SLAD) UBB Methodology Development and Analysis Team. He is responsible for planning and execution of technical programs to advance the Army's UBB M&S methodology, using his expertise in finite element M&S, live-fire test data analysis, and survivability analysis to support the Army test and evaluation community on various ground vehicle programs. Mr. Coward holds a B.S. in mechanical engineering from Virginia Tech and an M.S. in engineering management from the University of Maryland, Baltimore County.

DOUGLAS HOWLE is a mechanical engineer at ARL/SLAD, working on the UBB Methodology Development and Analysis Team. He is responsible for the planning and execution of technical programs related to the development of a robust M&S capability to support the Army test and evaluation community. He is experienced with the use of physics-based hydrocoes to simulate vehicle UBB events, including the use of arbitrary Lagrangian-Eulerian and purely Lagrangian analysis. Mr. Howle received a B.S. and an M.S. from the University of Maryland, Baltimore County.

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BRIAN BENESCH currently works for the SURVICE Engineering Company, serving as the Technical Project Lead with DSIAC, where he assists in all aspects of the technical and managerial oversite of the center. Prior to this position, he spent more than 8 years supporting efforts at ARL, where he gained significant experience assessing live-fire UBB tests, innovating accelerometer data reduction and analysis methods, and developing survivability and injury analyses used to expand and enhance the Army's UBB modeling methodology. Mr. Benesch holds a B.S. in engineering science from Loyola University of Maryland as well as an M.S. in engineering of energetic concepts from the University of Maryland.

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EXPANDING THE NAVY'S UNMANNED SYSTEMS PORTFOLIO

An Update

By Howard Berkof

OVERVIEW

Unmanned systems are a rapidly expanding warfare segment within the overall Program Executive Office (PEO) Littoral Combat Ships (LCS) portfolio. This segment includes both unmanned surface vehicles (USVs) (shown in Figure 1) and unmanned underwater vehicles (UUVs) (shown in Figure 2), many of which are under the program management of the Unmanned Maritime Systems Program Office, PMS 406. Funding for unmanned systems within the PEO has more than doubled in the last year, as the systems are a key enabler for both LCS and the Undersea Enterprise. These systems are also an important component of the strategic vision outlined by the Chief of Naval Operations (CNO), Admiral John Richardson, in his 2016 document "A Design for Maintaining Maritime Superiority." In that document, Admiral Richardson lays out four key "lines of effort" that the Navy will seek to implement. "Strengthening naval power at and from the sea" is one of these four lines, and that includes greater experimentation with unmanned systems and their rapid fielding.

Figure 1: Remotely Piloted USV in a Mine Hunting Exercise *(Source: U.S. Navy Photo by Ken Rose).*

Figure 2: UUV Being Prepared to Search for Mines During Exercise *(Source: U.S. Navy Photo by Mass Communication Specialist 1st Class A. Henry).*

In addition, the growing expertise and knowledge in USVs and UUVs being established within PEO LCS have become more widely recognized across the larger Department of Defense over the last year. PMS 406 is the acquisition lead for the majority of unmanned maritime systems and has established relationships and agreements with other entities working in the unmanned systems world. These relationships/agreements include science and technology work being performed by the Defense Advanced Research Projects Agency and the Office of Naval Research (ONR), advanced prototyping work being performed by the Pentagon's Strategic Capabilities Office (SCO), and the Fleet UUV Squadron (UUVRON ONE), located at Keyport, WA. These efforts and relationships are expected to continue to strengthen in coming years.

With the growing interest and investment in unmanned maritime systems, the Navy has focused on maintaining alignment among the many stakeholder communities in the respective UUV and USV segments and establishing agreed-upon strategies and executable program plans going forward. The net result of this strategic effort is the formulation of common visions for the family of UUVs and USVs, their associated technology enablers for the Navy, and the way in which these many diverse program efforts all fit together into a cohesive strategy. From small to extra large, and across multiple warfare domains, the entire family of UUVs and USVs has been mapped into a comprehensive approach. And this stakeholder alignment and development of a common narrative across the unmanned maritime systems portfolio

> From small to extra large, and across multiple warfare domains, the entire family of UUVs and USVs has been mapped into a comprehensive approach.

has been a critical program objective and continues to be key to efficient execution going forward.

As part of this stakeholder alignment effort, PMS 406 is also spearheading certain enabling efforts that are germane to programs in either the USV or UUV domains. Chief among these efforts is the establishment of an Autonomy Architecture Team. This small team is composed of representatives from the Navy, research laboratories, and technical institutions with the primary objective of developing and promulgating an autonomy standard applicable to both USVs and UUVs. The intent is to develop a fully accredited standard that meets required technical criteria and can be implemented across systems by the summer of 2018.

ONR, PMS 406, and UUVRON ONE are all strengthening relationships while coordinating and developing testing and experimentation schedules to help enable seamless UUV operations with fleet assets in the coming years. For example, as part of the Innovative Naval Prototype effort, ONR is transferring several developmental UUVs to PMS 406 for support and management. PMS 406 is then providing these experimental UUVs to UUVRON to jumpstart its experience and basic handling knowledge of larger UUVs. These relationships are expected to continue to grow as additional UUVs emerge from the developmental procurement pipeline.

The funding increases going to PMS 406 are a reflection of both the technical maturation of unmanned maritime systems and a growing understanding across the Navy that unmanned systems of all types—air, surface, and undersea—are critical enablers to help ensure future combat success. Admiral Richardson reinforced the role of unmanned systems, especially UUVs, following a daylong "deep dive" on UUVs held at the Naval Undersea Warfare Center in Newport, RI, in August.

This growing awareness at all levels of the special role unmanned systems will play in the Navy's future operations was amply demonstrated in the recommendations and conclusions of three independent Fleet Architecture Studies directed by Congress and publicly released in February. Each of these studies—separately executed by the Navy's own N81 assessment office, the federally funded MITRE Corporation, and the Center for Strategic and Budgetary Assessments (CSRA) think tank—envisions an expansive role for unmanned systems in the future fleet.

The MITRE study recommended the Navy determine how to boost production of larger UUVs, which it deemed a critical element of a growing undersea network of submarines, communications nodes, and ocean-bottom systems. Likewise, CSRA envisions the formation of unmanned squadrons composed of USVs and UUVs operating from a "mother ship." The Navy's N81 assessment, an independently conducted effort, was even more bold, advocating the development of USVs armed with weapons and larger numbers of UUVs.

Within PEO LCS, three essential UUV efforts are managed and coordinated by PMS 406: (1) the Knifefish UUV minehunting system, (2) the Snakehead Large Displacement Unmanned Underwater Vehicle (LDUUV), and (3) the Orca Extra Large Unmanned Underwater Vehicle (XLUUV). However, PMS 406's efforts are not limited to these three programs alone. The office's expansive portfolio also extends to managing the following:

- The Navy's new developmental Mining Expendable Delivery Unmanned Submarine Asset (MEDUSA)
- The Unmanned Influence Sweep System (UISS) USV
- The Mine Countermeasures (MCM) USV, which can conduct both influence minesweeping and minehunting operations
- The delivery of improved production AN/AQS-20 towed minehunting sonars
- The continued evolution of the rigid-hulled inflatable boat (RHIB)-based Minehunting USVs (MHUs) supporting 5th Fleet urgent operational requirements
- Evolving discussions with the Office of the CNO and the Fleet on the Future Surface Combatant family of USVs
- Collaboration with SCO's Ghost Fleet initiative, which includes both larger USVs and an XLUUV-class system. PMS 406 is the Execution Agent for the Ghost Fleet efforts funded by the SCO.

The following sections provide a program update on the current status and significant events expected to take place across PMS 406's unmanned portfolio over the next year.

UUVs

Knifefish

Knifefish (shown in Figure 3) is a self-propelled UUV that operates untethered from the ship or platform from which it deploys. Operating independently in shallow ocean waters, the UUV uses a low-frequency broadband sonar to search for volume, proud (secured to ocean floor), and buried mines. The program represents a true leap ahead in technology for MCM operations. Knifefish is a critical element in the Navy's evolving MCM efforts and its overall vision for removing ships and crews from the dangers of operating within a minefield. The 21-ft-long UUV can also be launched from other Vessels of Opportunity (VOOs), including the LCS or other surface platforms. The system is being built by General Dynamics' Mission Systems unit.

Knifefish recently completed a robust series of contractor trials in Boston Harbor, MA. As part of the testing, eight mine-representative targets were scattered across an underwater range, and Knifefish successfully found and categorized all eight "mines" in a key test of the vehicle's performance. Developmental testing will continue through the remainder of 2017, with the system expected to transition to a more robust Navy operational testing phase in 2018. Knifefish fully supported by senior Navy leaders in current budget deliberations.

Knifefish represents a true leap ahead in technology for MCM operations.

While Knifefish is well along on its development path, opportunities still exist for additional industry involvement in the program. A Pre-Planned Product Improvement effort is already envisioned for Knifefish, with PMS 406 interested in new ideas, concepts, and technologies that can improve the vehicle in the areas of launch and recovery, power and endurance, sensors and reliability, navigation precision, communications and data exchange, mission data download, and transmission.

Figure 3: Knifefish UUV *(Source: U.S. Navy Photo).*

Snakehead LDUUV

The Snakehead program has swiftly pivoted to a new acquisition strategy over the last year that seeks to speed this innovative capability to the Fleet, including starting in-water system testing by 2020, pending required funding in the budget. In January, the Snakehead LDUUV was approved as an accelerated acquisition effort, specifically as a Maritime Advanced Capabilities Office program. This approach enables the Snakehead program to use a modified, more rapid procurement approach to reduce design and development time and expedite the initial fielding of this capability. The Fleet can then conduct experimentation and assessment of the vehicle much sooner in the acquisition process and offer informed operational feedback to spur design changes and capability improvements to the Snakehead system.

Under this new, streamlined acquisition approach, initial Snakehead LDUUV vehicles will be ready for in-water testing and experimentation as early as 2020. Limited procurement of initial vehicles affords the Navy the opportunity to quickly switch to new payloads as Fleet demands or experimentation results warrant. Admiral Richardson and other acquisition leaders have repeatedly said that now is the time for the Navy to take calculated risks, and while some developments may work and others may fail, the Navy needs that knowledge to move ahead. The Snakehead effort is attempting to push innovation at the speed the Fleet is demanding.

PMS 406 is also leveraging the standard request for information process in new ways to assess the technical and manufacturing base, gauge its experience level and capabilities, and gain insights from industry. Phase I LDUUV efforts will procure subsystems, sensors, and materiel from numerous vendors across multiple states. The Government is leveraging various contract mechanisms to reach dozens of industry partners for follow-on LDUUV phases and its family of UUVs, including the National Armaments Consortium Other Transaction Authority and a Naval Undersea Warfare Center Newport multi-award, indefinite delivery indefinite quantity contract.

The current operational focus for Phase I will be on Intelligence Preparation of the Operational Environment (IPOE). Extensive use of the set-based design approach has proven valuable in determining the relevance of this early mission set for Snakehead LDUUV. Set-based design brings the Fleet, requirements, and acquisition officials together at the onset of a program to speed up the process, and it allows the right decision to be made up front rather than having each of the entities making decisions in a traditional stove-piped process. This approach will also be used to help determine mission priorities for follow-on phases of the Snakehead program.

Orca XLUUV

In September 2017, the Navy awarded two contracts for the Orca XLUUV for Phase 1 design efforts. Lockheed Martin was awarded a $43 million contract, while Boeing, teamed with Huntington Ingalls, was awarded a $42 million contract. This significant milestone achievement provides a vivid demonstration of the fast-track acquisition strategy being employed by PMS 406 to accelerate this capability to the Fleet. These contract awards were preceded by a request for proposal (RFP) built off of a draft RFP released in November 2016 and an industry day that the Navy conducted in January 2017, where more than 50 potential industry partners attended. The final RFP for Orca was released in March 2017, with proposal responses received from industry at the end of May. The PMS 406 team worked hard to partner with industry to ensure the rapid contract documents were reviewed and industry feedback incorporated.

Figure 4: Orca XLUUV Phase 1 Concept Renderings *(Source: PEO LCS).*

The Orca program is a Navy accelerated acquisition effort serving as the Navy's XLUUV class effort and is in response to a Joint Emergent Operational Need. This vehicle will help extend the range of current platforms to undertake specific maritime missions and can be launched from pier side or platforms at sea. Orca's modular design will enable the UUV to deploy multiple types of payloads. Key performance attributes include extended vehicle range and persistence, a reconfigurable payload bay, modular construction, autonomy, and pier-launch capability.

With the awarding of the Phase 1 contracts, the two contractors will conduct detailed design efforts over the the next 15 months. (Both the Lockheed Martin and Boeing design concepts are pictured in Figure 4.) Once the design phase is completed, a single contractor's design will be selected to build up to five vehicles, with the first XLUUV delivered in 2020, followed by two additional vehicles in 2021 and two in 2022.

USVs

UISS

UISS is a 38.5-ft USV that will provide stand-off, long-endurance, semi-autonomous, minesweeping capability to counter acoustic and/or magnetic influence mine threats in the water column. UISS comprises a modular USV and an Influence Sweep payload, consisting of a magnetic sweep cable and a modified Mk-104 acoustic generator. The craft's payload bay provides an opportunity to use different payloads in the future as missions and technologies evolve. UISS can be operated from VOOs, including LCS ships, or from shore. The system is being developed by Textron Systems Unmanned Systems Division.

A UISS Engineering Development Model craft initiated contractor testing in January 2017 and has accumulated more than 350 hr of progressively more strenuous in-water testing at Navy ranges in Florida. The test vehicle has achieved impressive in-water speeds at sustained levels of endurance. The USV has been controlled/operated from a land-based control station built as a surrogate of the LCS Command Center during these tests. Contractor testing will continue through the remainder of this year, with the system expected to transition to Navy developmental and operational testing in 2018.

MCM USV + Minehunting

The same UISS craft, the MCM USV, is a 38.5-ft craft with a 20-ft-long modular payload bay capable of employing multiple payloads. In addition to the influence sweep payload, the Navy is integrating both the AN/AQS-20 and AN/AQS-24 towed minehunting sonars with the MCM USV. The MCM USV + Minehunting payloads will provide the Navy with rapid, wide-area minehunting capability. Textron is currently building two MCM USVs to support the minehunting mission, Raytheon is developing and building a deploy-and-retrieve rig for the AN/AQS-20 sonar, and Northrop Grumman is developing and building a launch-and-recovery system for the AN/AQS-24 sonar. System testing will commence in late 2018 and will lead into a User Operational Evaluation System assessment period in 2019.

MHUs

Starting in 2014, four MHUs have been built and delivered to the 5^{th} Fleet Operating Environment in response to a Fleet Urgent Operational Need. The MHUs consist of an unmanned 11-m RHIB deploying an AN/AQS-24 towed minehunting sonar to conduct volume and bottom mine searches. The MHUs are maintained and sustained in the Arabian Gulf area and continue to support numerous 5^{th} Fleet exercises. Most recently, the MHUs were deployed aboard *USS Lewis B. Puller* (ESB-3), the first of the Navy's new class of Expeditionary Mobile Base ships. These systems provide much needed additional minehunting capacity, augmenting the MH-53E helicopter capability.

Figure 5: Design Concept of the Undertaker *(Source: PEO LCS).*

Ghost Fleet

Funded by the Pentagon's SCO, Ghost Fleet is an FY18 initiative that seeks to push the current technical limitations on USVs and UUVs to determine how these vehicles can boost the operational effectiveness of the Navy's manned fleet of warships.

The demonstration program consists of two distinct elements. First is the undersea component, called Undertaker. This element of Ghost Fleet was awarded to Boeing for analysis and testing of the Echo Voyager system to inform a prototype build (a design concept of which is pictured in Figure 5) in the future.

The second element is called Overlord and seeks to develop and demonstrate the capability for larger USVs to independently deploy. A draft RFP was issued to industry for Overlord in September, and an industry day was held in October to solicit industry interest in the effort. What sets the Overlord effort apart from other USVs is the intent to convert larger, existing, manned ships into USVs over the next 3 years so that they can conduct existing missions now undertaken by manned warships. The operational goals for Overlord are USVs capable of conducting 90-day missions at sea with zero crew. The USVs will be outfitted for optional manning and constructed to conduct testing of a variety of payloads, including electronic warfare, surface warfare, and strike warfare.

CONCLUSION

By all accounts, the role of unmanned systems in military operations—as well as in the Navy's strategic vision—is one that is only expected to increase as these systems become smarter, more accessible, and more effective. Thus, it will be increasingly important for all stakeholders involved in the planning, research, development, and acquisition of these systems to maintain awareness, alignment, and communication in this important field. ■

BIOGRAPHY

HOWARD BERKOF is currently the Deputy Program Manager for PMS 406/PEO LCS, where he is responsible for planning, management, and integration of full-scale development, test, procurement, installation, and life-cycle support activities for numerous Acquisition Category (ACAT) and non-ACAT unmanned platform and payload programs. In addition, Mr. Berkof has served in multiple roles in unmanned maritime vehicle acquisition during his 10 years of government service, and he completed a 1-yr assignment as a senior requirements analyst for the Expeditionary Warfare Division (N95) for the CNO. Mr. Berkof holds a B.S. in mechanical engineering from the Pennsylvania State University and an M.B.A. from Harvard Business School.

CONFERENCES AND SYMPOSIA

MARCH 2018

2018 Joint Undersea Warfare Technology Spring Conference
12–14 March 2018
Admiral Kidd Conference Center
San Diego, CA
http://www.ndia.org/events/2018/3/12/undersea-warfare-spring ▸

6th DoD Unmanned Systems Summit
14–15 March 2018
Mary M. Gates Learning Center
Alexandria, VA
http://unmannedsystems.dsigroup.org/ ▸

2018 Military Sensing Symposia Parallel Meeting
19–23 March 2018
Gaithersburg, MD
https://mssconferences.org/public/meetings/conferenceDetail.aspx?enc=dhY7%2BnK59GteJxMUQoeXrw%3D%3D ▸

Directed Energy to DC Exhibition
19–23 March 2018
Pentagon Courtyard
Washington, D.C.
https://protected.networkshosting.com/depsor/DEPSpages/DE2DC18.html#timeline ▸

19th Annual Science & Engineering Technology Conference
20–22 March 2018
AT&T Hotel and Conference Center
Austin, TX
http://www.ndia.org/events/2018/3/20/set-conference/agenda ▸

Building More Survivable Defense Systems and More Effective Weapons: A Short Course on LFT&E
20–22 March 2018
SURVICE Engineering Company
Becamp, MD
https://www.dsiac.org/events/building-more-survivable-defense-systems-and-more-effective-weapons-short-course-lfte ▸

2018 Aircraft Combat Survivability Short Course
27–29 March 2018
North Island Naval Air Station
Coronado, CA
https://www.dsiac.org/events/2018-aircraft-combat-survivability-short-course ▸

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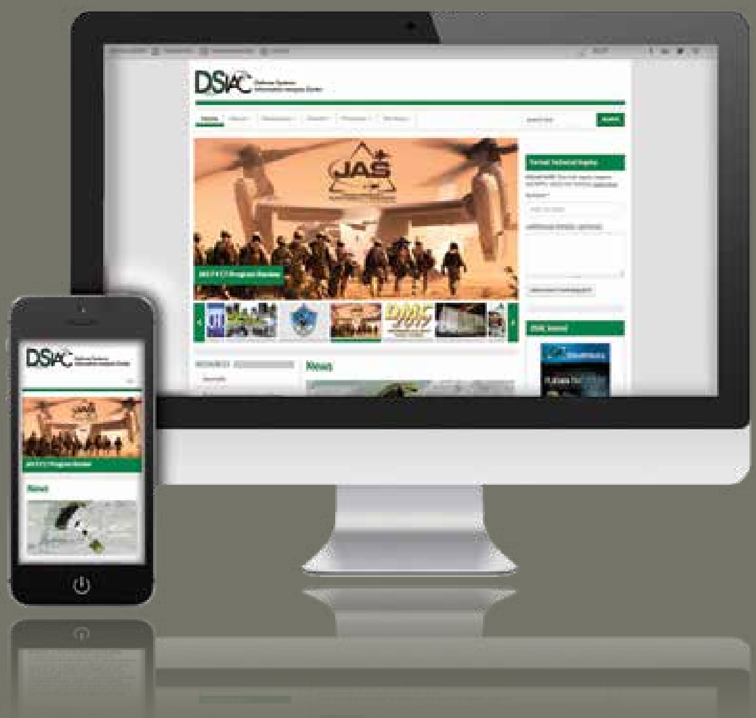

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