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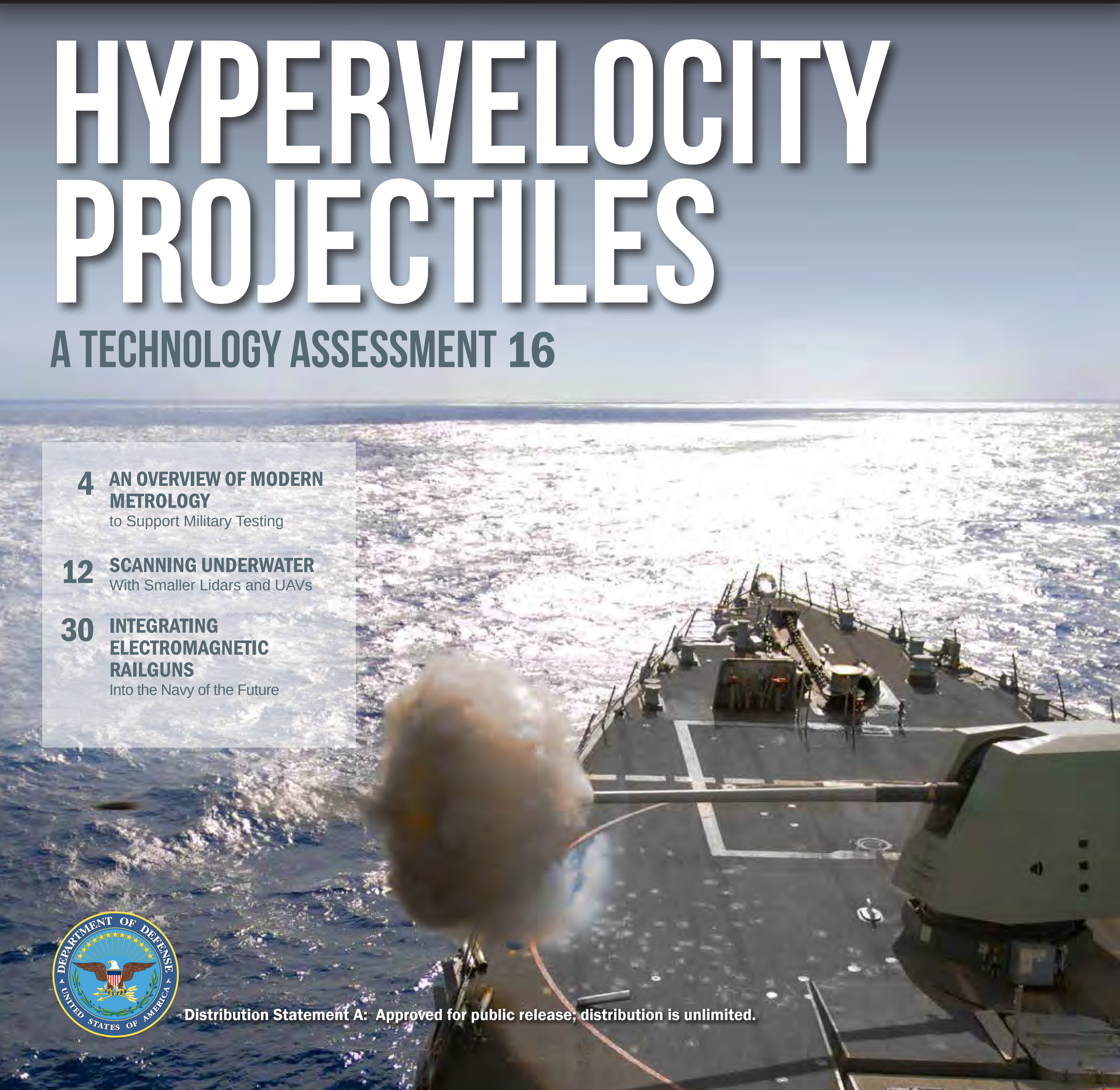

HYPERVELOCITY PROJECTILES

A TECHNOLOGY ASSESSMENT 16

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On the Cover:
The MK-45 5-inch/62-caliber lightweight gun of the guided-missile destroyer USS Mustin *(DDG 89) is fired at a shore-based target during Mustin's Naval Surface Fire Support (NSFS) recertification. (Image: U.S. Navy photo by Mass Communication Specialist 2nd Class Devon Dow)*

The *DSIAC Journal* is a quarterly publication of the Defense Systems Information Analysis Center (DSIAC). DSIAC is a Department of Defense (DoD) Information Analysis Center (IAC) sponsored by the Defense Technical Information Center (DTIC) with policy oversight provided by the Assistant Secretary of Defense for Research and Engineering, ASD (R&E). DSIAC is operated by the SURVICE Engineering Company with support from Quanterion Solutions Incorporated, Georgia Tech Research Institute, Texas Research Institute/Austin, and The Johns Hopkins University.

Department of Defense Information Analysis Centers

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MESSAGE FROM THE EDITOR

ERIC FIORE

You may not be aware that one of the core functions of the Defense Systems Information Analysis Center (DSIAC) is to perform technology assessments related to our nine communities of practice (see insert on this page). And with our consortium of subject-matter experts, DSIAC has access to some of the best and brightest minds in the Defense industry. In this issue of the *DSIAC Journal*, we present a technology assessment of hypervelocity projectiles (HVPs) performed by one of our experts. While the article is an abridged version of the original report, we devote much of this issue to discussing this increasingly important technology.

As our adversaries become increasingly capable of extending their anti-access/area-denial (A2/AD) capabilities, the tactical capabilities of U.S. forces are slowly diminishing. To mitigate these emerging concerns, the United States will have to rely on new technologies to supplement our legacy systems and capabilities. HVPs are promising technologies that may provide a viable solution to this complex problem.

In our feature article, Michael Fisher presents a technology assessment of HVPs. He examines the maturity and cost-effectiveness of HVP technologies and the solutions they offer for force protection, ballistic missile defense, and precision strike applications. The article concludes with a qualitative comparison of the technologies, their relative maturity, as well as a discussion of lingering challenges associated with the technologies.

In a companion article on weapon systems, Mathew Fox further discusses the current state of the art of railguns. He provides a synopsis of railgun features that have intrigued followers, such as how railguns work, their logistical advantages, and strike capabilities. And while this technology appears promising, the article also discusses the remaining technical challenges that need to be resolved to make railguns viable—namely, power and barrel life.

DSIAC SCOPE AREAS

Advanced Materials

Autonomous Systems

Directed Energy

Energetics

Military Sensing

Non-Lethal Weapons

Reliability, Maintainability, Quality, Supportability, and Interoperability (RMQSI)

Survivability and Vulnerability

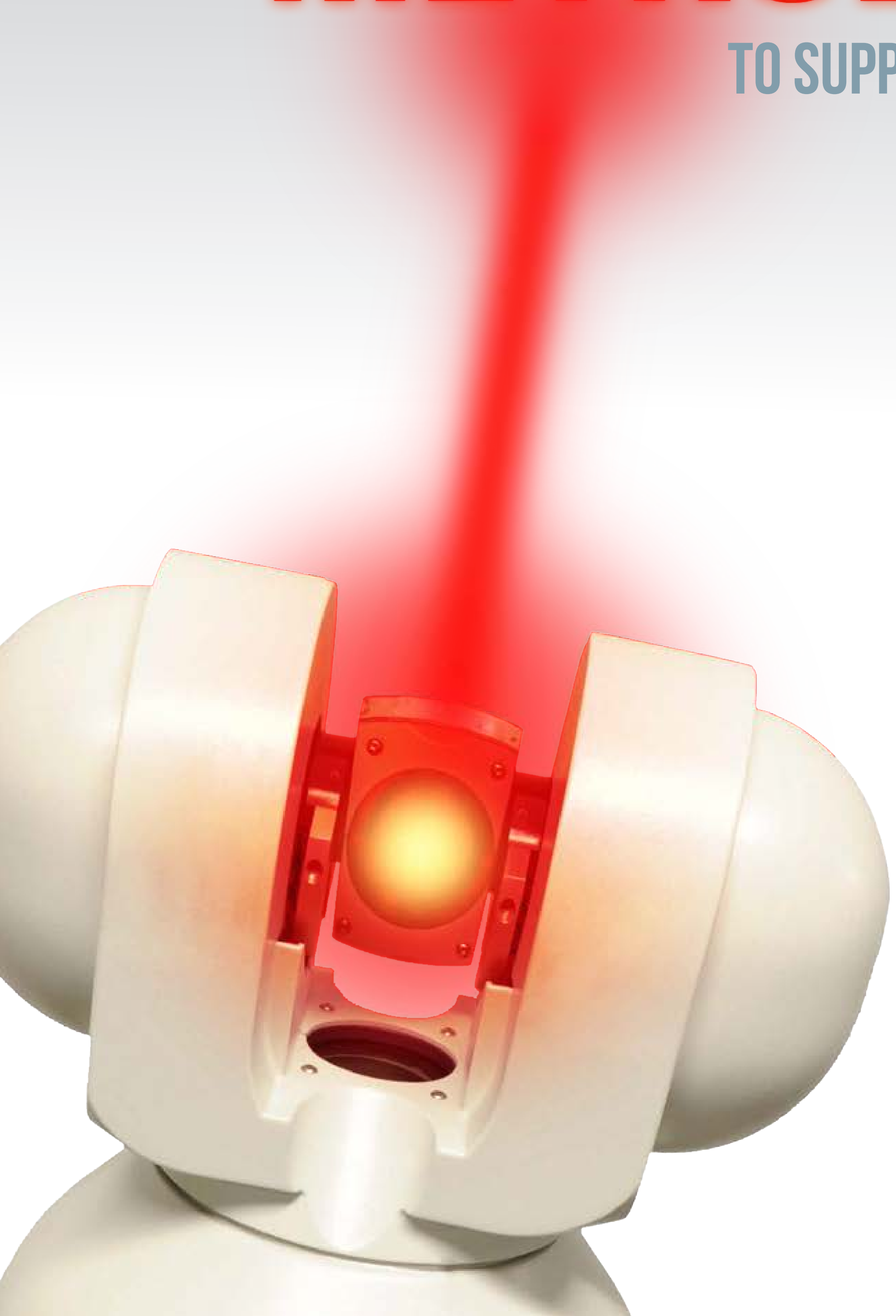
Weapon Systems

Bathymetric lidars are devices that employ powerful lasers to scan beneath the water's surface. At nearly 600 lbs, the systems are large and heavy, requiring costly piloted aircraft to carry them. But that situation may soon be changing. A team at the Georgia Tech Research Institute (GTRI) has designed a new approach that could lead to bathymetric lidars that are much smaller and more efficient than the current full-size systems. Rick Robinson discusses this new technology, called Active Electro-Optical Intelligence, Surveillance, and Reconnaissance (AEO-ISR), which would allow modest-sized unmanned aerial vehicles (UAVs) to carry bathymetric lidars. This new technology promises to substantially reduce the cost vs. conventional systems.

Finally, in our survivability and vulnerability article, Greg Robinson and Mickey Hardin present an overview of modern metrology and how it is used to support military testing. They provide several illustrative examples, including arena testing for the dispersion of fragmentation and collateral damage on the detonation of a missile or warhead, an analyses of buried blast craters for battlefield forensics and the verification and validation of predictive models, and three-dimensional (3-D) modeling of Mine Resistant Ambush Protected (MRAP) Cougar vehicle variants for space claim and testing purposes.

In our upcoming fall issue, the featured article is on infrared (IR) detector technology, in which our authors will be providing a brief history of IR technology and the latest developments and trends. ■

AN OVERVIEW OF MODERN METROLOGY TO SUPPORT MILITARY TESTING



By Greg Robinson and Mickey Hardin

INTRODUCTION

Although the word "metrology" may be unfamiliar to many in the world of military equipment design and testing, it is a word becoming increasingly important. Metrology can be defined as the science of measurement in support of engineering. And rapid advances in technology and computing power have brought about an abundance of new metrology equipment and techniques that are being employed to make various phases of military equipment testing—including test planning, test execution, and test evaluation—significantly more efficient and accurate.

This article provides an overview of the categories of basic metrology equipment currently available and gives an example of specific commercial versions of these tools that would typically be found in the inventory of a well-equipped metrology company. Also included are several examples of military testing and modeling projects in which some of these innovative tools and techniques have been employed to streamline and improve the results. These projects include:

- Arena testing for the dispersion of fragmentation and collateral damage on the detonation of a missile or warhead.
- Analyses of buried blast craters for battlefield forensics and the verification and validation of predictive models.
- Three-dimensional (3-D) modeling of Mine Resistant Ambush Protected (MRAP) Cougar vehicle variants for space claim and testing purposes.

DIGITAL METROLOGY

Traditionally, when models are created for test support, analog measurements tools—such as tapes, plumb bobs, and calipers—are employed. But these tools and techniques have their limitations. Such data collection is slower and is largely dependent on the skill of the person conducting the measurements. Additionally, for large vehicles or parts, measurement errors tend to stack up, leading to undesirable inaccuracies. And as the readings are logged manually, they may also be susceptible to transcription errors.

On the other hand, digital metrology methods are usually much faster and less susceptible to the measurer's personal measurement biases. Further, the accurate framework produced by digital technologies allows for manual measurements to be included as necessary, but without the disadvantage of excessive measurement uncertainty buildup.

Digital metrology supports many engineering applications, such as:

> Digital metrology methods are usually much faster and less susceptible to the measurer's personal measurement biases.

- **Reverse Engineering –** This application of digital metrology is used when a set of blueprints, or more commonly a 3-D computer model, is constructed from an actual part or vehicle for which no blueprints exist, or where blueprints do exist but are inaccurate, outdated, or not available (see examples in Figure 1).
- **Rapid Protoyping –** This area takes reverse engineering a step further to create a prototype, often by modifying measurements of an existing part. Generally, a full-size prototype is created using additive (3-D printing) or subtractive (computer numerical control [CNC]) manufacturing techniques to check for fit, form, and function before production commences.
- **Checking Parts and Surfaces Against a Blueprint or Computer Model –** This activity ensures that parts meet certain geometric requirements, usually defined, unambiguously, by geometric dimensioning and tolerancing (GD&T).

Metrology in support of testing is always in some form of geometric modeling and sometimes includes reverse engineering, as described later in the MRAP Cougar modeling discussion.

METROLOGY EQUIPMENT

While a large selection of metrology tools are currently available, newer, more portable, hi-tech tools are continuously being released into the marketplace. Because of the nature of modeling for test support, portable measurement solutions are generally favored over fixed

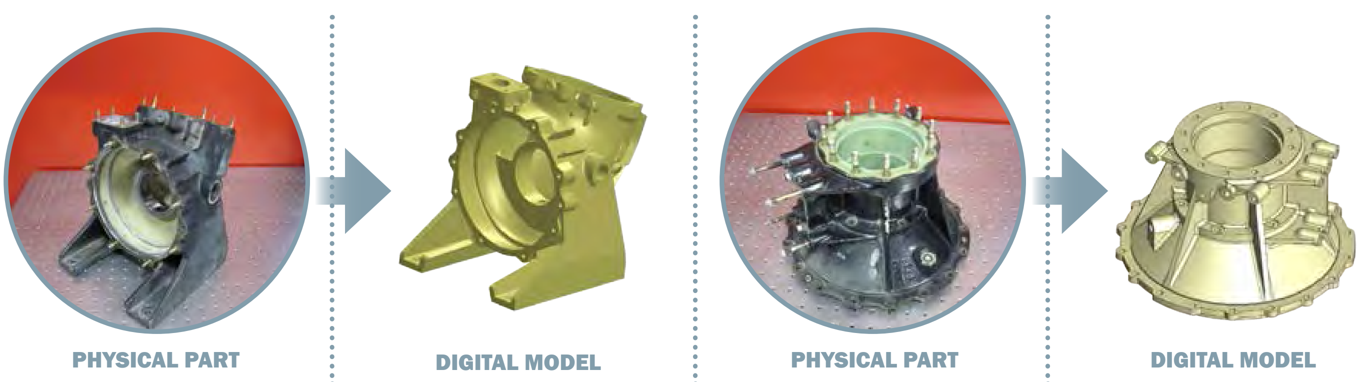


Figure 1: From Physical Part to Digital Model. (Photographs and models courtesy of SURVICE Engineering.)

solutions, as portable measurement devices can be brought directly to the test area, part, or vehicle. Thus, while large, fixed devices, such as coordinate measurement machines (CMMs), are also used extensively to support military testing, the discussion here is limited primarily to portable equipment. One notable exception to this limitation, however, is computed tomography (CT) scanners, which are also included in the discussion of noncontact measuring devices because of their particular suitability to inspecting internal damage of test items such as body armor or helmets.

The following is a brief overview of current portable metrology equipment and some of its unique capabilities.

Portable metrology equipment can be broadly divided into the following two categories:

- **Contact Devices –** Portable CMMs are easily transportable versions of the fixed CMMs that provide high-accuracy (often <0.001 inch) quality control in large manufacturing facilities. The accuracy of portable CMMs is >0.001 inch due to their portable nature and also because they are seldomly used in the climate-controlled environment that is generally required for fixed CMMs. Examples of portable CMMs are laser trackers and mechanical measurement arms. They are most often used for point-to-point measurements.
- **Noncontact Devices –** 3-D, noncontact scanners can rapidly collect clouds of many thousands of data points. They often are divided into several categories depending on their type of data capture process. Typical accuracies range from 0.001 inch to >0.050 inch.

Also common are hybrid devices that combine a noncontact scanner with a portable CMM so that the position and orientation of the scanner is known, thus referencing the point cloud to a global reference coordinate system. The most common of these hybrid devices are measurement arms combined with a triangulation-type laser scanner.

CONTACT DEVICES

Contact measurement devices are suited to many aspects of test support because of their portability, accuracy, and ability to operate outdoors when required. These devices are illustrated in Figure 2, with the most common contact devices being *mechanical measurement arms* and *laser trackers*.

The articulated measurement arms allow multiple degrees of freedom as the operator collects individual points or streams of points using a trigger-operated point probe. A laser tracker operates by centering a laser beam on and measuring two gimbal angles and a distance to a retroreflector target. The distance is generally measured using a time-of-flight technique known as absolute distance measurement. For the highest accuracy work, not generally applicable to modeling for test support, distance measurement interferometery may be used. The position of the retroreflector (and hence the part or vehicle surface) is then calculated from the two angles and a distance. As with articulated arms, measurements are triggered by the operator and are either individual points or streams of points a fixed distance or timing interval apart.

The less common intelligent GPS (iGPS) is a unique portable contact measurement device in which the position of a vector bar is determined by triangulating from multiple transmitters. The transmitters emit laser light and light pulses that the sensors in the vector bar convert to relative azimuth and elevation. A hand-held vector bar, which is equipped with dual sensors, is used to calibrate the system and define the global coordinate system. The iGPS system is capable of providing coordinates in the global coordinate system to an accuracy of approximately 0.004 inch.

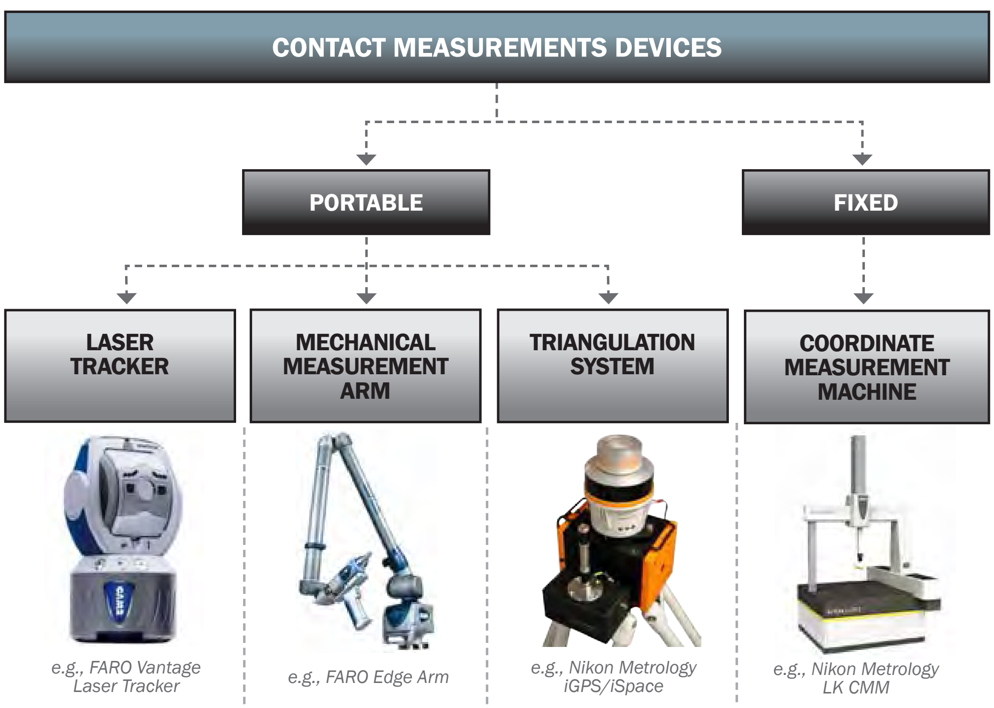


Figure 2: Contact Measurement Devices.

The advantages of contact devices include their high accuracy, ability to measure into slots and pockets sometimes with appropriate tooling, and insensitivity to the color or transparency of the part being measured. However, these advantages are partially offset by the slow data collection rate and possible distortion of soft objects when in contact with the probe or the retroreflector.

Table 1 provides the basic specifications for some typical commercial contact measurement devices.

NONCONTACT DEVICES

Noncontact scanners project a laser or light pattern onto the part and then observe either the transmitted or reflected energy. A point cloud representative of the geometry of the part is calculated by means of triangulation, time-of-flight, or wave interference information. There are many methods to classify noncontact data collection devices. One of the most common is illustrated in Figure 3.

Noncontact measurement devices are typically fast, provide good accuracy, and deliver large quantities of data. Optionally, they can sometimes collect object color texture information and can often scan detailed information that may be too small to be measured using a touch probe or laser tracker target. However, noncontact measurement devices may have difficulty with dark or reflective surfaces and with surfaces that are transparent or semi-translucent, such as composite materials.

Table 2 provides the basic specifications for some typical commercial noncontact measurement devices.

Table 1. Contact Measurement Devices: Typical Commercial Specifications

Technology	Company	Model	Volume	Specified Accuracy
Mechanical measurement arm with point probe	FARO Technologies, Inc.	FaroArm Edge	8 ft to 12 ft per setup. Much larger volume with rapidly reduced accuracy with multiple instrument setups using reference points	0.001 inch at 8 ft
Laser tracker	FARO Technologies, Inc.	Laser Tracker Vantage	Typically 40 ft per setup. Much larger volume with slightly reduced accuracy with multiple instrument setups using reference points	0.001 inch at 6 ft 0.002 inch at 20 ft
Triangulation	Nikon Metrology	iGPS	Unlimited depending on number of transmitters	From 0.004 inch

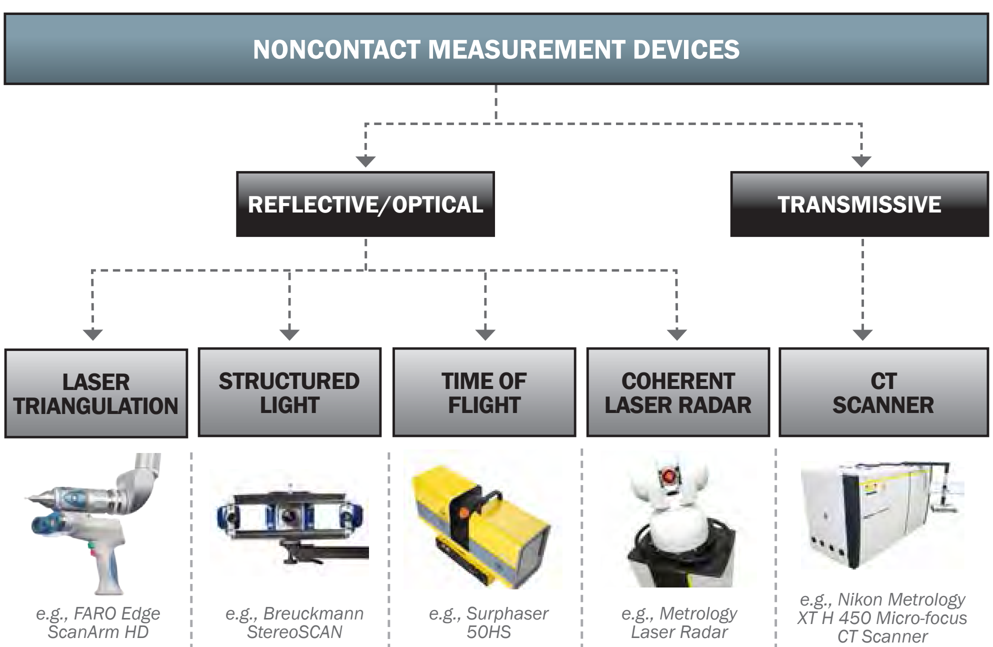


Figure 3: Classification of Noncontact Measurement Devices.

TRIANGULATION TECHNIQUES

Most laser scanners use triangulation to determine the location of points on the surface of a part. As shown in the simplified triangulation scheme in Figure 4, a laser beam is projected onto the surface of the part, and the location of this beam on the sensor, together with the known distance between the beam and sensor, is used to calculate points on the surface of the part. Laser triangulation systems may be self-contained and even hand-held for certain models and may also be mounted, in addition to or instead of a point probe, on the end of a mechanical measurement arm.

Table 2: Noncontact Measurement Devices: Typical Commercial Specifications

Technology	Company	Model	Volume	Specified Speed/Accuracy
Mechanical measurement arm hybrid	FARO Technologies, Inc.	Faro Edge ScanArm HD	8 ft to 12 ft per setup. Much larger volume with reduced accuracy with multiple instrument setup using reference points	500,000 points per second /from ±0.001 inch
Structured light	Aicon 3D Systems GmbH	StereoSCAN HE (blue light/ white light)	Field of view up to 2.5 ft × 2.5 ft × 1.8 inch	16 MB per measurement (0.1 s)/from ±0.005 inch
Structured light	Mantis Vision, Ltd.	Mantis Vision F5 (infrared)	Range 1.5 ft to 15 ft	Up to 50,000 points per frame and 10 frames per second/from 0.2 inch
Time of flight (phase shift)	Basis Software	Surphaser 50HS	Range 5 ft to 300 ft	Up to 1,000,000 points per second/from 0.026 inch at 30 ft
Coherent laser radar	Nikon Metrology	MV350	Range 3 ft to 150 ft	Up to 4,000 points per second/from 0.004 inch at 30 ft
X-ray computed tomography	Nikon Metrology	XT H 450	Measurement volume for single measurement: 16 inch × 24 inch × 24 inch	Several hours for measurement/from 0.001 inch

STRUCTURED LIGHT

In structured light scanning, a visible or infrared light pattern is projected onto the part, and an image of the reflected pattern is captured on a sensor. The image, which is distorted by the contours of the part, is processed to calculate coordinates of points on the surface of the part. Structured light scanners may use various colors of light—blue is an especially popular one—which provide advantages depending on the color of the surface being measured. However, white light remains a good compromise when objects of various colors are to be measured. Additionally, structured light scanners are capable of rapid data collection and can collect either black and white or color texture information.

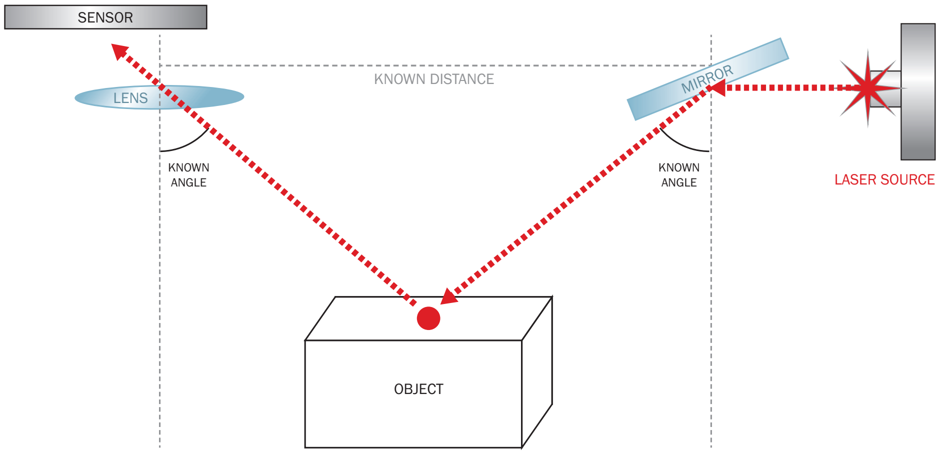


Figure 4: A Simple Laser Scanner Triangulation Configuration.

TIME-OF-FLIGHT (TOF) SCANNERS

TOF scanners effectively measure the time that a generated light pulse takes to travel to an object, bounce off of it, and return to a receiver. The distance from the scanner to the part may be calculated using the known speed of light. In practice, phase-shifting is often used in place of direct measurement of time, which also allows for a single line of sight rather than a discreet transmitter and receiver a set distance apart. TOF scanners provide an object's geometry but not its texture. These scanners are fast, suitable for the measurement of objects larger than 10 ft, and capable of medium accuracy (from about 0.02 inch).

COHERENT LASER RADAR (CLR)

CLR scanners transmit an invisible infrared laser beam to a point on the measurement surface and coherently process the reflected light. The beam passes through a reference path of a calibrated optical fiber. The two paths are combined to determine the range to the point that, when combined with angular information from two encoders, provides the position of the measured point in space. CLRs are capable of long-range (up to 150 ft) measurement and have a usable accuracy of 0.004 inch and upwards. They are relatively slow to operate but can run unattended and can successfully measure on black or reflective surfaces. In addition, CLRs provide high-quality point cloud data, virtually without small random uncertainties in the points. And CLRs can be used with certain measurement techniques to measure hard-to-access objects. For example, a CLR and a front-silvered mirror can be used to measure the underside of a vehicle or the inside of a gun barrel.

COMPUTED TOMOGRAPHY (CT)

Finally, although CT is not a portable technology, it is mentioned here because of its ability to determine internal damage of, for example, body armor. CT is an imaging procedure that uses computer-processed X-rays to produce 3-D visualizations of the inside of a part. X-rays through the part provide many cross-sectional images, which are then used to construct a 3-D image. CT scanners provide high-quality models of internal components (accuracy is from 0.001 inch) without damaging the part. Unfortunately, CT scanners are large and fixed and among the most expensive solutions.

PRACTICAL EXAMPLES OF GEOMETRIC MODELING

The particular metrology tool chosen for a project or part of a project depends on a number of factors, including:

- The accuracy required for the modeling.
- The time allocated to the data collection phase of the measurement task.
- The size of the part or vehicle to be measured.

The previously listed Tables 1 and 2 provide examples of typical contact and noncontact measurement devices that may be found in the inventory of a well-equipped metrology service provider. The characteristics and specifications of these devices (which are also given in Tables 1 and 2) thus provide the type of information metrologists and others should consider to ensure appropriate equipment selection.

The following three 3-D geometric modeling projects provide practical examples of different measurement requirements, as well as the metrology equipment needed for those projects to be successfully completed. Note that, in some cases, multiple equipment types were suitable for the work, but the final selection depended on practical considerations such as equipment availability.

Arena Test Support

The U.S. Army Research Laboratory (ARL) Weapons and Materials Research Directorate (WMRD) at Aberdeen Proving Ground, MD, required geometric modeling in support of ongoing arena test programs. These tests are typically conducted to determine the dispersion of fragmentation and collateral damage on the detonation of a missile or warhead, and metrology support was required during each of the following test phases:

- Pre-test determination of the location of the test components
- Post-test determination of the fragmentation impact locations on the array of witness panels
- Post-processing of the collected data to determine the fragmentation dispersion patterning.

Metrology data were collected with an iGPS contact measurement device, consisting of a dual-sensor vector bar and two transmitters. The following steps were required to collect and process the measurements and prepare the data for delivery:

- The location of the threat detonation, the size and shape of each panel in the arrays, and their relative positions to each other were surveyed in approximately 4 hr (see test setup in Figure 5).
- The 3-D coordinates of approximately 1,000 fragmentation locations on the witness panels arrays were collected. The iGPS's ability to quickly store and label coordinate points allowed these data to be collected in approximately 8 hr.
- A 3-D computer model of the test arena, including the array of panels, the threat location, and the dispersion pattern of the fragmentation, was generated (see Figure 6).

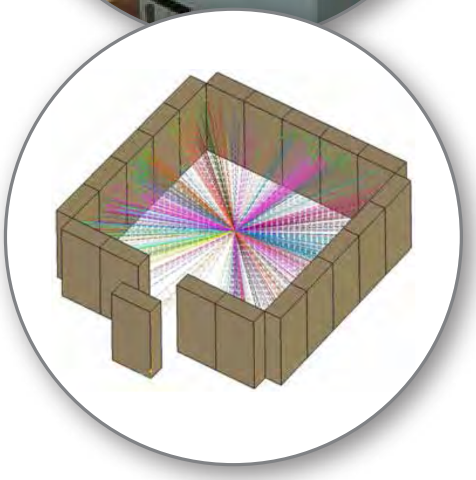


Figure 5 (top): Arena Test Setup.
Figure 6 (bottom): 3-D Model Showing Test Setup and Fragmentation Dispersion.

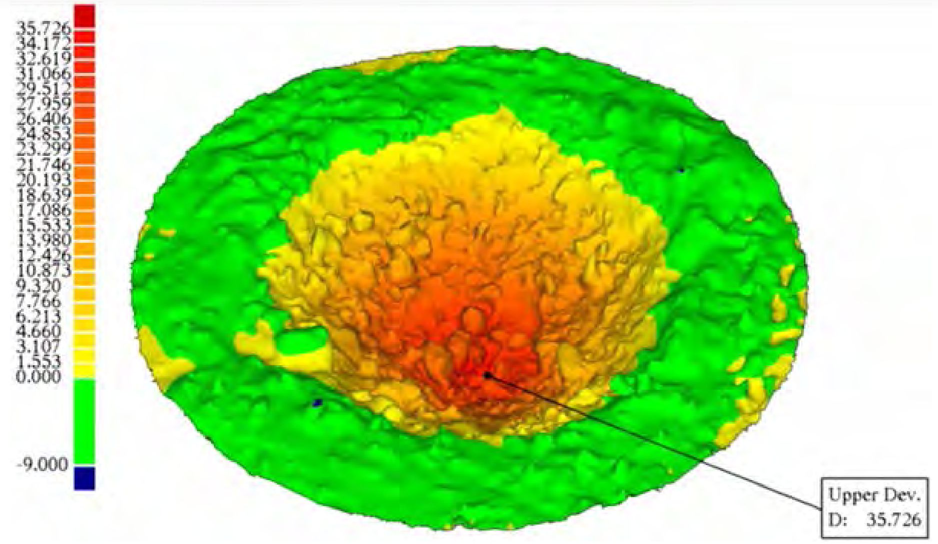


Figure 7: Crater Surface Model Deviation Plot.

Buried Blast Crater Analysis

ARL's Survivability/Lethality Analysis Directorate (SLAD), also at Aberdeen Proving Ground, MD, performs analyses of buried blast craters for battlefield forensics and for the verification and validation of predictive finite element analysis (FEA) and computational fluid dynamics (CFD) models. There were two main requirements for the measurement and modeling of these craters:

- The measurements must be accurate enough to support the forensic and computer modeling requirements.
- Field data must be captured rapidly so as not to delay the testing schedule.

The Mantis Vision F-5 was a good fit for this task. It is lightweight and stand-alone (as it is battery operated and is operated by its own tablet computer). Crater surface data can be captured in minutes, which is much quicker than with other measurement systems. In addition, the 0.2-inch accuracy easily met the test requirements. Post-processing and analysis of the large amounts of data collected did take several hours, but this time investment was regarded as a reasonable trade-off and did not impact the test schedule. The resulting surface model deviation plot is shown in Figure 7.

MRAP Cougar Modeling

The U.S. Marine Corps in Quantico, VA, required 3-D models to be created of variants of the MRAP Cougar vehicle for testing and space claim purposes. The space claim requirement of this modeling is so that adjustments can be made to the vehicles in the form of additional instrumentation, antennae, and weapon systems. The following three measurement systems were used for this task:

- The exterior of the vehicles was modeled using the iGPS system (see Figure 8).
- The interior of the vehicles was modeled using the point-probing capability of measurement arms.
- The engine and suspension were measured using the SURVICE Reverse Engineering (SRE) system, which is a customized system developed by the SURVICE Engineering Company that employs a measurement arm and specialized software, allowing for a "direct to CAD" modeling process (see Figure 9). SRE allows complex models to be built up feature by feature at the measurement site. As the metrologist has the vehicle part in front of him while the model is being constructed, errors are much less likely. It is thus possible to quickly and accurately generate highly detailed models. Data collection is admittedly slower using SRE, but little post-processing is required.

CONCLUSION

As discussed in this brief overview, many good metrology tools currently exist to facilitate effective modeling for test support. And new tools continue to appear on the market every day. As they do, careful selection and application of these devices will continue to be important in helping to ensure that measurement tasks and subsequent models successfully meet the accuracy and detail requirements for each project and that the results delivered are both timely and effective. ■

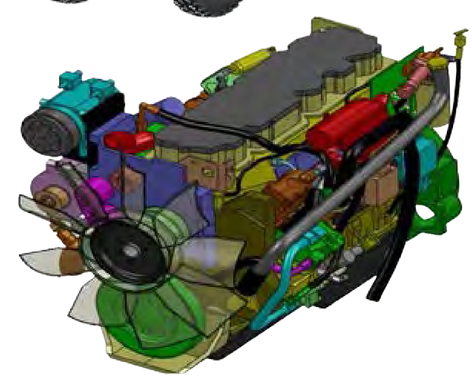


Figure 8 (top): MRAP Cougar Cat I A2 Model.
Figure 9 (bottom): Detailed Cougar Engine Model.

BIOGRAPHY

GREG ROBINSON is Deputy Manager of the SURVICE Engineering Company's Metrology Group. He has more than 20 years of experience providing metrology services to Department of Defense (DoD) and commercial customers. He has worked in the fields of hydroelectric equipment, medical equipment, and nuclear accelerators; and he has managed Small Business Technology Transfer (STTR) and Small Business Innovation Research (SBIR) programs for the DoD and U.S. Air Force. Mr. Robinson has a B.S. in Land Surveying from the University of Natal, South Africa, and an M.S. in Geomatics from the University of New Brunswick, Canada.

MICKEY HARDIN is currently a senior metrologist and Engineering Measurements Team Lead of the SURVICE Engineering Company's Metrology Group. He has 22 years of experience in reverse engineering, scanning, surfacing, and computer-aided design (CAD) modeling applications for DoD and commercial applications. Mr. Hardin's experience includes using numerous contact and noncontact 3-D measurement devices, CAD software, and evaluation and inspection software.

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*See page 15 for explanation ▸

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Mechanical Design Reliability Instructor

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DSIAC is pleased to announce the Fall 2015 Open Training from 15 to 17 September in San Diego, CA. Held at the San Diego Training and Conference Center, this year's schedule will include three of DSIAC's featured courses:

- Mechanical Design Reliability
- Weibull Analysis
- Reliability 101.

You may purchase seats for any one of these courses by visiting the DSIAC Store, clicking on 2015 Open Training, and selecting the course you wish to purchase.

SCANNING UNDERWATER WITH SMALLER LIDARS AND UAVS

By Rick Robinson

Bathymetric lidars, which are devices that employ powerful lasers to scan beneath the water's surface, are used today primarily to map coastal waters. Unfortunately, at nearly 600 lbs, the systems are large and heavy, requiring costly piloted aircraft to carry them. But that situation may be changing. A team at the Georgia Tech Research Institute (GTRI) has designed a new approach that could lead to bathymetric lidars that are much smaller and more efficient than the current full-size systems. The new technology—

called Active Electro-Optical Intelligence, Surveillance, and Reconnaissance (AEO-ISR)—would allow modest-sized unmanned aerial vehicles (UAVs) to carry bathymetric lidars, which could lower costs substantially.

Furthermore, unlike current bathymetric systems, AEO-ISR technology is designed to gather and transmit data in real time, allowing systems to produce high-resolution three-dimensional (3-D) undersea imagery with greater speed, accuracy, and usability. Together, these advanced capabilities could support a wide range of military uses, such as anti-mine and anti-submarine intelligence and nautical charting, as well as civilian mapping tasks. In addition, the new technique could enable bathymetric lidar to probe not only maritime zones but forested areas as well.

"Lidar has completely revolutionized the way that ISR is done in the military, and also the way that precision mapping is done in the commercial world," said principal research scientist Grady Tuell. "GTRI has extensive experience in atmospheric lidar going back 30 years, and we're now bringing that knowledge to bear on a growing need for small, real-time bathymetric lidar systems."

Tuell and his team have developed the Pathfinder Lidar, a prototype that has successfully demonstrated AEO-ISR techniques in the laboratory. The team has also completed a preliminary design for a deployable mid-size bathymetric device that is less than half the size and weight of current systems and requires half the electric power.

MEASURING LASER LIGHT

To simulate the movement of an actual aircraft, the Pathfinder prototype must be "flown" over a laboratory pool. To do this, the researchers have installed the lidar onto a gantry above a large water tank in Georgia Tech's Mechanical Engineering Department and operate it in a manner that simulates flight (see Figure 1).

The Pathfinder uses a special green laser (shown in Figure 2) that can penetrate water to considerable depths. Firing a laser beam every 10,000th of a second, the proxy aircraft allows the team to study the best methods for producing accurate images of objects on the floor of the pool. The ultimate goal is to obtain accurate reflectance from the sea floor, but the presence of water makes that difficult. To capture good images, the Pathfinder must make a series of adjustments that let it measure reflected laser beams as if there were no water present.

One challenge is that when a tightly focused light beam, such as a laser, hits water, it loses speed and bends, which is a familiar underwater effect called refraction. Due to changes in the water surface, the angle of refraction varies constantly, and these changes in the refracted angle must be accounted for when computing the path of the light.

> The ultimate product of a bathymetric lidar is a 3-D point cloud that describes the seafloor at high spatial resolution.

Another challenge is that the photons in the laser beam scatter in the water, like light from a car headlight hitting fog. The amount of this scattering depends on the water's turbidity, which refers to the number of particles suspended in it. In addition, the water absorbs some of the light.

Figure 1: The GTRI Lightweight Lidar Prototype Gantry-Mounted Over a Laboratory Water Tank.

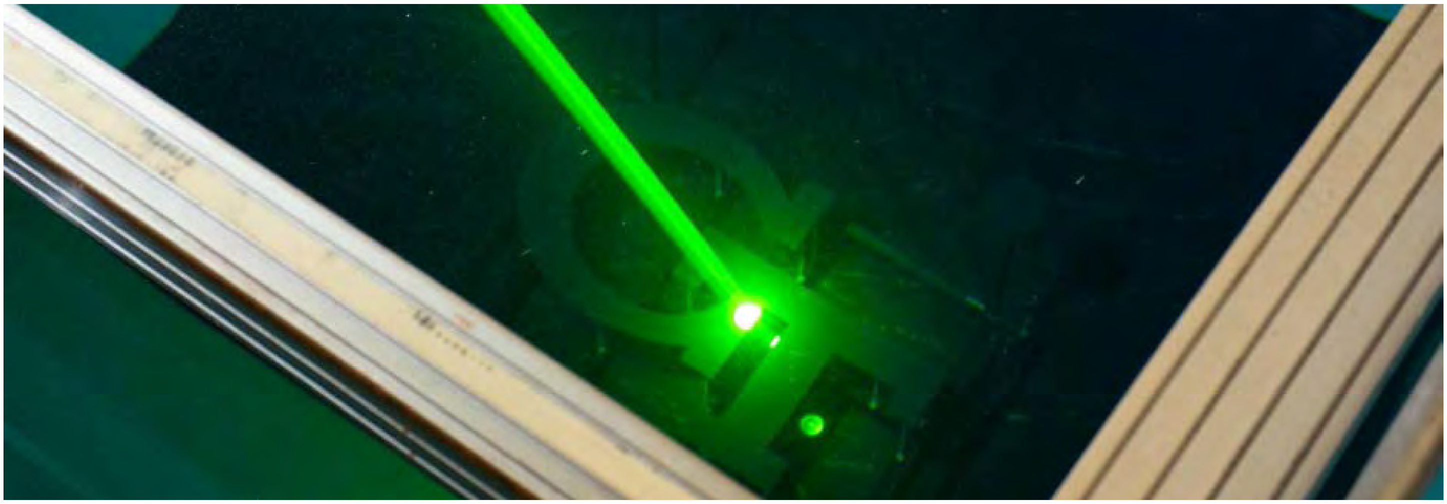

Figure 2: The Special Green Laser of GTRI Lightweight Lidar Prototype System Used to Penetrate Water and Help Researchers Study the Best Methods for Producing Accurate Images of Objects on the Pool Floor.

Because of these two effects, a lidar system receives back only a tiny signal when its laser beam bounces off an underwater surface, such as the sea floor. The Pathfinder's signal-conditioning and sensor-processing capabilities must be sophisticated enough to detect that small returning signal in an overall sea and air environment that is extremely "noisy" (i.e., the environment is filled with extraneous signals that interfere with the desired data).

IMPROVING CRITICAL TECHNIQUES

The ultimate product of a bathymetric lidar is a 3-D point cloud that describes the seafloor at high spatial resolution. Users of these data need to know the accuracy of each point. GTRI's researchers have devised a new approach for accuracy assessment called total propagated uncertainty (TPU). Using statistics, calculus, and linear algebra, the TPU technique propagates errors from the individual measurements—navigation, distance, refraction angle—to estimate the accuracy of sea-floor measurements.

In a major milestone, the GTRI team was the first to demonstrate bathymetric lidar coordinate computation and TPU estimates in real time. To achieve the necessary processing speed, the team employs a mixed-mode computing environment composed of field-programmable gate arrays (FPGAs), along with central-processing and graphics-processing units. The team has also produced the first hybrid lidar combining a waveform-resolved linear mode green lidar with an infrared geiger mode lidar. This hybrid lidar enables precise beam steering through the water surface to improve the accuracy and fidelity of 3-D images of the seafloor.

Each time a laser is fired, it takes only a few nanoseconds for the beam to reach the bottom of the pool and bounce back. Once the beam returns, the Pathfinder's high-speed computer needs only an additional nanosecond to digitize the returned beam and convert the analog light signal containing floor-reflectance points into digital location coordinates, from which distance and other information can be computed.

"In our laboratory tests," Tuell said, "we're computing about 37 million points per second, which is exceptionally fast for a lidar system and gives us a great deal of information about the sea floor in a very short period of time. The key is we're using FPGAs to do the necessary signal conditioning and signal processing, and we're doing it at exactly the time that we convert from an analog signal to a digital signal."

A DEPLOYABLE DESIGN

In addition to developing the proof-of-concept Pathfinder prototype, the GTRI team has produced a computer-aided design (CAD) for a deployable bathymetric device that is half the size and weight of current devices and has lower power needs. The immediate goal is to field such a mid-size device on a larger UAV, such as an autonomous helicopter.

The longer-term aim is to use AEO-ISR technology to develop bathymetric lidars that could fly on small UAVs with payloads of 30 lbs or less. To help these lidars deliver maritime surveillance and mapping data in real time, most of the necessary signal processing would be performed on the aircraft and only essential data would be transmitted to ground stations.

"We've provided a prototype that demonstrates the key technology," Tuell said, "and we've completed a design for a mid-size design. In the future, we believe small bathymetric lidars will perform military tasks, and also civilian geographic tasks such as county-level mapping, with increased convenience and at greatly reduced cost."

BIOGRAPHY

RICK ROBINSON has worked for Georgia Tech since 1994. With 32 years of journalism experience, he is currently a science writer for the Georgia Tech Research News Office, covering technical areas such as electronics/optics, materials, and national security.

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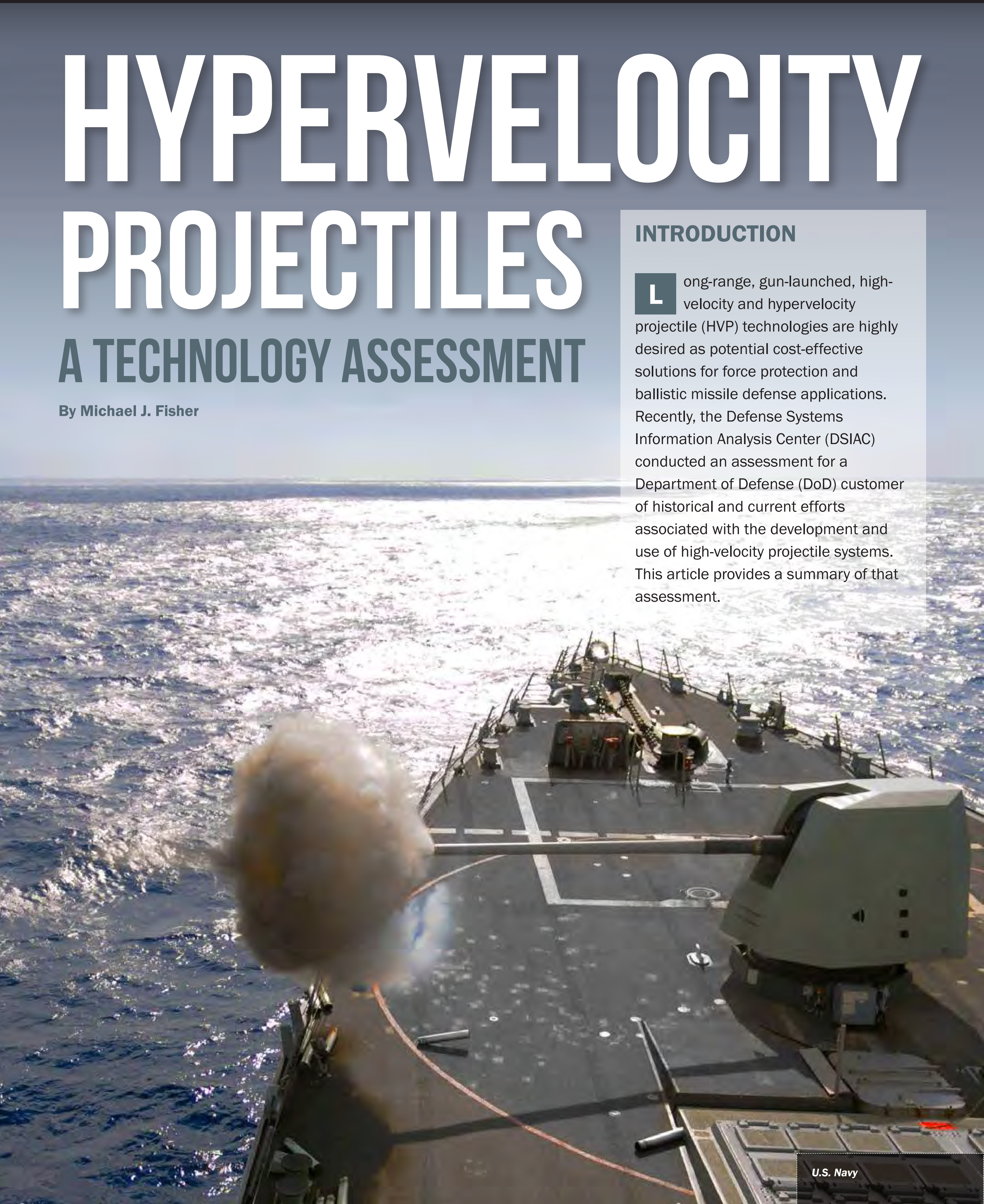
HYPERVELOCITY PROJECTILES

A TECHNOLOGY ASSESSMENT

By Michael J. Fisher



U.S. Navy

INTRODUCTION

Long-range, gun-launched, high-velocity and hypervelocity projectile (HVP) technologies are highly desired as potential cost-effective solutions for force protection and ballistic missile defense applications. Recently, the Defense Systems Information Analysis Center (DSIAC) conducted an assessment for a Department of Defense (DoD) customer of historical and current efforts associated with the development and use of high-velocity projectile systems. This article provides a summary of that assessment.

ASSUMPTIONS, DEFINITIONS, AND SCOPE OF RESEARCH

To begin, it is necessary to understand what exactly is meant by the term "hypervelocity." The *Dictionary of United States Army Terms* defines the term as [1]:

- Muzzle velocities of an artillery projectile of 3,500 ft/s or greater.
- Muzzle velocities of tank cannon projectiles in excess of 3,350 ft/s.

For this study, DSIAC assumed "hypervelocity" refers to gun-launched munition systems with muzzle velocities exceeding 3,500 ft/s. Other assumptions and/or qualifiers are as follows:

- While the focus of this assessment largely considers mobile land-based and sea-based systems, other technologies are also included for comparison and completeness.
- The literature search emphasizes development activities of the previous 10 years, to focus results on recent and ongoing research efforts.
- Search resources include the Defense Technical Information Center (DTIC), Chemical Propulsion Information Analysis Center (CPIAC) Propulsion Information Retrieval System (PIRS), Internet resources, and personal communications with subject-matter experts.

TECHNOLOGY OVERVIEW

Limitations of Current Technology

Most gun technologies can be placed into one of the following four main categories:

1. Chemical guns (propellant-based)
2. Light gas guns
3. Electromagnetic (EM) guns (confined magnetic fields)
4. Electrothermal (ET) guns (electrical source external to the gun).

For a conventional solid-propellant (chemical) gun, the constraining factors on performance in terms of muzzle velocity are chamber volume, gun strength, tube length, and the combustion characteristics of the propellant. The gun chamber volume limits the amount of propellant and hence the total available energy; gun strength limits the pressures at which the gun can operate; and tube length affects the expansion ratio. Finally, the burning characteristics of the propellant determine the pressure profiles in the gun.

Due to nonideal effects, such as projectile friction, viscous drag, and heat loss to the wall, the performance of an idealized gun is not generally achieved. However, the parameters that control the performance of any chemical combustion gun are similar. The pressure transmitted from the combustion chamber to the projectile base is largely controlled by the combustion gas sound speed and ratio of specific heats.

Challenges

A number of promising technologies have been, and continue to be, studied to overcome the limitations of current chemical combustion-driven projectile launch systems. Although a great deal of progress has been made, the following are several technical challenges that have plagued these advanced systems. Overcoming these challenges will be key to the eventual implementation of any of the technologies reviewed in this article.

Developing cost-effective, compact, lightweight, and efficient pulsed power is one of the most critical challenges faced.

Barrel Wear. Just as conventional gun barrels experience wear with use, EM railgun barrels are not immune to damage, with the leading causes being attributed to the following:

1. Arc transition and excessive heating of the rail/armature interface in the breech area of the gun, where projectile velocity is low.
2. Hypervelocity gouging of rails by the passage of the armature.
3. Erosion of rails near the muzzle due to failure to maintain galvanic contact between the rails and armature.

High G Loads. The extreme g-loading experienced by projectiles requires new materials and design techniques, particularly with regard to electronic components and solid-propellant rocket motors (both case and propellant) for extended-range munitions.

Power Supplies. Many hypervelocity concepts require extremely high levels of pulsed-electrical power for their operation. Compact pulsed power supplies for volume-constrained systems continue to be a challenge, although advancements have been made. Developing cost-effective, compact, lightweight, and efficient pulsed power is one of the most critical challenges faced. High energy-density capacitor development is another area of technological challenge for these systems.

EM GUN SYSTEMS

EM Gun. EM guns fall into two basic classes: railguns and coilguns. These guns differ in the geometry of achieving confined magnetic fields and of coupling the resultant forces to achieve projectile acceleration. As a rule, railguns are conceptually and geometrically simpler than coilguns and have lower impedance (i.e., they require higher current and lower voltage for a specific propulsion task). In addition, railguns have received far more developmental attention, even despite the potential for greater energy efficiency that coilguns provide [2].

Railgun. The EM railgun is a long-range weapon that fires projectiles using an electrically induced magnetic field instead of chemical propellants. As illustrated in Figure 1, magnetic fields created by high electrical currents accelerate a sliding metal conductor, or armature, between two rails to launch projectiles at 4,500 to 5,600 mph. In the naval design, electricity generated by the ship is stored over several seconds in the pulsed power system. Next, an electric pulse is sent to the railgun, creating an EM force accelerating the projectile to Mach 7.5 [3].

Experimental velocities of 7.2 km/s (23,620 ft/s) with 10% efficiency have been demonstrated for the electric light-gas gun. In theory, the gun should reach velocities in excess of 8 km/s.

Coilgun. As with railguns, coilguns also use magnetic forces to accelerate the projectile. However, in a coilgun, these forces are applied inductively and impulsively in a series of distributed coils along the length of the barrel. Coilguns consist of stationary solenoid coils (stators), which create a magnetic field for propelling a moving coil (armature). On paper, these guns seem to overcome many of the disadvantages of railguns. The coilgun requires no sliding contacts, and the muzzle arc frequently seen on railguns is absent. More importantly, a coilgun, being a many-turned device, can have considerably higher inductance than railguns. This fact makes matching to a power supply more convenient [5]. However, large coilguns theoretically require extremely high voltage operation and extremely fast switching.

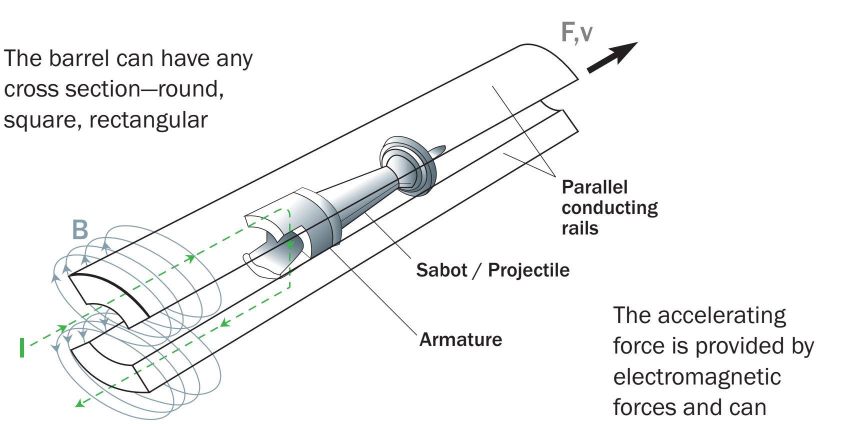


Figure 1: The Operation of an EM Railgun [4].

ELECTRICALLY OPERATED GUN SYSTEMS

Electric Light-Gas Gun. This gun should not be confused with a two- or three-stage light-gas gun. The only common element is the use of a light gas such as hydrogen. This gun is an extremely high-velocity gun-launch technology. Experimental velocities of 7.2 km/s (23,620 ft/s) with 10% efficiency have been demonstrated for the electric light-gas gun. In theory, this gun should reach velocities in excess of 8 km/s.

Electrothermal (ET) Gun. The ET gun, or electrothermal accelerator, is a propulsion concept in which all or a portion of the energy used to accelerate the projectile is provided by an electrical source that is external to the gun breech. The "pure" form of ET propulsion (as opposed to variations, such as electrothermal chemical) involves the use of electrical energy to create high-temperature plasma, which mixes with and vaporizes an inert working fluid to generate the high-pressure gas needed to accelerate a projectile.

A complete ET gun system comprises four major components. The first component consists of the necessary equipment for generation and storage of the required electrical power. A capillary is then required through which the electrical current (energy) flows, creating a plasma of low mass but extremely high pressure and temperature. This plasma passes into the third component, the combustion chamber, in which the plasma interacts with a working fluid, producing gases that accelerate the projectile through the final component of the system: the gun tube.

An ET gun is limited by similar constraints as those faced by chemical propellant guns. Because an ET gun relies on combustion gases to accelerate the projectile as in a conventional gun, gun strength and tube length will have the same limiting effect as in a solid propellant gun system. The rate and magnitude of the electrical energy input, in combination with the thermochemical properties of the working fluid, determine the pressurization rate and pressure profiles in the gun.

However, the ET gun differs from a conventional solid propellant gun in that chamber volume no longer represents a limitation on the total amount of energy available to the system. In theory, the electrical energy source is capable of providing unlimited energy. However, from an operational point of view, the maximum operating gun temperature limits the amount of energy that can be introduced into the system. In fact, thermal management for an ET gun may be more difficult than for conventional gun systems. For the conventional gun, the overall temperature is bounded by the propellant flame temperature.

Even if the rate of energy input increases due to an increase in the burning rate of the propellant, the maximum gun temperature is still limited to the flame temperature of the propellant. For an ET gun, there is no upper limit on gas temperature. The temperature of the gases resulting from the interaction of the electrically created plasma and working fluid is an increasing function of the amount of electrical energy being transmitted to a unit mass of the working fluid. Thus, temperature limitation results only through controlling the magnitude and rate of electrical energy input in combination with the mass and properties of the working fluid [6].

By using an external power supply to create propellant pressure, ET guns are not bound by the limitations of conventional propellants; energies and velocities can be as high as the structure of the gun will allow [7].

Electrothermal Chemical (ETC) Gun. ETC propulsion is an alternative to conventional methods of firing large-caliber cannon ammunition. In conventional ignition, a relatively low-powered electrical discharge sets off a primer cap that burns a small powder charge within an ignition cartridge, in turn triggering the combustion of surrounding chemical propellant in the round. This sequence of cascaded chemical reactions can take as long as 30 ms to effect projectile motion, with a significant variation in launch times. Consequently, accuracy, particularly when the gun barrel is vibrating due to vehicle motion, is detrimentally affected.

In ETC gun ignition, however, the conventional ignition components are replaced with a plasma injector (as illustrated in Figure 2). The plasma injector houses a bridge wire attached between two electrodes. When a high-current, high-voltage pulse is applied, the bridge wire initiates a high-temperature plasma discharge that vents into the surrounding chemical propellant. The electrically conductive plasma transfers energy into the propellant, initiating its combustion much more quickly and repeatably than does conventional ignition [8].

The ETC gun, which is sometimes called a hybrid gun, is a variation of the ET gun and has demonstrated the same velocity and barrel erosion effects as the ET gun. The main difference between ETC and ET guns is that smaller amounts of electrical energy are required for ETC guns. As the electrical energy is reduced, solid propellants are added; thus, smaller electrical power supplies are needed.

Electrothermal Ignition (ETI) Gun. The term "electrothermal ignition" is sometimes used to refer to ETC at energy levels of less than 100 kJ. ETI provides the same benefits as higher energy ETC, with the exception of thermal compensation for certain propellants, for which levels of 300 kJ or

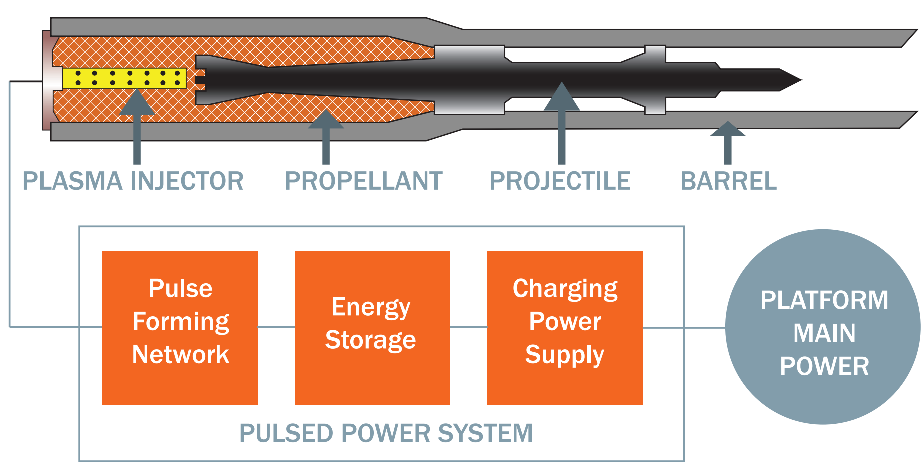


Figure 2: The Basic ETC Gun Concept [9].

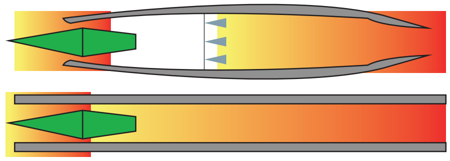
more are required. However, ETI offers precision ignition in a smaller and lighter package, suitable for vehicle integration [8].

Side-Injection Gun. The side-injection gun is enhanced by the accelerating energy coming in from chambers distributed along the barrel. Several different versions of the side-injected gun using ET and electrothermal light gas gun (ELGG) technologies have been built and tested.

RAM CANNON/ RAM ACCELERATORS

The ram accelerator is not a gun in the normal sense. As illustrated in Figure 3, its basic operation is more analogous to an inverse ramjet. Instead of confining the combustion gases to a combustion chamber, which then expand to push on the projectile with an ever-decreasing base pressure, they are instead distributed throughout the entire volume of the launch tube. The projectile does not fly ahead of the propelling gases but instead flies through them, basically “surfing” on a wave of high-pressure combustion, which immediately follows the projectile down the bore.

Combustion energy is released dynamically as the projectile flies through the gas, creating a localized region of high pressure immediately behind the projectile, which travels along with the projectile. The gas expends no energy accelerating itself, which thus increases efficiency dramatically and locates the high pressure exactly where it is needed, right behind the projectile, instead of far back in a combustion chamber (as illustrated in Figure 4). Accordingly, traditional gun limitations no longer apply, and velocities in excess of 10 km/s are theoretically possible.



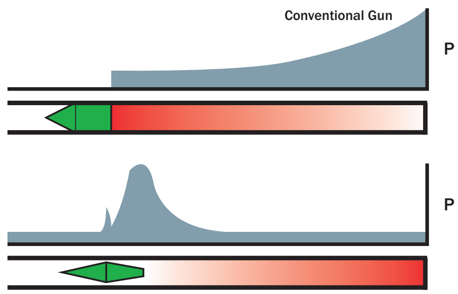


Figure 3 (top): Ram Acceleration Process: Ramjet (upper); Ram Accelerator (lower).
Figure 4 (bottom): Pressure Profile of Ram Accelerator (lower) Compared to Exponentially Decaying Profile of Conventional Gun (upper) [10].

GAS GUNS

Two-Stage Light Gas Gun (LGG). The two-stage LGG has achieved the highest demonstrated performance to date and has been the standard workhorse for high-velocity experiments for decades. A heavy piston is accelerated in the first stage pump tube by a conventional powder charge or combustion of light gases. This piston then adiabatically compresses a light gas, usually hydrogen restrained by a diaphragm at the beginning of the second stage, which also contains the projectile and barrel. When the compressed hydrogen reaches a threshold value, the diaphragm bursts and the hot, high-pressure hydrogen accelerates the projectile down the barrel. At 7 km/s and greater, such a system is only a few percent efficient and imparts an extremely high initial acceleration to the projectile. Size and barrel design/life issues have precluded the consideration of LGG for weaponization.

Electrothermal Light Gas Gun (ELGG). The ELGG has achieved performance close to that of a conventional LGG and has the potential to exceed it. This gun, which is scalable to large bore sizes, replaces the pump tube structure of the LGG with an electrical power supply. The ELGG uses an electrothermal chamber that is first pressurized prior to a shot with high-pressure hydrogen at about room temperature. A high-powered electric arc pulse is then initiated over the axial length of the chamber, resistively heating the hydrogen and thereby driving the pressure to several kilobars, which bursts a diaphragm and propels the projectile. The peak pressure reached in the chamber depends on the preshot fill pressure, electrical pulse time, projectile mass, and diaphragm burst pressure. In some cases, the prefill hydrogen pressure makes an important energy contribution to the chamber, thereby reducing the electrical energy requirement.

Combustion Light Gas Gun (CLGG) [11]. As shown in Figure 5, the CLGG consists, in its simplest configuration, of a chamber sealed with a diaphragm and filled with a combustible mix of light gaseous propellants such as methane, hydrogen, oxygen, and helium, in various combinations. Prefill pressures can range from a few thousand psi up to 20 kpsi or more. The helium (and hydrogen) acts as a diluent to lower the average molecular weight of the gas. The mixture is ignited using a specially designed ignition system. As the combustion pressure rises, the diaphragm bursts or shears, allowing

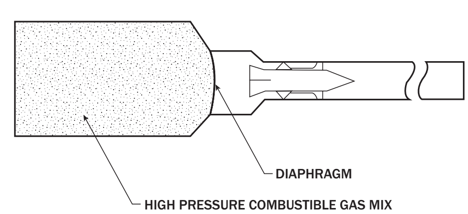


Figure 5: Basic CLGG Concept [10].

the projectile to accelerate down bore propelled by the high-pressure, *light* combustion gases. Note that at 20 kpsi, these gases are near cryogenic liquid density, even though still at room temperature, which is an important factor in generating high pressure at moderate temperature, thus lengthening barrel life.

Single-stage LGGs, by using propellants with low molecular weight, achieve much higher sound speed for a given temperature and are able to achieve considerably higher performance (as shown in Figure 6). In physical terms, the pressures produced in the "combustion" chamber of the LGG are transmitted much more efficiently to the projectile base as the projectile accelerates down bore [10].

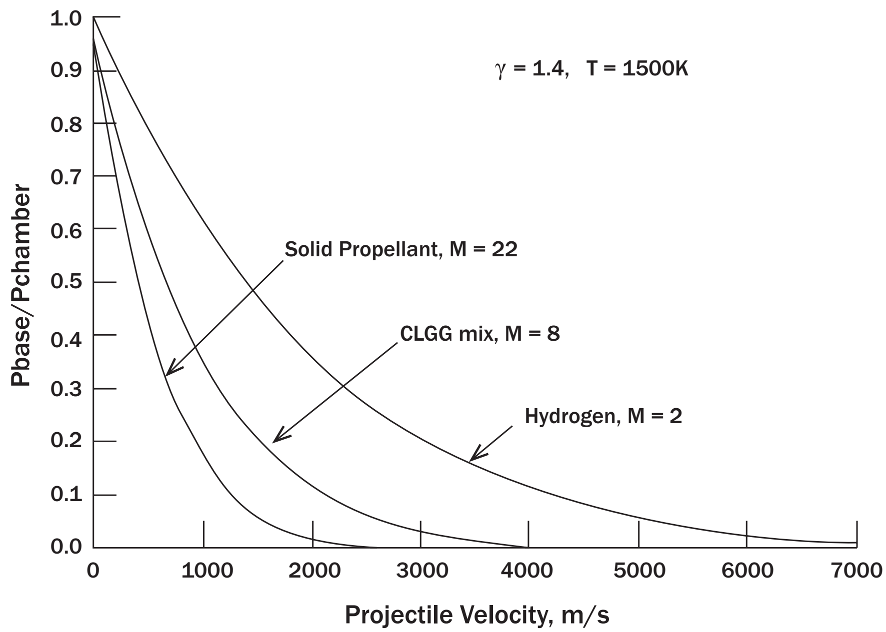


Figure 6: Low Molecular Weight Gases Providing Higher Velocities Than Solid Propellants [10].

EXTENDED RANGE MUNITIONS (ERMs)

ERMs are munitions that are rocket-boosted and use a global positioning system (GPS) guidance system, as opposed to long-range projectiles, which receive all of their kinetic energy in the gun barrel and have no guidance systems. In general, all ERMs operate similarly. The projectile is fired out of a gun, providing its initial kinetic energy. A short time after exiting the gun barrel, the projectile's stabilizing fins deploy and a solid propellant rocket motor ignites, providing additional boost. As the round flies to its apogee, its guidance package activates and searches for GPS satellites while its steering canards deploy. Once the round reaches apogee and has acquired a GPS signal, its guidance system uses the fins and canards to fly or glide the round directly to its target. The Extended Range Guided Munition (ERGM), Ballistic Trajectory Extended-Range Munition (BTERM), and Long-Range Land Attack Projectile (LRLAP) are all examples of ERMs.

ROCKET-ASSISTED PROJECTILES (RAPs)

RAPs are specially equipped projectiles with their own source of power in the form of a built-in rocket motor. Such a rocket motor is usually rigidly affixed to the projectile with gas evolved from an ignited propellant, providing additional propulsive force. Ignition of the rocket motor can be accomplished after leaving the gun barrel with a suitably designed ignition system contained within the casing, or ignition can be accomplished by means of the high-temperature gases from the launching charge in the gun barrel.

RAPs provide an incremental improvement in projectile range. For example, General Dynamics' 155-mm M549A1 HE-RAP extends the range of the standard round from 19.5 km to 30.1 km, a range extension of 54%.

RECENT RESEARCH EFFORTS

Gun System Developments

Advanced Gun System (AGS). The Zumwalt-class's two AGSs are each expected to fire up to 10 rounds per minute, using an automated magazine. As illustrated in Figure 7, the 304-round magazine has to organize and process ammunition and propellant charges from up to 38 pallets. Each pallet holds eight propelling charges and eight of the 230-lb, GPS-guided 155-mm LRLAP shells. The gun can load and fire up to 10 rounds per minute. The AGS ammunition is equivalent to the U.S. Marine Corps (USMC) M198 155-mm howitzer in firepower, and its GPS/Inertial Navigation System (INS)-guided LRLAP is capable of hitting targets accurately up to a distance of 70 to 100 nmi. This performance represents significant improvement over the current 13-nmi range of existing 127-mm/5-inch guns [12].

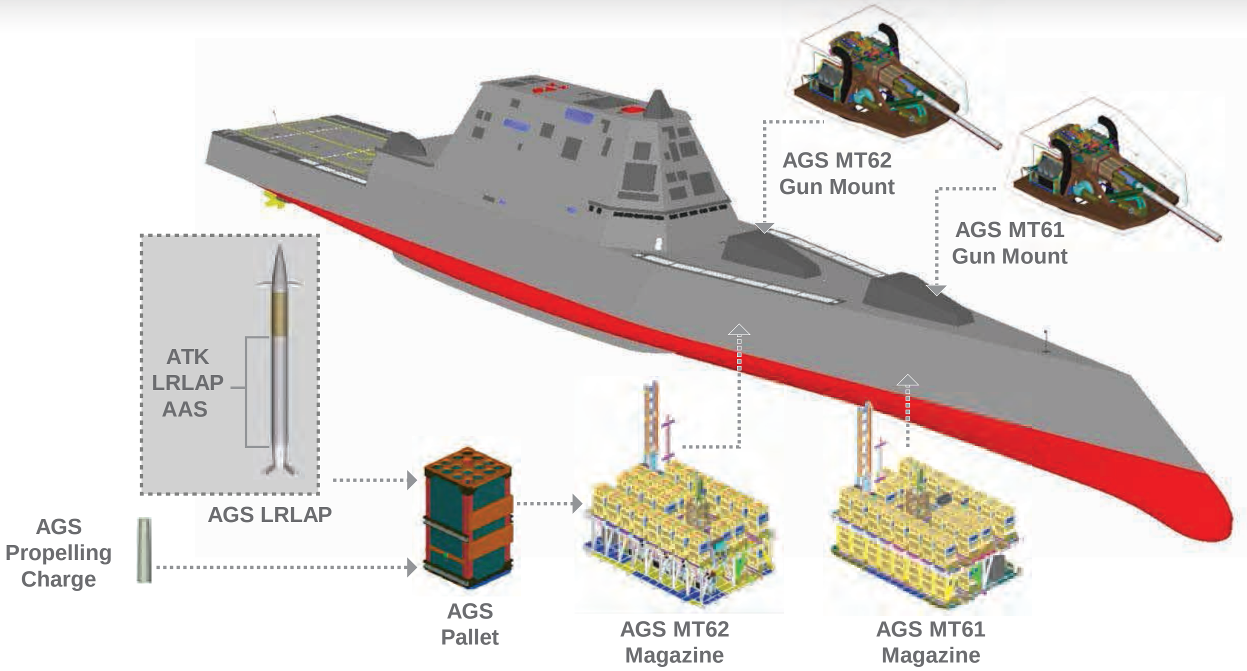


Figure 7: AGS Element Overview [13].

Office of Naval Research (ONR) EMRG. The EMRG Innovative Naval Prototype (INP) was initiated in 2005. The goal during Phase I was a proof-of-concept demonstration at 32 MJ of muzzle energy, which has been achieved. A future weapon system at this energy level would be capable of launching a projectile 100 nmi.

Phase I was focused on the development of launcher technology with adequate service life, development of reliable pulsed power technology, and component risk reduction for the projectile. Phase II, which started in 2012, will advance the technology for transition to an acquisition program. Efforts will concentrate on demonstrating a rep-rate fire capability. Thermal management techniques required for sustained firing rates will be developed for both the launcher system and the pulsed-power system.

Using its extreme speed on impact, the kinetic energy warhead eliminates the hazards of high explosives in the ship and unexploded ordnance on the battlefield. With its increased velocity and extended range, the EMRG will give personnel a multi-mission capability, allowing them to conduct precise naval surface fire support or land strikes, ship defense, and surface warfare to deter enemy vessels. Navy planners are targeting a 50- to 100-nmi initial capability. A variety of new and existing naval platforms, including the DDG 1000 and DDG 51, are being studied for integration of a future tactical railgun system [14].

The Navy has contracted for and tested two railguns: one built by BAE Systems (see Figure 8) and one built by General Atomics. Both will be put to sea in 2016 for demonstration, but the Navy will choose just one for final testing.

The EMRG's projectiles have several advantages over the current ERMs in that these projectiles will be smaller, have greater range, and will not require propellants or explosive warheads, which will make the projectiles easier to store and increase the ship's capacity. It is estimated that a railgun magazine might hold as many as 10,000 rounds using the same 600-round magazine capacity of the AGS.

CLGG. UTRON first developed a 15-mm CLGG, which successfully proved the concept, and then designed and built a 45-mm CLGG, which successfully proved the scalability of the concept [15]. UTRON's 45-mm CLGG has fired with projectile speeds of 2.5 km/s. In addition, an automatic loader has been developed, installed, and successfully operated. A special fuel-loading system and ignition device have also been successfully developed and deployed. The light-gas propellant mixture can be manufactured on the battlefield.

UTRON then developed and built the 155-mm CLGG that was successfully fired at its gun range in West Virginia. The CLGG has experimentally demonstrated velocities greater than 4 km/s (13,120 ft/s). In some tests, it has demonstrated a muzzle energy

Figure 8: BAE Systems EMRG.

increase of 400% when compared to guns with conventional powder propellants. The UTRON CLGG used no large external electrical power supply or conventional powder propellants. It achieved its performance by combusting light gases. Figure 9 illustrates a notional concept for implementing a CLGG and gas production system for a Navy ship. One of the benefits of the CLGG was that it also provided longer barrel life. The UTRON CLGG was designed to fire projectiles to ranges approaching 200 nmi, providing substantial advantages over the current 20-nmi range achievable with traditional powder propellant guns [16].

Line-of-Sight (LOS)/Beyond-Line-of-Sight (BLOS) ETC Launcher. The LOS/BLOS ETC launcher program, funded by the U.S. Army Armament Research, Development, and Engineering Center (ARDEC) at Picatinny Arsenal, NJ, was a comprehensive effort to advance ETC launcher technologies. Objectives of the program were to develop ETC plasma injectors for 120-mm M829A2s, and a 100-kJ pulsed power supply that is small and robust enough to be realistically integrated into a combat vehicle. The program also included the improvement of power connections to the gun to allow electromagnetic field containment and automated connection to the round, as well as tests of the completed ETC system with various chemical propellants and electrical energy levels.

Projectile and Munition Developments

ONR HVP. The HVP is a next-generation, common, low-drag, guided projectile capable of completing multiple missions for gun systems such as the Navy 5-inch, 155-mm, and future railguns. Types of

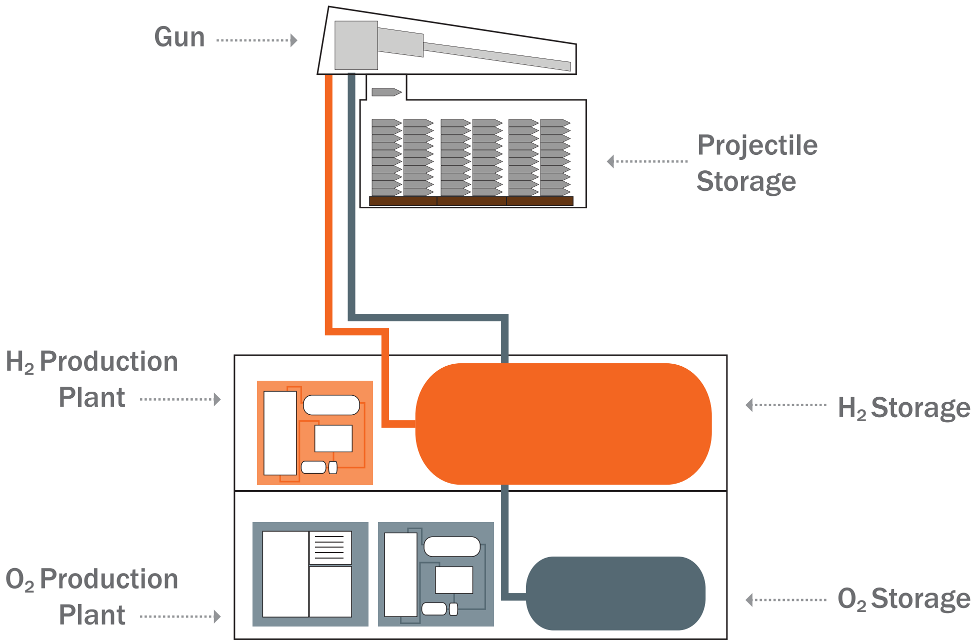


Figure 9: Shipboard Arrangement of CLGG Gas Production System [17].

missions performed will depend on the gun system and platform. The program goal is to address mission requirements in the areas of naval surface fire support, cruise missile defense, anti-surface warfare, and other future naval mission areas. Mission performance will vary from gun system, launcher, or ship. The HVP's low-drag, aerodynamic design enables high-velocity, maneuverability, and decreased time-to-target. These attributes, coupled with accurate guidance electronics, provide low-cost mission effectiveness against current threats and the ability to adapt to air and surface threats of the future.

The high-velocity compact design relieves the need for a rocket motor to extend gun range. Firing smaller, more accurate rounds improves collateral damage requirements and provides potential for deeper magazines and improved shipboard safety. Responsive, wide-area coverage can be achieved using HVPs from conventional gun systems and future railgun systems. The modular design will allow HVPs to be configured for multiple gun systems and to address different missions. The HVP is being designed to provide lethality and performance enhancements to current and future gun systems. An HVP for multiple systems will allow for future technology growth while reducing development, production, and total ownership costs [17].

Excalibur. The M982 Excalibur precision-guided, extended-range artillery shell is a fire-and-forget smart munition with better accuracy than existing 155-mm artillery rounds. These shells are fin-stabilized and are designed to glide to targets with base bleed technology, as well as with canards located at the front of the munition, which create aerodynamic lift. Although the M982 is perhaps the

Rear Adm. Matthew Klunder, Chief of Naval Research, shows off an HVP to CBS News reporter David Martin.

longest-range artillery ammunition in the U.S. arsenal, it has the ability to be fired nearly straight up from positions in cities or hilly terrain, engage its precision-guidance system at high altitudes, and detect and attack moving targets—even individual vehicles—with an accuracy of better than 65 ft from the desired aim point. The shells are guided by GPS signals and inertial measurement units and can be fired from the M109A6 Paladin self-propelled howitzer, as well as from the M198 and M777A2 towed howitzers [18].

LRLAP. The LRLAP, illustrated in Figure 10, is a 155-mm naval projectile system developed by Lockheed Martin for the next-generation DDG 1000 Zumwalt-class destroyers of the U.S. Navy. It is the Navy's longest-range projectile. The guided projectile is capable of operating in all weather conditions. It provides off-shore precision fire support, from a safe stand-off distance, to troops deployed in expeditionary assault operations conducted ashore by Marine Corps, Army, and Joint/Coalition forces [19].

LRLAP is part of a family of 155-mm projectiles designed to be fired from the AGS. Because LRLAP has three times the lethality of traditional 5-inch naval ballistic rounds, fewer rounds can produce similar or more lethal effects at less cost. To withstand the punishing gun-launch environment, LRLAP uses g-hardened electronics, including a GPS and INS, to provide a precision munition that maximizes effectiveness and minimizes collateral damage [20].

With DDG 1000 as part of a naval task force or as an independent expeditionary strike force, AGS will launch LRLAP at high velocity from over the horizon to prepare and shape the battlefield. AGS will be capable of a maximum sustained firing rate of 10 rounds per minute to deliver high-volume, 155-mm LRLAP fires at ranges of up to 74 nmi. Each DDG 1000 can mass 140 to 160 projectiles in the air at once and direct multiple-round, simultaneous impact effects against single or multiple targets [21].

Early development of the LRLAP rocket motor proved difficult until lessons learned from previous rocket-assisted, gun-launched systems were

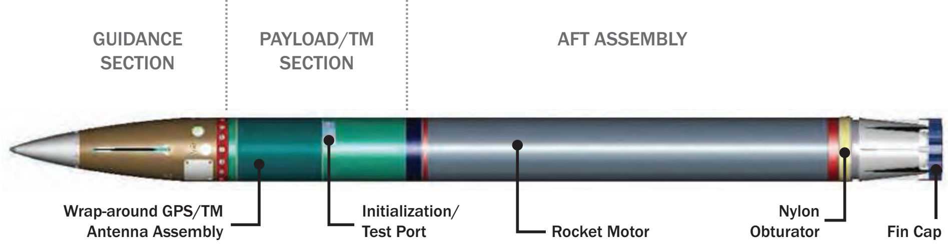
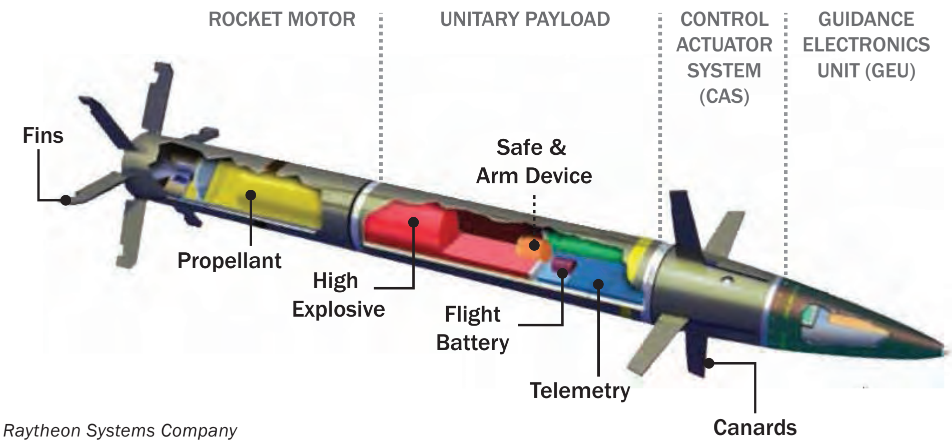


Figure 10: LRLAP Components [13].

incorporated. In addition, since the design was larger than earlier rocket-assisted, gun-launched projectiles, the aerodynamic control surface design required an iterative analysis/wind tunnel test cycle to optimize. This round has also exceeded preliminary cost estimates due to the integration of design improvements during development, but it remains within the acceptable cost target established by the Navy for the AGS.



Raytheon Systems Company

Figure 11: The ERGM.

ERGM. The EX-171 ERGM, illustrated in Figure 11, is a 5-inch diameter, precision-guided, rocket-assisted, naval gun projectile. It uses a special high-energy propelling charge intended to achieve a threshold range of 41 nmi from the MK 45 Mod 4, 5-inch/62-caliber gun. The ERGM uses a coupled GPS/INS for guidance and aerodynamic flight control surfaces to steer the projectile to the preselected impact point. The ERGM was intended to provide highly responsive naval gunfire in support of Marine Corps and Army ground combat forces operating ashore, prior to the establishment of organic fire support assets, and to supplement organic field artillery once ashore [22].

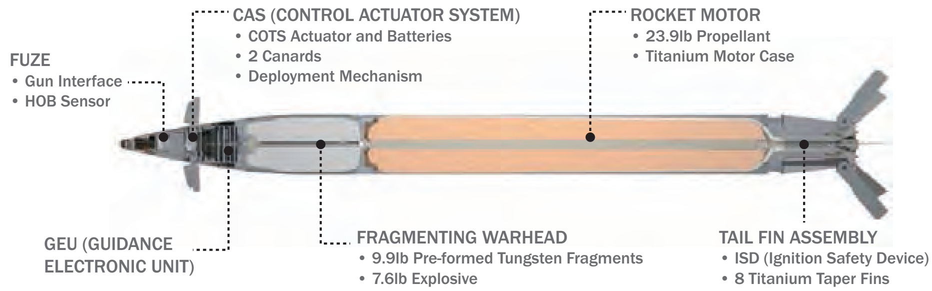
The development of the Extended Range Munition began in 1994, when the U.S. Navy contracted Raytheon to begin developing a long-range, rocket-assisted, precision-guided projectile for the MK 45 5-inch/62-caliber gun. The project eventually took on the title ERGM. After 2 years of research and development, the Engineering and Manufacturing Development phase began in July 1996 when the Navy awarded a contract to Raytheon to develop and produce ERGM or EX-171 as a "low cost" projectile capable of reaching 41 nmi.

The round is fired at a predetermined, fixed target whose location is determined prior to firing. Once the round exits the barrel, eight stabilization fins deploy. Five seconds later, the projectile's rocket motor ignites, providing the increased boost allowing it to reach a flight apogee of 75,000 to 80,000 ft. As the round travels to its flight apogee, it deploys four control canards, and its navigation system uses GPS data to correct its flight path, allowing it to reach its intended target. As it enters its glide path phase, the round uses an internal measurement unit and the GPS to "fly" or "glide" it to its intended target.

The development of ERGM technology was more difficult than expected, with multiple difficulties arising. The guidance system had to be hardened to withstand the high acceleration force of firing. The development of the canards for the projectile's aerodynamic design proved functionally and structurally unreliable. Rocket motor development was challenging due to the development of a reliable propellant grain to withstand the gun launch environment as well as the operational requirements. Also, there was a requirement for a new, longer gun barrel that was capable of handling the higher firing energy required by the ERGM [23]. In addition, due to incorporation of the technical improvements to address the development challenges, the estimated cost of this projectile significantly exceeded the "low cost" target established by the Navy. Accordingly, the program was defunded in 2008.

BTERM. Confronted with the high estimated per-round cost of the ERGM, the Navy issued a broad agency announcement for the development of alternative precision-guided munition concepts to the EX-171 ERGM in October of 2003. The Navy stated its projectile target cost of $35,000 or less per unit with a unit cost objective of $15,000. In response, ATK submitted the Autonomous Naval Support Round (ANSR) to the Navy. The program to develop this round was renamed the BTERM, illustrated in Figure 12. BTERM was developed using commercially available components and a minimum of moving parts, following a purely ballistic flight trajectory to reach its target. This design gives the BTERM projectile several advantages: it can get to its target in less time; it uses less airspace to get to the target, thus decreasing airspace deconfliction issues; and it requires fewer in-flight adjustments. In September 2003, a BTERM projectile successfully flew 100 km (54 nmi) in a flight test. However, the BTERM also had its own development problems. In June

2005, a BTERM projectile failed to reach its range objective in a test flight, and although it flew over 79 km (43 nmi), it did not reach the target. Then in October 2005, an unguided BTERM suffered a rocket engine failure [24]. The BTERM's rocket motor caused test failures that led the Navy to cancel the program and abandon plans to recompete the development contract for extended-range munitions. However, knowledge gained from both ERGM and BTERM has aided the development of later rocket-assisted, gun-launched munitions (see BTERM and ERGM trajectory comparisons in Figure 13).



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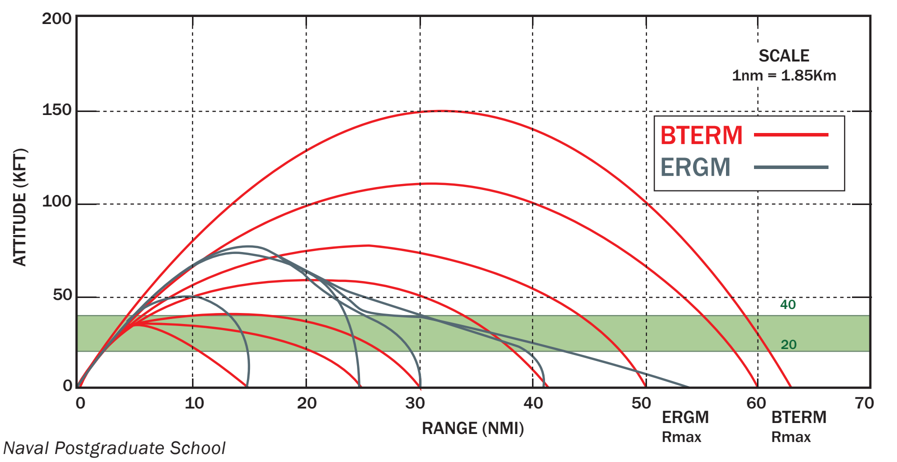


Naval Postgraduate School

Figure 12 (top): BTERM.
Figure 13 (bottom): BTERM and ERGM Trajectory Comparisons.

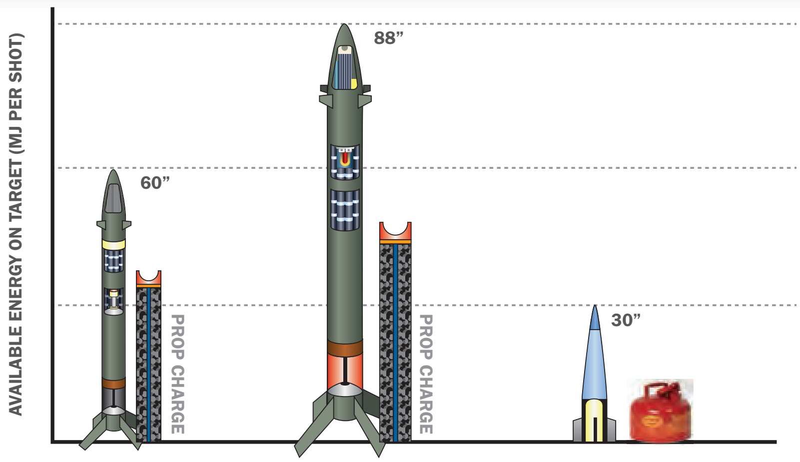
SUMMARY AND CONCLUSIONS

There have been significant technology development activities over the last 10 years in the area of gun-launched high-velocity and hypervelocity projectiles by university, industry, and government agencies. All gun technologies have had development challenges, with some providing solutions that result in technology readiness levels that would warrant taking the next steps to achieving a deployable land-based mobile platform.

Figure 14 is a comparison of the highest Technology Readiness Level (TRL) technologies, showing the various characteristics of each. As shown, the railgun provides higher energy on target at a much longer range than the ERMs. Its physical characteristics (both weight and length) lend itself to a more mobile platform application, and using electromagnetic energy in place of explosive chemical energy provides for a safer weapon application on a mobile platform. Based upon the data available for high-velocity or hypervelocity gun-launched projectile technologies, the EMRG appears to be the best approach for a sea-based and deployable, land-based mobile platform weapon, providing the required energy on target at the ranges needed. However, adapting EMRG technology to a land-based system the size of a tank may prove unachievable.

In addition, the following excerpt is a conclusion of a study conducted by the Naval Research Advisory Committee in 2004:

> *Consider the Naval Surface Fire Support (NSFS) mission, which involves primarily indirect fire. The EM gun is the only alternative to expensive missiles or Tactical Air if the Fleet is to support the Marines in Ship-to-Objective Maneuver (STOM). STOM requires ranges in excess of 135 nm. No conventional gun can achieve that range. Furthermore, the railgun offers other attractive options. It would permit gunners to select from a new range of warheads appropriate to different target or different missions—cubes for volume fire, a unitary warhead for hard target, kinetic energy kill, etc. It would also increase usable magazine capacity by 3–5 times the number of rounds over what a ship armed with AGS could carry. Railgun ammunition also offers the prospect of simpler and safer handling and storage. In direct fire applications, including missile defense, anti-ship, and asymmetrical or counter-swarm roles, the railgun should be far more effective than CIWS [close-in weapon*



TRL OPTIONS:	ERGM 7 MJ	LRLAP 14 MJ	NAVAL RAILGUN 17 MJ
OBJECTIVE RANGE:	63 nm	100 nm	220 nm
FLIGHT TIME:	6 Minutes	6+ Minutes	6 Minutes
WEIGHT:	110 lbs + 40lbs	260 lbs + 90 lbs	44 lbs + 3 gals
WARHEAD:	Explosive	Explosive	Non-Explosive

Figure 14: Comparison of Characteristics of Highest TRL Options [22].

system]in terms of projectile pattern and velocity. Railguns might be able to replace current tank main guns in the anti-armor role, and may prove to be the best answer to reactive armor. For all these applications, we find that the electric warship is the key enabler. It can provide the power and can easily accommodate the railgun's weight and volume. ***With other platforms we find that volume and weight constraints are far more severe. Meeting these constraints, and handling the thermal loads a railgun generates, in a vehicle the size of a tank presents a considerable challenge [24].***

Comparing the characteristics of various projectiles in Figure 14 illustrates that the railgun's HVP is smaller than the other rounds, so a ship (or a mobile, land-based platform) can accommodate about four times as many rounds in its magazine as it could if it were carrying conventional ammunition. The HVP delivers approximately 17 MJ to a target, and it does so from much greater ranges. The HVP is inert and so poses no explosive threat to its handlers. Hazards of electromagnetic radiation to ordnance, electrostatic discharge, fragment and bullet impact, and cook-off risks would be eliminated, and no unexploded ordnance would remain after a target was serviced. Similarly, since the railgun uses electric current as opposed to burning propellant to accelerate the projectile, no rocket motors or propellant charges would be required [24].

Under Navy and Defense Advanced Research Projects Agency (DARPA) funding, Sandia National Laboratories conducted a study to determine the applicability and maturity of coilgun technology for littoral and strategic strike missions requiring increased range and increased rate of fire on target, using rapid response, cost-effective means. Sandia's conclusion was that a coilgun system could be developed to meet this requirement, as long as technological development in several critical areas continued. The critical areas identified included high-density capacitor technology for energy storage, barrel structural integrity (mechanical strength, insulation, thermal properties), firing control at full velocity, and projectile terminal maneuvering. It is not known by the author if continued research in these areas has overcome all outstanding issues in the intervening years since Sandia's study. However, because many of the technological concerns are shared with railgun systems, we can assume that railgun research and development efforts have made major strides toward solutions for coilgun issues as well. In its study, Sandia concluded that a coilgun system designed to fit on a destroyer is feasible, for both fixed and trainable gun types, with projectile ranges and mass in the regions of interest for littoral and inland mission support. Sandia's coilgun design study found that coils can be designed to meet mission requirements of 100–300 nmi [25].

Numerous technical problems, both of a fundamental and practical nature, remain to be solved before ram acceleration becomes a serious contender in the field of tactical gun propulsion. Understanding, control, and optimization of the fluid dynamics/reaction kinetics in this environment present formidable challenges. Incorporation of this emerging technology into a practical weapon with acceptable safety, reliability, and survivability characteristics as well as performance levels offers even greater uncertainties.

Today's armed forces face challenges protecting troops and assets in littoral zones and ashore. There is a need to provide supporting fire from longer

> The EMRG appears to be the best current approach for a deployable, land-based mobile platform weapon, providing the required energy on target at the ranges needed.

stand-off ranges, delivered in less time. For example, Naval Surface Fire Support (NSFS) requires a 2–10× increase in the range achievable by conventional naval guns, which are limited to about 12 nmi. Rocket-assisted projectiles have been able to double this range, while extended-range munitions have provided ranges of 40–70 nmi. Ranges approaching and exceeding 100 nmi require a paradigm shift from conventional chemical combustion guns. This paradigm shift will be accomplished using electrically and/or electromagnetically driven projectiles fired from advanced gun systems, such as ONR's railgun. The challenge remains whether these technologies can be adapted to affordable, mobile, land-based platforms.

FOCUS OF FUNDING

The Navy continues development of the railgun system and the hypervelocity projectile (for conventional and electromagnetic gun use). The ONR Program Officer for the Hypervelocity Projectile Future Naval Capability (FNC) has verified that development is on course to meet the objective of 2016 sea trials for the railgun systems.

The Army has funded a great deal of research into EM guns over the past several decades, primarily through the Institute for Advanced Technology at the University of Texas at Austin. This research has paved the way for the current ONR program, helping to overcome many of the technological challenges faced by EM guns, including railgun bore life (gouging, arc transition, muzzle blast), novel HVP design with low parasitic mass, advanced pulse alternator technology, and high-g capable electronic components. However, the Army concluded that the railgun was not adaptable to a tank vehicle and suspended funding for EM gun development. Conversations with ONR representatives indicate that the Army is closely watching development of the ONR railgun system to determine if the technology reaches a point where some type of mobile land-based system is achievable.

FUTURE/ONGOING TECHNOLOGY DEVELOPMENT AREAS

The following are ongoing development areas:

1. Thermal protection materials
2. High-temperature-capable alloys
3. High-strength advanced composites
4. Pulsed power supplies (power, cost, size)
5. Component size reduction for mobile application
6. High-g capable components.

BIOGRAPHY

MIKE FISHER is a senior staff engineer for DSIAC, specializing in propulsion, energetic materials and weapons systems. During his 30-year career, he has provided propulsion system design and program management support to a variety of Navy weapons programs, and managed propulsion and advanced materials research and development projects for a small business. Prior to joining the DSIAC team, Mike supported both the NATO Munitions Safety Information Analysis Center (MSIAC) in Brussels, and the Chemical Propulsion Information Analysis Center (CPIAC) as a technical specialist. He has presented numerous papers on propulsion design, insensitive munitions and energetics at conferences and workshops in the US and abroad.

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DTIC SEARCH TERMS:

Hypervelocity Projectiles

RESULTS: 8,080

- Hypervelocity Projectiles (1,424)
- Ballistics (1,072)
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- Guns (840)
- Projectiles (809)
- Penetration (781)
- Velocity (637)
- Hypervelocity Guns (598)
- Terminal Ballistics (568)
- Antimissile Defense Systems (511)

*See page 15 for explanation ▸

NEW RELEASE ALERT

Updated ESAMS 5.1

On behalf of AFLCMC/EZJ, DSIAC would like to announce the latest release of the Enhanced Surface-to-Air Missile Simulation (ESAMS), version 5.1, with respective documentation.

The ESAMS software model is a program used to simulate the interaction between an airborne target(s) and a surface-to-air missile (SAM) air defense system. ESAMS is routinely used by the survivability and vulnerability community to estimate aircraft survivability, estimate effectiveness, set requirements, and develop concept of operations (CONOPS) and tactics. ESAMS simulates the relevant elements of a SAM engagement, which include radio frequency (RF) radars, detailed area performance, countermeasure algorithms, environmental factors (e.g., terrain, clutter, multipath, noise), tactics (launch computer, target maneuvers), and endgame. ESAMS operates on Linux and Microsoft Windows.

ESAMS 5.1 incorporates several bug fixes and enhancements, including:

- More than 25 available SAM systems
- Availability of more than 5 battalion level acquisition radars
- 19 software updates from ESAMS 5.0
- Availability of more than 75 pedigree documents
- Revised ESAMS testmatrix (input and output files) to compare and reference
- Updated user manuals ■

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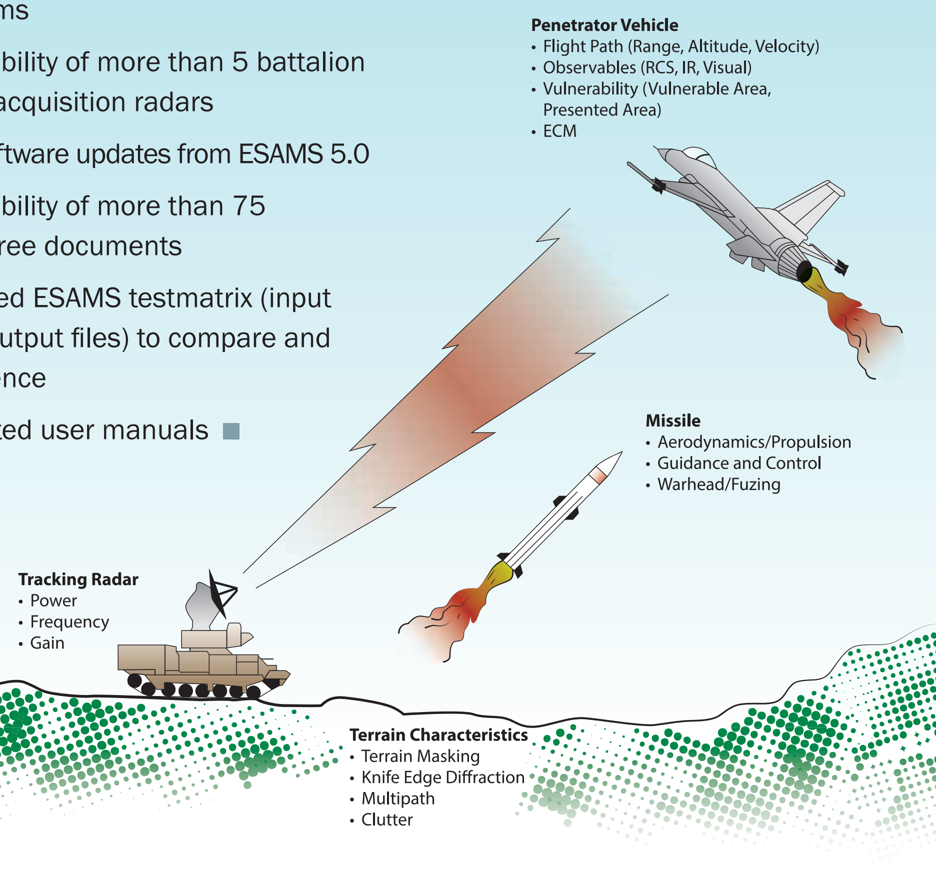

U.S. Navy

INTEGRATING ELECTROMAGNETIC RAILGUNS

INTO THE NAVY OF THE FUTURE

By Matthew Fox

INTRODUCTION

For many years, the U.S. Navy has held a distinct technological advantage over its adversaries in the area of large conventional guns that use explosive energetic propellants to fire projectiles (e.g., those found on U.S. cruisers and destroyers). Over the last few decades, that advantage has been in a steady state of decline as the amount of permissive operating space has become more contested. New advanced weapon systems have long been promised as solutions intended to reverse this trend. Accordingly, advanced weapons systems such as railguns offer greatly increased range, firing rate, and lethality while also promising substantial improvements in storage and handling safety. However, the transition of such advanced weapon systems from the laboratory to the theater has become quite precarious as decision-makers have struggled with the challenges of competing research and development (R&D) priorities. Recently, with a renewed desire to ease such impasses, national leaders are displaying greater optimism with regard to the outlook for advanced weapon systems development.

In November of 2014, then U.S. Secretary of Defense, Chuck Hagel, released a memorandum for the Defense Innovation Initiative (DII). In the memorandum, Secretary Hagel stated that "We are entering an era where American dominance in key warfighting domains is eroding, and we must find new and creative ways to sustain, and in some areas expand, our advantage even as we deal with more limited resources." He concluded the memorandum with "America's continued strategic dominance will rely on innovation and adaptability across our defense enterprise" [1].

One such program with the potential to accomplish this imperative is the Electromagnetic Railgun (EMRG) Program. The Office of Naval Research (ONR) has contracted with BAE Systems and General Atomics to develop a next-generation weapon system (such as that shown in Figure 1), which aims to perform as a long-range weapon with rapid response capabilities, while also being more efficient and safer than current gun and even certain missile systems.

HOW RAILGUNS WORK

Railguns operate by using energy stored in a bank of capacitors to send a large electric current through two conducting parallel rails and a sliding armature. This current creates a magnetic field and interacts with the current flowing through the armature, generating a force called the Lorentz force, which accelerates the armature through the barrel. The projectile, encased in a sabot (pronounced sa-'bō), is pushed by the armature and leaves the barrel at speeds around Mach 7 [2]. Once the projectile leaves the barrel, it separates from the sabot and armature and continues towards its target. The process is illustrated in the cut-away diagram and firing process of Figure 2.

Figure 1: EMRG Firing at the Naval Surface Warfare Center in Dahlgren, VA.

LOGISTICAL ADVANTAGES OF RAILGUNS

Contemporary U.S. warships are armed with guns and missiles that require a chemical energy propulsion system. These chemically propelled weapons are expensive to manufacture and can provide numerous logistical challenges. Further, warships have limited storage capacity and are difficult to restock at sea; most often they must return to a depot for resupply.

Additionally, because of the explosive nature of the energetic materials required to propel such weapons, special safety measures are required for handling. Chemically propelled weapons also carry with them a hefty price tag. And, in this age of increasingly tight budgets and threats of sequestration, such legacy systems may not be the best long-term solution.

Alternatively, railgun ammunition has absolutely no chemical propellant. Instead, the projectile is launched by making use of the previously mentioned Lorentz force, which is generated by sending large amounts of current through the rail. This approach allows for the projectiles to be handled much more safely because there is no explosive propellant to be concerned with. And since railgun projectiles have no chemically propulsive elements, they can be stored without extensive munitions safety procedures and without logistical issues associated with managing projectiles. Such projectiles can be more easily transported out to sea to restock remotely located warships. Furthermore, in the same

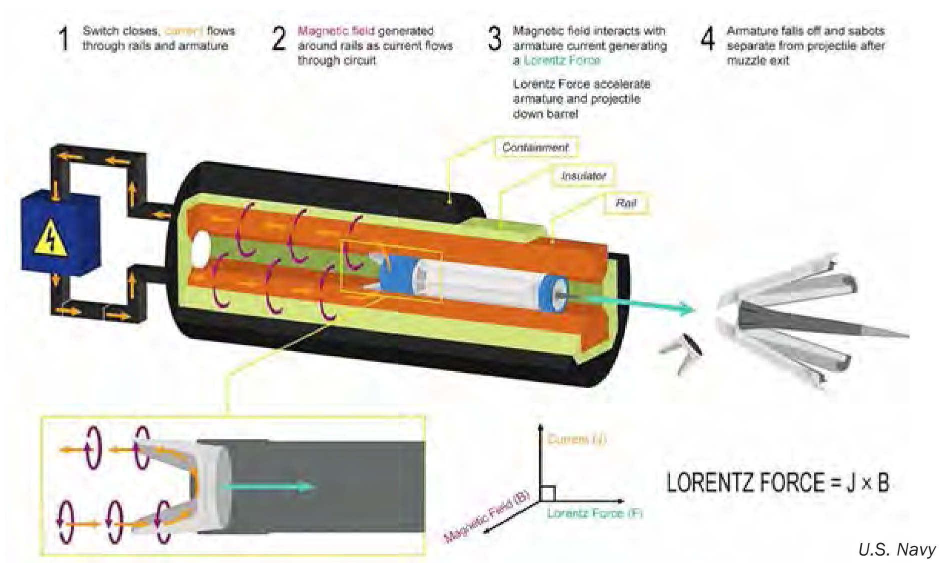

Figure 2: Railgun Cut-Away Diagram and Firing Process [2].

amount of space that a few hundred chemical projectiles require, thousands of railgun projectiles can be stored [3].

PRECISION STRIKE CAPABILITY

Railgun systems can launch projectiles on ballistic paths to precisely strike their targets in the range of 100 to 200 nautical miles. Such projectiles can reach altitudes around 500,000 ft before using global positioning system (GPS) technology to operate their navigational control and zero in on the target. This precision targeting is all accomplished in a time of flight to target of approximately 6 minutes [4].

Railgun strikes can also be called in by ground troops requesting support, as illustrated in the notional concept of operations (CONOPS) in Figure 3. Weapons that use chemical propulsion tend to have a large area of overpressure and fragment spray when hitting a target, which can sometimes lead to collateral damage. Railgun-launched projectiles will reach their targets around Mach 5. And since there are no explosives in railgun projectiles, the fragment pattern on impact is much more focused, allowing for much greater precision with a decrease in collateral damage [4]. An air burst variant of a railgun projectile is also a possibility for certain area effect scenarios. With this type projectile, fragments would effect the surrounding target area, which could be useful when engaging personnel or lightly armored targets.

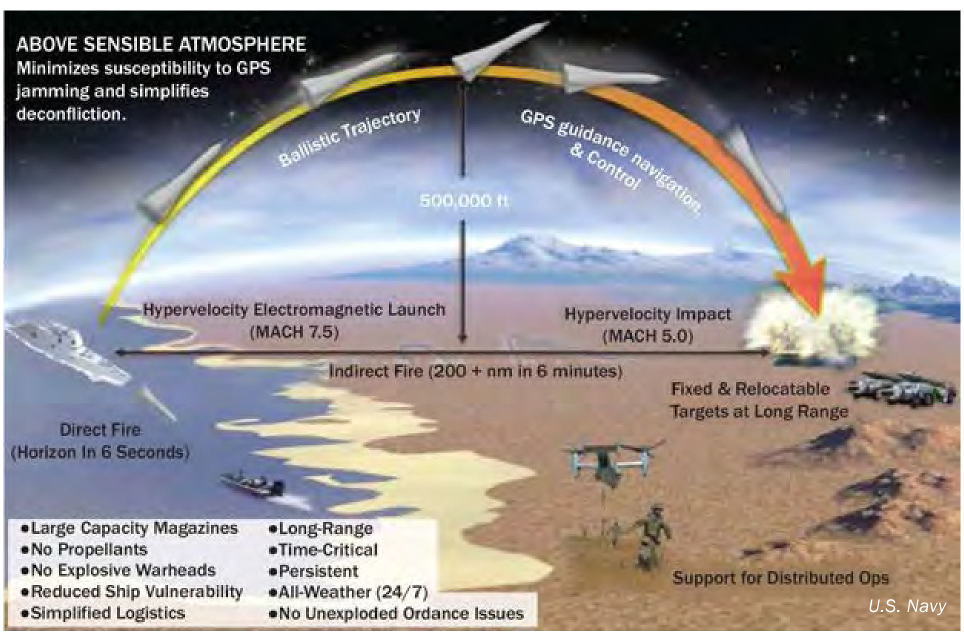

Figure 3: CONOPS for Railgun Scenario (NAVSEA) [5].

TECHNOLOGICAL CHALLENGES

Not surprisingly, railgun development has had to overcome numerous challenges for the technology to be considered a plausible next-generation system. One challenge in particular has been the ability of the barrel to withstand multiple firings. The intense electric current and heat generated during a firing creates a harsh environment for the barrel (a prototype of which is shown in Figure 4). Currently, barrels only have the mechanical integrity to withstand tens of shots. This lifespan needs to be greatly increased if the railgun is going to be a viable next generation weapon. Hence, work is ongoing to improve the material properties and the resiliency of the barrel.

Figure 4: Railgun Prototype on Display Aboard the *USS Millinocket* (Navy).

Of course, increasing the resiliency of the barrel goes only so far if the heat produced from the immense amount of energy released cannot be mitigated. Accordingly, efforts are also underway to develop an efficient cooling system that incorporates active cooling channels in the barrel.

Another challenge is managing the immense gravitational forces that the projectiles will be subject to as they experience an acceleration of nearly 100,000 g's when launched [6]. Current electronics hardening has proven to be satisfactory for railgun projectiles near the 100-nmi range, but further development will be necessary for ranges beyond 200 nmi.

RAILGUN POWER REQUIREMENTS

Accelerating a projectile to Mach 7 with only electricity is no small task. The current railgun prototype at the Naval Surface Warfare Center (NSWC) in Dahlgren, VA, is a 32-MJ system with the capability to send a projectile 110 nautical miles (nmi). Current estimations claim the railgun should be capable of firing between 6 and 12 rounds per minute [5]. The amount of power required for railgun operation can vary depending on the situation, but it usually ranges from tens to hundreds of megawatts [5]. To achieve these high energy levels, a pulsed power system has been developed to charge a bank of capacitors so they can be rapidly discharged into the gun system. This amount of power requires massive capacitor banks that add tons of weight and take up valuable shipboard space. So, for railguns to even be plausible, the power system of the respective platform will need to be designed to accommodate the weapon system.

THE INTEGRATED SHIP POWER SOLUTION

Current combatant ships allocate about 90% of engine power solely for propulsion [7]. To support the hundreds-of-megawatts power requirement of an electro-magnetic railgun and possibly other directed energy weapon systems such as high-energy lasers, more power must be allocated for weapon systems, requiring an immense power system that will consume valuable shipboard space and add a tremendous amount of weight. Such demands suggest that railguns most likely cannot be retrofitted to older Navy vessels and must instead be integrated with the development of an electrically driven warship designed for electric weapon systems.

In an integrated ship power scenario, the weapon systems would all be on the same power grid as the propulsion system. When high-speed operations are needed, most of the shipboard electric power can be directed to the propulsion system. In tactical scenarios, the engine power can be diverted to generate electricity for the weapon system.

Studies have shown that retrofitting an entire railgun system separately from the propulsion system would increase ship weight by approximately 17%. On the other hand, integrating the power systems together would only increase total ship weight by 6% [7]. When one considers that some of the new warships (such as the Zumwalt-class DDG 1000) are weighing in at more than 14,000 tons, this potential weight differential is substantial.

By 2016, the Navy hopes to have its first test fire at sea, with a railgun mounted on a JHSV.

THE FUTURE RAILGUN

As previously mentioned, General Atomics and BAE Systems are both working with ONR on the development of railgun systems. By 2016, the Navy hopes to have its first test fire at sea, with a railgun mounted on a Joint High-Speed Vessel (JHSV). A primary objective of the test is to fire 20 rounds over the horizon at a stationary target. And to evaluate the system's precision capability, five of the rounds will be GPS-guided [8].

Further, General Atomics, which envisions railguns to be a valuable weapon not only at sea but also on land, has shown interest in developing both fixed and mobile land-based railgun systems. The company's mobile Blitzer system plans to use existing military vehicles to transport the railguns components to the desired location. The Blitzer system will also use guided projectiles to provide rapid response defense against inbound missiles and enemy launchers. Additionally, the fixed-base version of the General Atomics railgun is much more expandable and will be able to provide longer ranges than shipboard applications.

While there is growing support for continuing railgun research, significant challenges remain with regard to integrating the system into a warship. The original plan was to install railguns on future combat ships such as the DDG 1000 (Zumwalt-class) destroyer, which is an electric warship with an integrated power system. The problem is that only three DDG 1000s are planned to be built, and the first two are too far along in development to incorporate a railgun [9].

Consequently, the Navy has forgone the DDG 1000 in favor of reverting back to the DDG 51 (Arleigh Burke-class) destroyer. A potential problem with this decision is that the DDG 51 is much smaller and cannot support the railgun system unless the railgun system size decreases or the DDG 51 Flight III version larger than the Flight IIA version. Another problem is that the DDG 51 Flight III will not have an electric drive system [10]. This could significantly limit the power generation capability and may not support the power requirements of railguns or other directed energy systems in development, such as the Solid State Laser [10]. This limitation means there would have to be an additional power system on board for these weapons, adding even more weight.

CONCLUSIONS

Clearly, railguns are weapons with great potential to increase combat effectiveness, reduce logistical burdens, improve safety, and decrease operational costs. To make this potential a reality, however, a long-term, viable ship platform to support the system will be needed. Currently, there are no ship designs planned to meet this need. A railgun can be installed on the last DDG 1000, but with the Navy's pivot back to the DDG 51 (which would require challenging modifications), that solution may only be a limited one. If the United States is to maintain its long-held technological advantage in this area, future ships will need to be designed and developed to comprehensively integrate this important weapon technology. ■

BIOGRAPHY

MATT FOX currently works for the SURVICE Engineering Company, where he is an associate engineer for the Defense Systems Information Analysis Center (DSIAC). He holds a B.S. in mechanical engineering and aerospace engineering from West Virginia University

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DTIC SEARCH TERMS:

Railgun Rail Gun

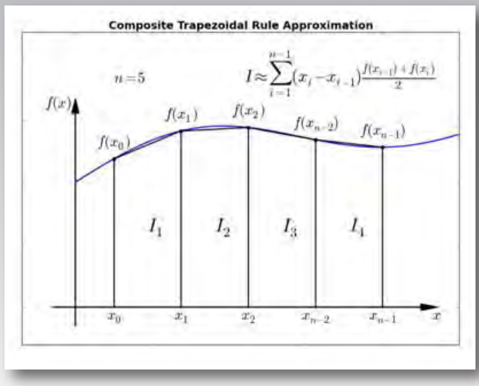
RESULTS: 1,240

- Guns (469)
- Electromagnetic Guns (434)
- Electricity & Magnetism (216)
- Armatures (195)
- Railguns (167)
- Projectiles (156)
- Rails (156)
- Launchers (144)
- Electric Guns (122)
- Hypervelocity Guns (122)

*See page 15 for explanation ▸

CORRECTION

Please note that there was an incorrect figure on p. 38 of the 2015 spring issue of the *DSIAC Journal*. Figure 11, titled Composite Trapezoidal Rule Approximation, should have appeared as follows. The editors apologize for any inconvenience.



CONFERENCES AND SYMPOSIA

JULY 2015

ISS R&D Conference
7–9 July 2015
Boston Marriott
Boston, MA
http://issconference.org ▸

The 58th Annual NDIA Fuze Conference
7–9 July 2015
Hilton Baltimore
Baltimore, MD
http://www.ndia.org/meetings/5560/Pages/default.aspx ▸

2015 MSS Tri-Service Radar
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https://www.sensiac.org/meeting/tsr ▸

2015 Summer Simulation Multi-Conference
26–29 July 2015
Palmer House Hilton
Chicago, IL
http://www.scs.org/summersim ▸

Next Generation Integrated ISR
27–29 July 2015
Washington, DC
http://integratedisr.com ▸

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27–29 July 2015
Hilton Orlando
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http://www.aiaa-propulsionenergy.org ▸

AUGUST 2015

2015 Transformative Vertical Flight Workshop
3–5 August 2015
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http://www.ndia.org/meetings/5480 ▸

ICOAM 2015
4–7 August 2015
The City College of New York
New York, NY
http://spie.org/x110947.xml ▸

SPIE Optics + Photonics 2015
9–13 August 2015
San Diego Convention Center
San Diego, CA
http://spie.org/x30491.xml ▸

7th Annual EW Capability Gaps and Enabling Technologies Operational & Technical Information Exchange
11–13 August 2015
Crane Club Lakeview Event Center
Crane, IN
http://crows.org/event/192-aoc-conferences/2015/08/11/16-7th-annual-ew-capability-gaps-and-enabling-technologies-operational-technical-information-exchange.html ▸

32nd Annual International Test and Evaluation Symposium
18–21 August 2015
Crystal Gateway Marriott
Arlington, VA
http://www.itea.org/component/content/article/35-share/conferences/352-32nd-annual-international-test-and-evaluation-symposium.html ▸

2015 Annual Tactical Wheeled Vehicles Conference
24–26 August 2015
Hyatt Regency Reston
Reston, VA
http://www.ndia.org/meetings/5530/Pages/default.aspx ▸

Next Generation Rotary Wing Requirements
24–26 August 2015
Pensacola, FL
http://militaryhelicoptersusa.com/ ▸

2015 MSS Electro-Optical & Infrared Countermeasures
24–27 August 2015
Springfield, VA
https://www.sensiac.org/meeting/ircm ▸

TECHNET AUGUSTA 2015
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Augusta Marriott at the Convention Center
Augusta, GA
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AIAA SPACE 2015
31 August–2 September 2015
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https://www.aiaa-space.org/default.aspx ▸

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https://www.navalengineers.org/events/individualeventwebsites/Pages/FMMS2015.aspx ▸

2015 IEEE 82nd Vehicular Technology Conference
6–9 September 2015
Westin Boston Waterfront
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http://www.ieee.org/conferences_events/conferences/conferencedetails/index.html?Conf_ID=35391 ▸

2015 IEEE Nanotechnology Materials and Devices Conference
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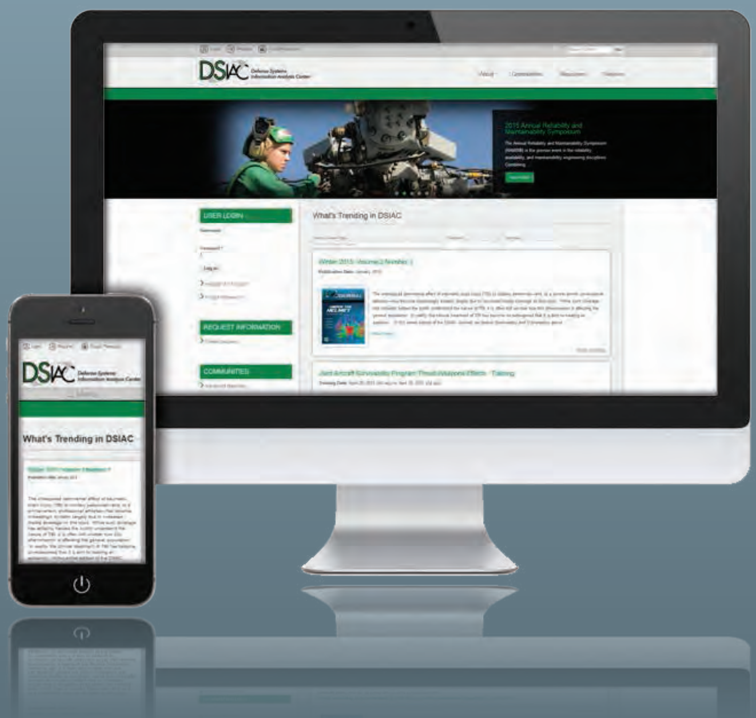

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