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Editor-in-Chief: Brian Benesch

Copy Editor: Maria Brady

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On the Cover:

A mine-resistant, ambush-protected (MRAP), all-terrain vehicle, graphically modified (source: U.S. Marine Corps).

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CONTENTS

CONTACT DSIAC

Ted Welsh
DSIAC Director

Brian Benesch
DSIAC Technical Project Lead

DSIAC HEADQUARTERS
4695 Millennium Drive
Belcamp, MD 21017-1505
Office: 443.360.4600
Fax: 410.272.6763
Email: contact@dsiac.org ▸

WPAFB SATELLITE OFFICE
704 TG/OL-AC/DSIAC
2700 D Street, Building 1661
Wright-Patterson AFB, OH 45433-7403
Office: 937.255.3828
DSN: 785.3828
Fax: 937.255.9673

DSIAC CONTRACTING OFFICER REPRESENTATIVES

Peggy M. Wagner (COR)
704 TG/OL-AC
2700 D Street, Building 1661
Wright-Patterson AFB, OH 45433-7403
Office: 937.255.6302

Brad E. Forch (ACOR)
U.S. Army Research Laboratory
RDRL-WM
Aberdeen Proving Ground, MD 21005
Office: 410.306.0929

DSIAC PROGRAM MANAGEMENT ANALYST

Marisiah Palmer-Moore
IAC Program Management Office (DTIC-I)
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6218
Office: 703.767.9109

MESSAGE FROM THE EDITOR

By Brian Benesch

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Our domain of expertise for technical inquiry research encompasses nine subject areas: Advanced Materials; Autonomous Systems; Directed Energy; Energetics; Military Sensing; Non-lethal Weapons; Reliability, Maintainability, Quality, Supportability, Interoperability (RMQSI); Survivability and Vulnerability; and Weapon Systems. Any and all inquiries that touch on these subject areas are within the scope of our research expertise.

> We work with the client to ensure we grasp the topic and scope of the question and then begin to conduct our 4 hours of free technical information research.

The type of technical inquiries we field and respond to varies. Many inquiries request our support with identifying recent publications and research conducted on a given technical topic; some are looking for available or in-development technologies that meet given capability requirements; and some simply need an answer to a direct technical question. Please take a few minutes to read through short summaries of recent notable technical inquiries that we have responded to by accessing this link: https://www.dsiac.org/resources/notable-ti. These summaries are intended to give the defense community a sampling of the wide range of questions presented and responses produced by DSIAC under the free 4 hours of information research support.

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Brian Benesch

Characterizing Cyber Intelligence as an ALL-SOURCE INTELLIGENCE PRODUCT

By Christopher Seedyk

INTRODUCTION

Gathering overt and covert information and its analysis and evaluation to produce an intelligence product is critical for assessing vulnerability and assuring the survivability of military systems. As traditional intelligence-gathering disciplines cannot address the expeditious assimilation of cyberspace technologies and capabilities into platforms and the subsequent challenges for survivability and vulnerability analysis, cyber intelligence (CYBINT) has emerged as a foundational discipline. This article surveys intelligence gathering relating to system survivability and vulnerability and the role of cybersecurity intelligence. Characterizing CYBINT as an intelligence product vs. an isolated intelligence-gathering discipline is presented, along with a proposed framework for fusing cybersecurity intelligence sources. This research provides valuable future direction for collecting, analyzing, and assessing cybersecurity intelligence sources for survivability and vulnerability assessment.

(Photo Source: 123rf.com)

SURVIVABILITY AND VULNERABILITY

In the most basic sense, survivability refers to the ability of an object to remain alive or continue to exist. In a defense context, this is specifically referred to as the ability of the system to remain mission-capable after an engagement [1]. An example is the definition of survivability for airborne combat systems as determined via four criteria [2]:

1. **Detectability** - how well, if at all, the system avoids identification.
2. **Susceptibility** - the capability of the system to avoid an attack.
3. **Vulnerability** - the ability of the system to withstand an attack.
4. **Recoverability** - the post-attack impact to the system; specifically, how well the system returns to a functional and fully capable state.

Vulnerability, in the context of defense, refers to the instantaneous or near-instantaneous impact of an attack on a system; specifically, whether there was a realized effect and, if realized, how it affected mission capability [3]. When considering vulnerability, it is often convenient to consider this a construct of susceptibility and vulnerability—how well the system avoids an attack and, if attacked, how well it can withstand that attack [4].

The constructs of survivability and vulnerability are attack centric. Assessing systems survivability and vulnerability and the effectiveness of these assessments is dependent on how well militaries can identify and test avenues to degrade or eliminate system capability and survivability (attack vectors), either through actual or simulated means. Several attack vectors are often obvious and can be gathered through overt means. Other attack vectors are not readily obvious or even available. Militaries try to protect their offensive and defensive capabilities to maintain strategic, operational, and tactical advantages over adversaries [5]. In these instances, intelligence gathering, analysis, and assessment (the "intelligence cycle," shown in Figure 1) play a critical role in assessing survivability and vulnerability.

Ideally, the intelligence cycle identifies the greatest number of known attack vectors that threaten survivability and create vulnerability, allowing systems to be designed or modified to decrease (or remove) vulnerability and increase overall survivability [6–8].

INTELLIGENCE GATHERING

Intelligence is the product of collecting and analyzing information for decision-making; in defense, intelligence uses information collected and analyzed to guide and direct the decisions of military commanders. As illustrated in Figure 2, this intelligence process is combined with the commander's operations process to produce increased situational understanding and better decision-making.

As described in the U.S. Army's Field Manual 2-0, intelligence gathering and analysis consists of five disciplines [9]:

1. **Human intelligence (HUMINT)** - actively and passively collecting information from persons and media.
2. **Imagery intelligence (IMINT)** - exploiting visual, infrared, laser, radar, and spectral-sensor imagery to identify information.
3. **Measurement and signature intelligence (MASINT)** - using technically derived intelligence to detect, locate, track, identify, or describe characteristics of target objects and sources.

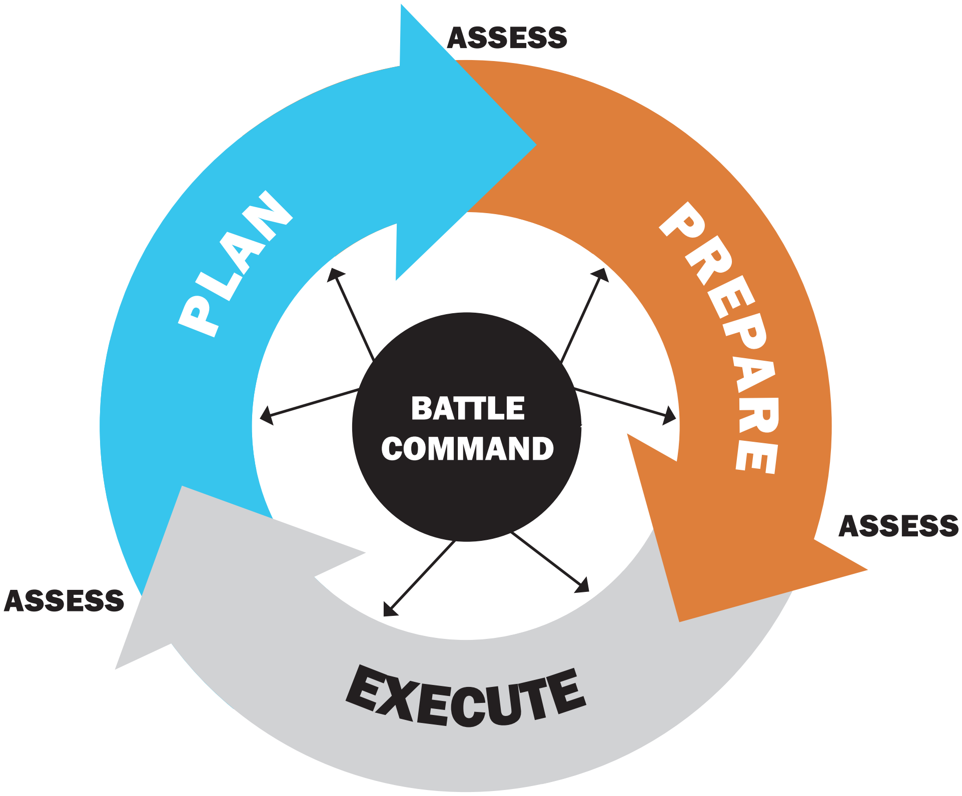

Figure 1: The Intelligence Cycle *(Source: Army FM 2-0).*

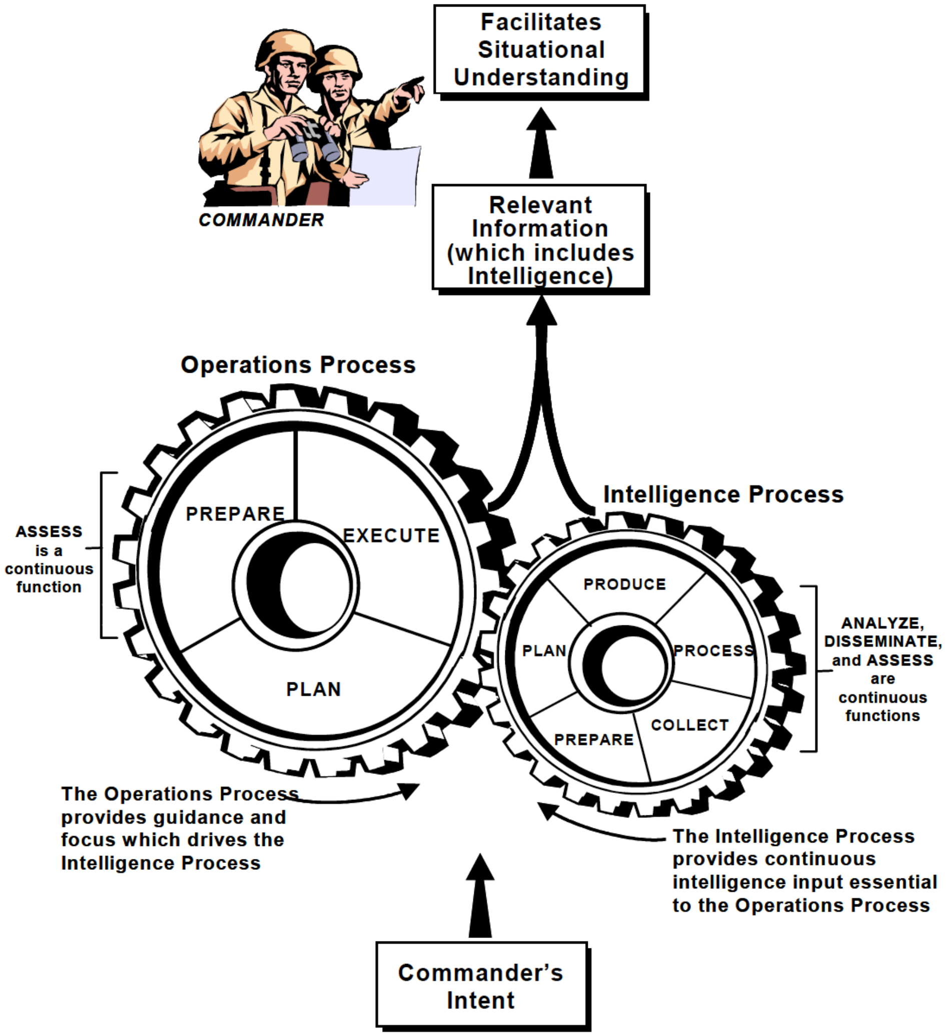

Figure 2: The Intelligence Process Contributions to Commander's Decision-Making *(Source: Army FM 2-0).*

4. **Signals intelligence (SIGINT)** - obtaining information from intercepting and analyzing signals.
5. **Technical intelligence (TECHINT)** - gathering information from collecting and analyzing military equipment and material.

In the Pentagon's Joint Publication 2-0 [10], the intent is to combine all the information gathered from these distinct intelligence disciplines into intelligence products. This generates all-source intelligence products with significant amounts of relevant information for commanders [10].

Fusing information-gathering and analytical efforts has improved dramatically since the siloed U.S. efforts of the Cold War [11]. Most notably, post-9/11, government agencies dramatically improved their intelligence sharing, increasing the accessibility of disparate intelligence sources for consolidated use. Thus, organizations can ensure that intelligence requirements are obtained from many sources, empowering source identification and uses most capable for the intelligence task and building intelligence reliability and credibility [12]. As such, militaries and governments can perform all-source intelligence fusion through analyzing and assessing all available sources. As the RAND Corporation discussed in 2012, using all-source intelligence is critical to the continued success of military operations. While intelligence-gathering disciplines can be segregated by type of intelligence, the product cannot—the U.S. military must strive to use the largest number of sources possible [13].

CYBERSECURITY INTELLIGENCE

Gathering intelligence and using it as a decision-making tool far predates the advent of computer systems or cybersecurity. Intelligence-gathering tools, techniques, and procedures have long existed and been used for offensive and defensive military and government operations [14]. The traditional practice of intelligence, and its fundamental principles, remains relevant for cybersecurity [15]. In cybersecurity, intelligence is used to generate a resultant product concerning hostile or potentially hostile forces or elements in cyberspace or areas of actual or potential cyberspace operations [10]. The result of intelligence in cybersecurity is a product that informs military commanders for decisions in or involving cyberspace [16]. Commonly referred to as cyber threat intelligence, this is used to research and analyze trends and developments in cyber threats and espionage, enabling militaries or governments to develop preventative measures in advance of the actual threat [17].

Traditional intelligence in cybersecurity has focused on collecting, analyzing, and assessing information concerning threats to cybersecurity systems [17]. Common intelligence disciplines for cyber threat intelligence are as follows:

Open-source intelligence (OSINT) - publicly available information about the cyber characteristics of systems or platforms, such as information found in advertising, press releases, requests for proposals, or contract information [18].

Social-media intelligence (SOCMINT) - details about cyber posture, configuration, or existence of platforms gathered from social media profiles of individuals or companies involved with the cyber status or posture of a system or platform, commonly through using social engineering [18].

HUMINT - cyber information about platform or systems gathered through covert or overt interaction with individuals knowledgeable of or affiliated with the cyber posture or status of systems or platforms [19].

TECHINT - scientific and technical information about the cyber equipment used on systems and platforms that describes or identifies the technical capabilities and characteristics of a platform or system [20].

In line with the intelligence-gathering process, each discipline is used to gather information about cyber threats that exist for a system or platform, either through knowing what attack vectors' adversaries have or what information they must exploit. Each of these disciplines (potentially) presents actionable intelligence products that can be used by commanders to make decisions about their platform and systems [21]. Using these intelligence disciplines and products has immediate applicability to militaries, informing them about threats and vulnerabilities to platforms and the expected survivability of the system or systems. This critical information is obtained by analyzing and assessing these vulnerabilities.

DEFINING CYBINT

Any definition of the cyber intelligence-gathering discipline is elusive [22]. Under the premise that SIGINT is gathered from signals and HUMINT is gathered from humans, an emergent simple definition of CYBINT is intelligence gathered from cyberspace. This is problematic, though, given that cyberspace generally refers to "interconnected technology" while no fewer than 28 different definitions of cyberspace exist [23]. One proposed definition is "[the] global and dynamic domain (subject to constant change) characterized by the combined use of electrons and electromagnetic spectrum, whose purpose is to create, store, modify, exchange, share and extract, use, [or] eliminate information and disrupt physical resources" [24].

The lack of consensus of what comprises cyberspace makes the definition of cyber intelligence equally pervasive. Unlike other intelligence-gathering disciplines, CYBINT is not formally defined in any service-specific or joint doctrine [22]. The idea of cyberspace operations is commonly accepted as the capability of a service to operate and maneuver within its own specific definition of cyberspace; however, there is a distinct lack of definition of how this can be leveraged to deliver CYBINT and how CYBINT can be used to inform and support these operations [25, 26]. Cyberspace presents several unique challenges for continued intelligence and operations. While cyberspace is largely a virtual domain created exclusively by humans, modifications and effects in this domain ultimately manifest physically within areas of operations [22]. The subtle intricacies and predominantly nonlinear nature of cyberspace—designed to allow anything to connect to everything—means seemingly minute or arbitrary changes commonly have impacts inversely proportional to their size and are well out of the militaries' bounds or foresight. Cyberspace manifests far less as a defined environment and more as a series of complex relationships. Furthermore, its near-instantaneous nature of operations and effects renders the traditional military consideration of time obsolete [22]. While traditional fundamentals of intelligence gathering are applicable to CYBINT, the distance of cyberspace from traditional military areas of operation and lack of alignment of cybersecurity operations with traditional "military operations" makes a futile attempt to define and address CYBINT within the bounds of traditional thinking on intelligence.

CYBINT AS AN INTELLIGENCE PRODUCT

If we adopt a simple definition of CYBINT as intelligence gathered from cyberspace, the grand challenge becomes not only discerning what compromises cyberspace but also addressing potential overlap and conflict with definitions of existing intelligence-gathering disciplines. In SIGINT, signals information has a concrete definition of communications among people (the focus of communications intelligence) or noncommunication electromagnetic signals such as radar (the focus of electronic intelligence). In CYBINT, the cyberspace information cannot be concretely defined. The exact components that make up cyberspace vary widely between operation areas, depend on numerous unknown factors, and can be changed instantaneously with relatively minimal effort [22, 27]. Further, with a lack of consensus on the cyberspace definition, information that would commonly be considered a component of other intelligence-gathering disciplines can easily be defined as a CYBINT component. For example, intercepting signaling channels of digital-communications links to capture information in establishing links between systems is traditionally a practice of SIGINT. Using the "interconnected technology" cyberspace definition and the fact that this intelligence was gathered from connecting two (or more) technological systems brings this intelligence into the realm of CYBINT, as it was arguably gathered from cyberspace. Hence, any information gathered from any technical interconnection could now become CYBINT.

Defining CYBINT based on intelligence sources used is not feasible given the multitude of available sources and substantial variances in these sources. Further, the intelligence gathered from these sources has the potential to be applicable to or part of the core concepts of other intelligence-gathering disciplines. As such, it is unlikely that collecting, analyzing, and assessing CYBINT cannot be accomplished in a way that does not encroach on the practice of other intelligence disciplines. This is evident in the current use of HUMINT in gathering cyber threat intelligence. If a HUMINT collector (a spy) covertly gathers information from a source about a known vulnerability to a cyber system or platform, is this HUMINT or CYBINT? The existence of the intelligence source as *human* supports assignment to HUMINT, while the applicability of the intelligence to *cyberspace* operations supports assignment to CYBINT. To a limited extent, this phenomenon is readily evident in all intelligence-gathering disciplines, but the pervasiveness is not similar. While integrating cyberspace into other intelligence operations is a realized doctrinal principle [9, 10, 13], the same cannot be said for integrating other intelligence-gathering disciplines into cyberspace.

Rather than defining CYBINT as simply the collection, analysis, and assessment of cyberspace information, it can instead be defined as the fusion of all intelligence relevant to cyberspace operations—derived also from traditional intelligence-gathering disciplines—into a product that informs military commanders' decisions about offensive and defensive cyberspace operations.

Traditional intelligence-gathering disciplines can continue intelligence-gathering activities in the traditional fashion. The resulting intelligence information or products relevant to cyberspace or cyberspace operations can then be collected and assigned to CYBINT, where the all-source fusion of this information will produce actionable products to address the informational needs of commanders. Figure 3 shows a high-level representation of the use of cyberspace-relevant information from intelligence gathering as the source for CYBINT. Figure 4 illustrates the clear division between the traditional and cyber intelligence processes.

In the cyber intelligence process (shown in blue), the cyberspace-relevant information from the activities of each of the traditional intelligence-gathering disciplines is collated to form cyberspace information. Through the process, this all-source information is fused to produce input for CYBINT; through the application, a CYBINT product is produced. In the traditional process (shown in grey), the five existing and well-defined intelligence-gathering disciplines use the process to produce

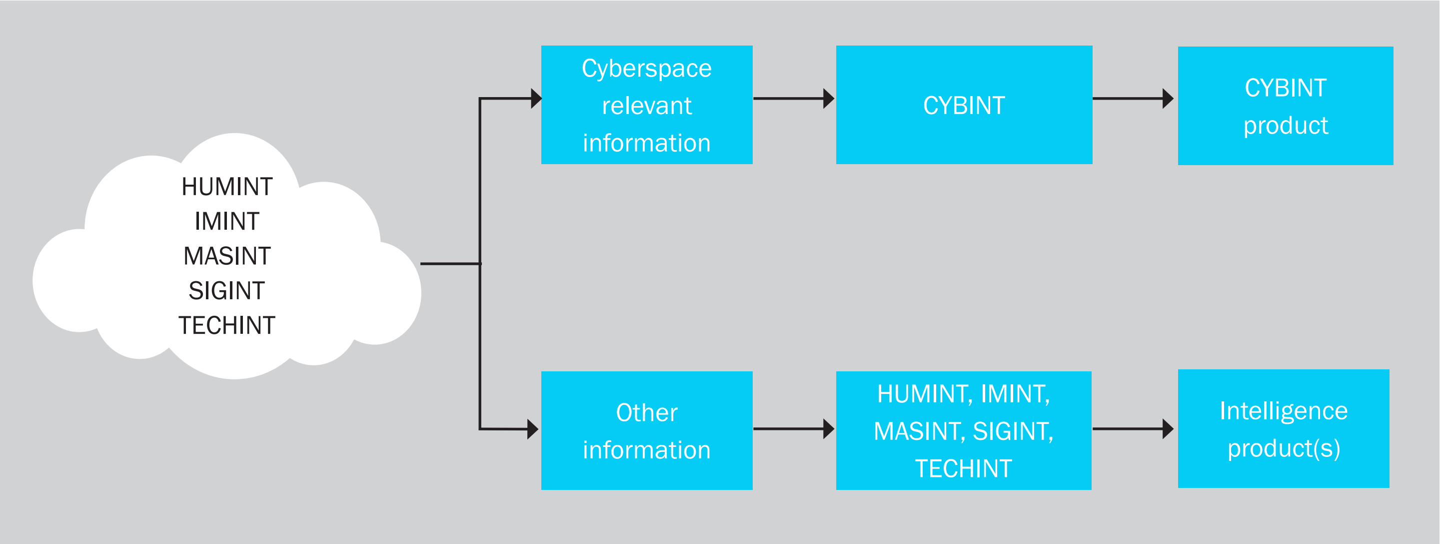

Figure 3: Separating Existing Intelligence to Form Inputs for CYBINT *(Source: Christopher Seedyk).*

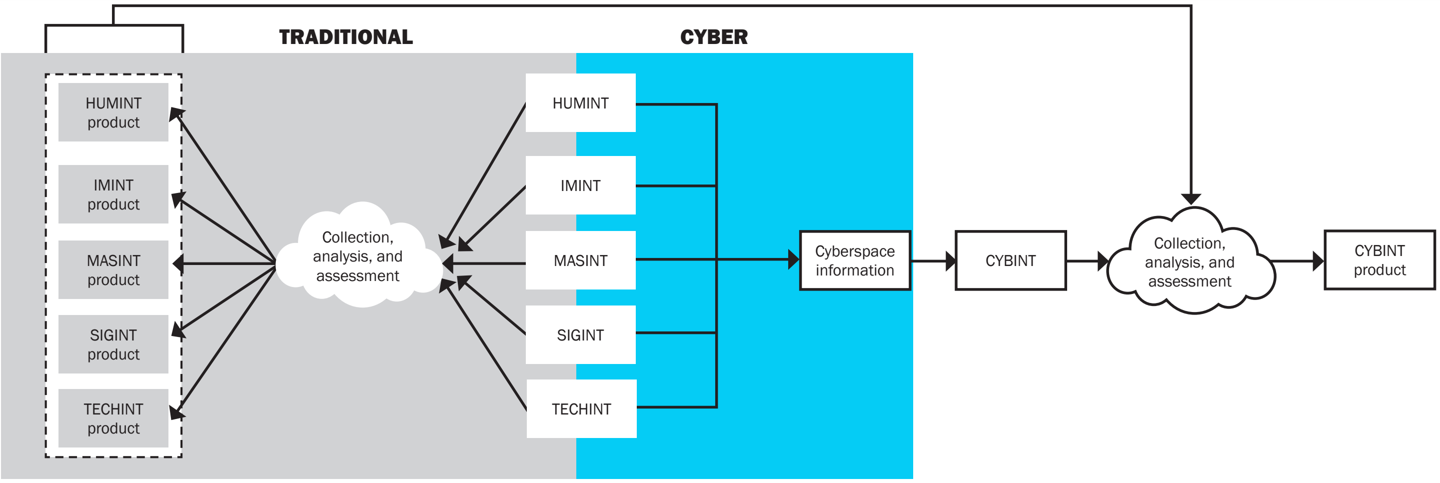

Figure 4: Framework to Support CYBINT Characterization as an All-Source Intelligence Product *(Source: Christopher Seedyk)*.

their intelligence products. Should any of these finalized products contain cyberspace-relevant information, they would be used as additional input to all-source infusion for a CYBINT product.

BENEFITS OF CYBINT AS AN INTELLIGENCE PRODUCT

Through this framework, it is possible to overcome limitations in the definition of and insight into *cyberspace* and *cyberspace operations* and, ultimately, the ability to identify and express informational needs. As shown in Figure 5, information needs play a key role in effective decision-making by commanders.

In situations where commanders are unable to express specific informational needs for CYBINT, such needs could dynamically emerge as by-products of existing intelligence disciplines. When commanders have a specific informational need, the relevant intelligence can be specifically identified, sought, and input into CYBINT as part of structured efforts for existing intelligence-gathering disciplines. This would potentially reduce the overall effort for CYBINT information-gathering as some, if not all, of the intelligence gathering occurs organically as part of an already existing process. When CYBINT can emerge organically from existing intelligence disciplines and as part of a structured CYBINT effort, there is opportunity for both greater *breadth* of coverage, by leveraging existing all-source efforts, and greater *depth* of coverage, through focused efforts for specific informational needs within these disciplines. Thus, in response to elusive cyberspace and CYBINT definitions, there is no longer a need for a concrete definition of either to collect, analyze, and assess CYBINT for military platforms or systems.

> Using CYBINT would enable designing and creating platforms and systems under an approved standard of cyber survivability and vulnerability to evolve as assessed threats change.

The benefit is apparent for survivability and vulnerability—effectively collecting and using CYBINT as part of a decision-making process enables militaries to assess which attack vectors, and associated attacks, are likely for their platforms and systems. Using this information, it is then possible to assess how well the system or platform could avoid detection to prevent executing these attacks; how well the system could avoid the attack or attack vector; how well the system could withstand the attack; and how well, if at all, the system could recover from the attack and return to a functional and capable state. Developmentally, using CYBINT would enable designing and creating platforms and systems under an approved standard of cyber survivability and vulnerability to evolve as assessed threats change.

FUTURE WORK

Key limitations to characterizing CYBINT as a product of all-source intelligence fusion (using emergent or focused cyberspace relevant information) are the current intelligence-gathering

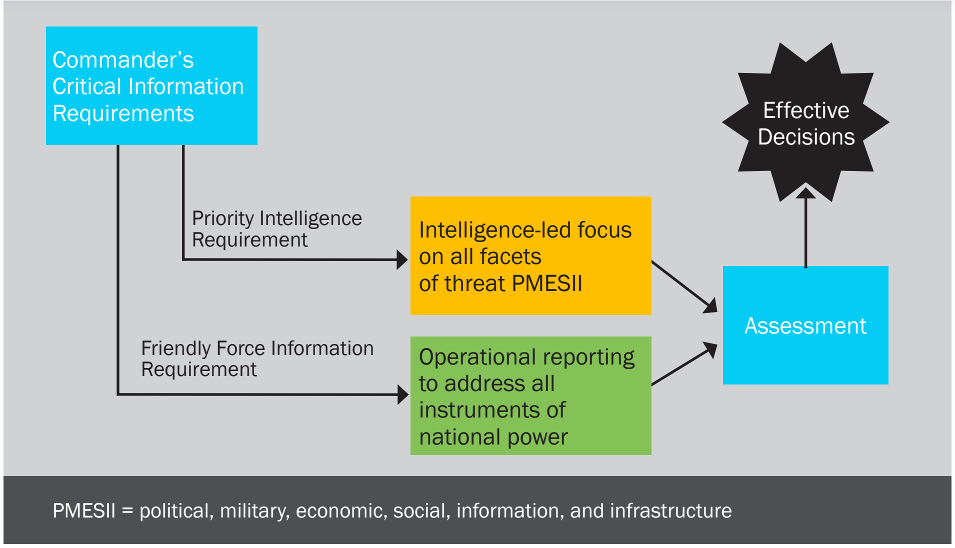

Figure 5: Separating Existing Intelligence to Form Inputs for CYBINT *(Source: JP 2- 0).*

disciplines and processes. While CYBINT inputs likely exist in these disciplines and processes, there is neither an established process to identify these as part of the analytical process nor the conduit to export them for CYBINT analysis. Further, there is a lack of criteria for establishing cybersecurity relevance in military intelligence and the frameworks for using this information in the overall CYBINT process.

To address this, the U.S. Army Research Laboratory's (ARL's) Survivability/Lethality Analysis Directorate (SLAD) is leading a design-science research study using HUMINT-inspired collection techniques to generate a framework for actionable CYBINT. In addition to improving existing capabilities, the goal of this effort by ARL/SLAD's Cyber Vulnerability Analysis and Assessment Division–Cybersecurity Branch is proof of concept of developing the conceptual framework supporting this new characterization of CYBINT. Beyond this, further research is necessary in developing the frameworks (taxonomies, criteria, and processes) to fully integrate CYBINT into existing intelligence-gathering disciplines. Future work must address developing a framework for introducing the IMINT, MASINT, SIGINT, and TECHINT disciplines and relevant supporting taxonomies. ■

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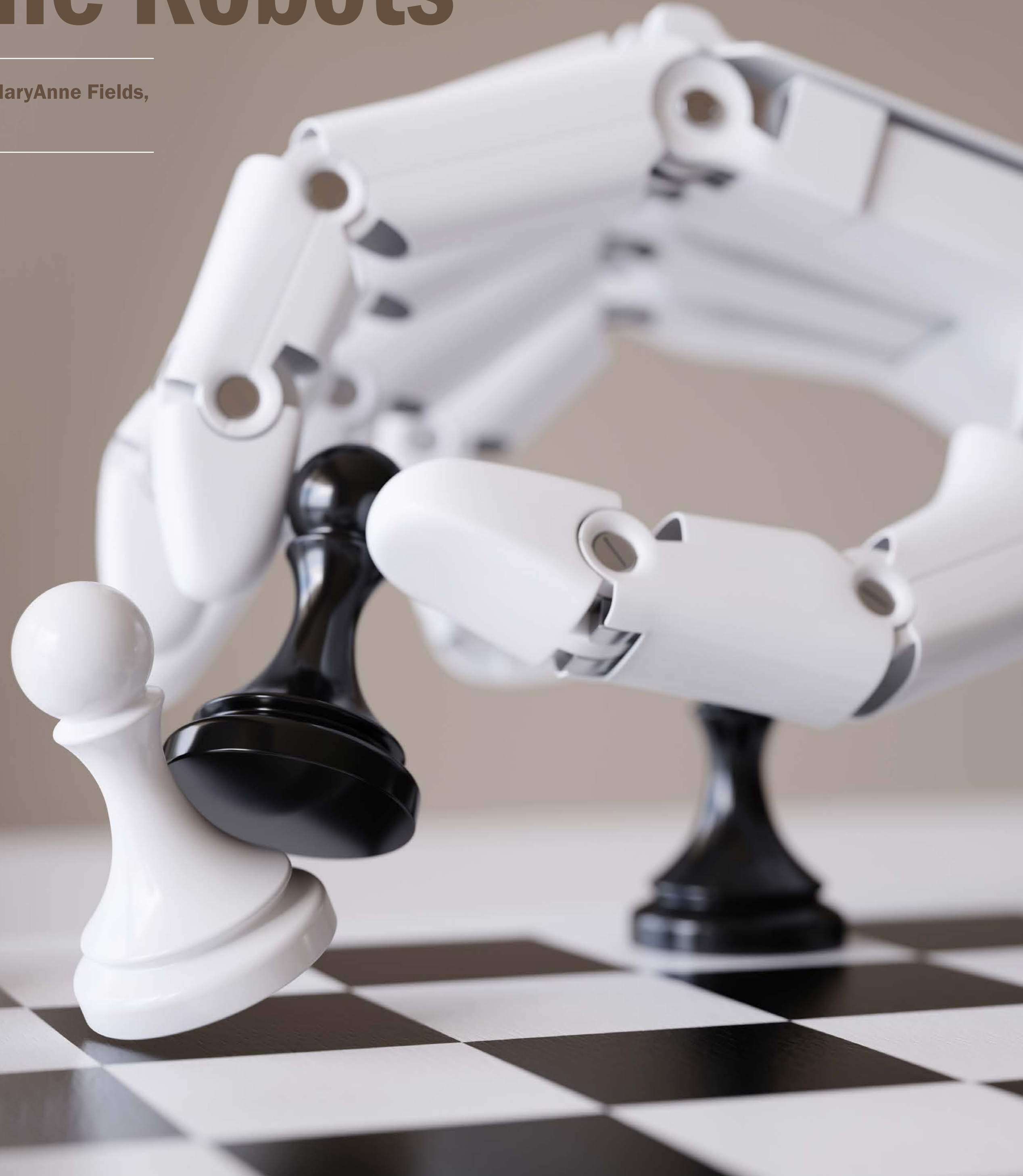
BIOGRAPHY

CHRISTOPHER SEEDYK currently works as a computer engineer at the U.S. Army Research Laboratory and is a cryptologic warfare officer in the U.S. Navy Reserve. His research interests include human-centric cybersecurity, user behavior-efficacy modelling, and cyber intelligence. Dr. Seedyk has a Ph.D. in computer science from Colorado Technical University.

TO USE OR NOT TO USE Mobile Robots

By Robert St. Amant, MaryAnne Fields, and Philip Osteen



(Photo Source: 123rf.com)

INTRODUCTION

The modern world surrounds us with the products of artificial intelligence (AI) research. These AI systems mainly work behind the scenes, in information space; they're the filtering algorithms on a social media platform or the recommender algorithms on a retail Web site, for example. A new generation of intelligent systems that operate in information and physical space is emerging [1]—mobile robots.

Autonomous vehicles are probably the best-known examples of intelligent mobile robots. Although the definition of "robot" is flexible, in general, a robot can be thought of as a computer-controlled machine that senses and interacts with the physical environment—legged robots with cameras and manipulators but also cars that decide where to drive. Related systems with intelligence include robots that carry out tasks in the home, such as vacuuming the floors, cutting the lawn, or taking out the trash. In more specialized environments, we find delivery robots that move through warehouses or offices, carrying products or documents to people who need them, and urban search and rescue robots that assist human rescue workers to find survivors in collapsed buildings.

This article gives the nontechnical reader interested in military operations an overview of three areas central to AI research, in general, and robotics, in particular: perception, knowledge representation and reasoning, and decision-making for action.

1. **Perception** - How can a robot make sense of its environment, a multiscale, dynamically changing world that includes friendly forces and enemies?
2. **Knowledge representation and reasoning** - How can a robot turn the huge data stream of its perceptions into a persistent representation that supports questions and answers, relevance judgments, and progress toward military goals?
3. **Decision-making for action** - How can a robot decide to act?

Before we describe these three areas, we must first consider the technical and strategic perspectives when building and using intelligent mobile robots.

TECHNICAL AND STRATEGIC PERSPECTIVES

Broadly speaking, we can judge intelligent robot behavior in each domain from two perspectives—technical and strategic. From a technical perspective, we can apply relatively well-understood engineering principles to the interested behavior to guide us in constructing a robot, judge how difficult that construction will be, or predict how well our robot will perform. From a strategic perspective, we must make judgment calls about prospects and tradeoffs.

Some technical considerations generalize beyond AI and robotics. For example, movement over an unfamiliar, unstable surface might be facilitated by extensive physics simulations, but a mobile robot does not have the computational resources or the time to carry them out. Some problems can be categorized as probably intractable. Other considerations, however, are specific to AI and robotics.

Let's take a simple example. For centuries, chess-playing skills have been associated with human intelligence; this naturally made the game prominent in early AI research. Imagine a robot designed to play chess—not ordinary chess on a tabletop, but outdoors, with large pieces set up on a lawn (see Figure 1). What makes this task easy or hard? A snapshot of the board, visible to players and spectators, conveys all relevant information about the state of play, which facilitates problem solving. For the robot, however, this depends on its ability to recognize pieces and locations, and even to perceive the board in its totality. The robot can pause for minutes or hours,

Figure 1: Traditional Oversized Street Chess in Parc des Bastions *(Source: 123rf.com).*

in principle, and the game remains in stasis the entire time. Whenever the robot does act, it chooses from a fixed set of legal moves. Executing those moves, however, involves planning paths, lifting and carrying pieces, and not disturbing the other pieces on the board.

As a purely abstract game, chess is appealing, in part, for its simplicity—the board does not change with the passage of time; players choose from a small fixed set of actions; and the result of an action is completely predictable. But a physical game of chess changes this picture. The environment may not be completely observable; the robot may drop pieces on the wrong square or produce other unintended results; and unruly spectators can disturb the board or interfere with the robot's actions. Here, we see the textbook features of a task environment [1], which include (in easy/hard terms) full/partial observability, discrete/continuous spaces of states and actions, deterministic/stochastic outcomes, and a static/dynamic environment. Robots, especially mobile robots, are often required to operate in task environments that pose serious challenges regarding these features.

Consider this task for a robot vehicle (see Figure 2) [2]: *The commander's orders are to deliver supplies from division rear up to the Armored Brigade Combat Team. Some of the long-haul trucks are outfitted to move as unmanned ground vehicles (UGVs). A convoy is formed of a chain of segments, each segment consisting of a vehicle with a human driver and a small crew at the head, followed by four or five UGVs. The crews have been briefed on safety as well as rules of engagement. The vehicles will maintain a distance of 25 meters between crews and watch for civilian vehicles or pedestrians that cut into the convoy. There is an alert that insurgents are known to be operating along the convoy's route. The insurgents, armed with small arms weapons, explosives, and possible vehicle-borne improvised explosive devices, could pose a threat to the convoy. Because of the possibility of attack, the convoy should stop only in case of emergency… During the movement through one of the small towns along the route, a young man steps off the sidewalk, walking between two of the UGVs. It could be a ploy to get the convoy to stop. It could be a teenager crossing the street.*

From our technical perspective, some of the same issues carry over from the robot chess example to the behavior of a hypothetical intelligent UGV. A UGV has a limited range of sensors for gathering information (implying partial observability); that information (continuous video, sound, scan data, etc.) requires interpretation to be meaningful. The UGV has limited time for its processing; aside from the dynamics of driving, detecting, identifying, and evaluating, the pedestrian must happen within seconds. The UGV, even with its limited repertoire, has a difficult choice between actions—is braking enough to avoid hitting the pedestrian or is swerving required as well? Is there a risk of crashing into a parked car or a permanent structure, with resulting damage and a halt of the convoy? How should these risks be evaluated?

Some questions cannot be answered from the technical perspective we have presented. Strategic issues must also be addressed. We will frame our discussion around what is known vs. unknown.

Often, we grapple with the unknown when dealing with a domain itself. That is, we want robots for tasks and environments that are problematic for human beings; these cases tend to

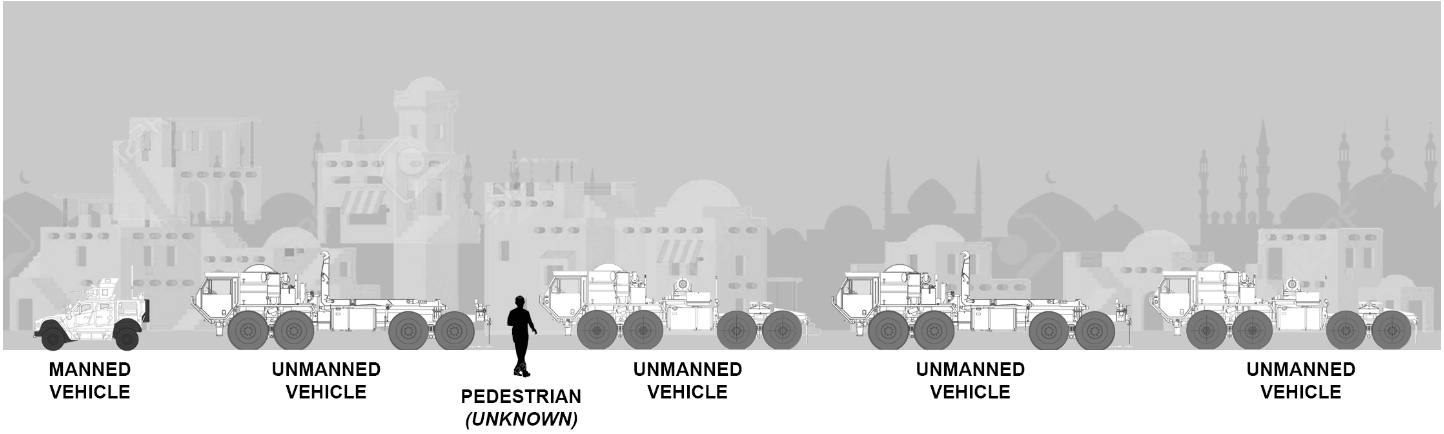


Figure 2: Task for a Robot Vehicle *(Source: 123rf.com and the-blueprints.com).*

involve unknowns. We value intelligence in a mobile robot because it can adapt to and deal with unknowns (e.g., driving on unfamiliar roads or off-road, searching a half-collapsed building, or finding a concealed perch for aerial surveillance). In the convoy scenario, unknowns might extend to the plausible actions and reactions of the people in the areas the UGV is driving through. Developing systems for incompletely understood tasks and environments is difficult.

Even if we do have a reasonable, informal understanding of a domain, theory is often lacking. For example, the rules of engagement have legal and ethical foundations. However, legal reasoning is still a challenge in AI, despite decades of research, and computational ethics is in its infancy. Sometimes, we do not have a clear path toward an intelligent system, one built on well-understood principles that give us reason to believe the system will be competent.

We may face another challenge in establishing good performance measures. In the convoy scenario, the timeliness of the delivery and whether the crews arrived safely are obvious measures, but other qualitative factors are more difficult to evaluate. For example, were the crews at special risk at any point in time? Was every UGV action consistent with the rules of engagement? We may be able to formalize such questions; after all, we can evaluate human performance along these lines. But this points out a new concern—the UGV is an autonomous system, and it may be hard to determine the exact contribution of its decisions to overall performance. This is characteristic when evaluating robots. We may be tempted to judge them in the same way as other machines; however, autonomy requires deeper analysis.

Finally, sometimes we can build a system for a domain that we do understand and can reasonably evaluate its performance. Even in these situations, we often don't completely understand how the system works. We might have tested our robot in the laboratory, under tightly controlled conditions; we have run it through endless simulations; we have even put it through live exercises. And yet, uncertainty remains about whether the system's performance will degrade gracefully when put to the test in the most demanding environments.

> Legal reasoning is still a challenge in AI, despite decades of research, and computational ethics is in its infancy.

When dealing with machine learning, it is reasonable to ask, "Isn't it possible for a robot to learn autonomously about the domain, even theory about solving problems, and about its own performance—perhaps even to explain itself?" Machine learning, including deep learning, is not a panacea, despite many recent success stories [3]. One limitation is relevant as a strategic issue—sometimes we cannot effectively train a system or tune its performance because the data are too sparse. This may have to do with the accessibility of a domain (as with outer space or undersea navigation) or with the cost or risk of data collection (as with real military operations).

To summarize, it is important to judge what is known about the application domain, the theoretical underpinnings for effective problem solving, performance evaluation, and the causal factors driving a system's behavior in practice. In cases where risks and benefits can be quantified, we may be able to treat the development and deployment of an intelligent mobile robot in technical and economic terms—we can ask about its expected utility. This is not always possible, however. Instead, we must make qualitative judgments about the risks of proceeding with limited knowledge. As a final point, it is useful to know that the AI and robotics literature contains decades of research on problems that are persistent and difficult. We will see examples of hard problems later in this article.

AI AND ROBOTICS RESEARCH AREAS

We will now focus on the three areas of ongoing research within the Autonomous Systems Division's (ASD's) Intelligent Control group in the Vehicle Technology Directorate of the U.S. Army Research Laboratory. Our descriptions will not be detailed or complete; however, we intend to give a representative picture.

To unify our discussion, we will use the convoy scenario previously outlined. Consider a human planner who is mentally running through what might possibly happen as the scenario plays out. What should be attended to, how should it be evaluated, and what are the options for action? The planner is, in some ways, behaving like a detective, but not analyzing existing clues. Instead, he or she is imagining and evaluating situations that might occur toward the end of achieving the mission goals and ensuring that Soldiers are safe.

Perception

Dana Ballard and Christopher Brown's early account of machine perception [4] begins at a low level, with the extraction of features from sensor data (e.g., image processing), recognition of patterns over those features, and eventually object recognition. Perception goes well beyond object recognition, as might be expected. Much of an agent's intelligence derives from his or her perception of the task environment. This means that perceptual processing is "effectively inseparable" from high-level cognitive faculties, including memory, reasoning, and learning. Perception research in the ASD group takes a comparable, general view. The goal is to develop a framework that integrates perception, cognition, and knowledge so that adaptive learning from experience becomes possible.

In our convoy scenario, consider what a UGV might be expected to sense and flag when suggesting possible danger, acting as a proxy for a Soldier. Fewer people than usual might be moving along a given street, or perhaps the typical balance between men and women is different. One of the usually-open markets is shut down. A young man appears at the opening to a side street or is seen running toward an intersection ahead of the UGV. In these examples, basic perceptual tasks integrate and interact with higher-level processes.

Robots cannot yet manage perception and interpretation at this level. In general, we can expect near-term progress to be made in some supporting areas, however. Sensor hardware will expand and grow more refined. For example, over the past decade or so, robots have increasingly included RGB-D data (see Figure 3) that provide color and depth information. Perception for navigation-specific tasks, including localization and mapping, will improve. Object recognition will be possible over a broader range. Machine judgments of salience—what is important in a scene, such as the detection of the movement of the young man previously mentioned—will become more accurate.

However, some perception challenges are likely to remain for the long term. Salience, for example, depends on more than visual patterns; it requires evaluating context and applying knowledge. Not all movement is important, such as people walking along a sidewalk or a child chasing after a ball, even if the visual patterns are similar. Context comes into play in evaluating the clues mentioned. Our human planner automatically realizes that people's activities vary depending on the time of day and the day of the week; a special event such as a festival or funeral might change their behavior. Context and applying background knowledge can change the evaluation of

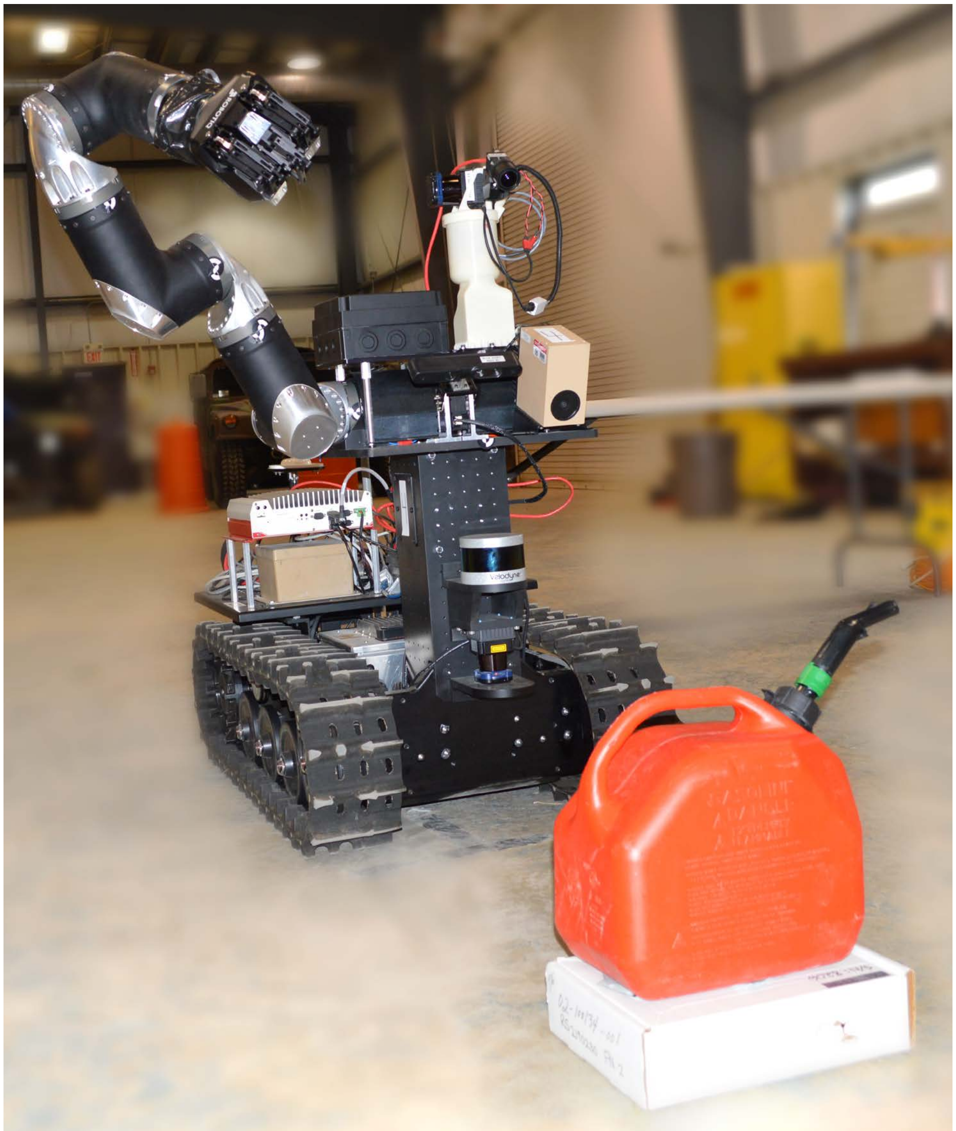


Figure 3: Robotics Collaborative Technology Alliance Robot Manipulator With RGB Camera and Multiline LADAR Localizing an Object in Its Environment.

what is perceived. Unfortunately, these are notoriously difficult challenges in AI, especially for interpreting scenes that include human beings and human artifacts. What are people doing now or in the recent past, and what does that suggest about their beliefs, plans, and future actions?

Knowledge Representation and Reasoning

The question just posed clearly does not only belong to perception; it involves knowledge and reasoning. In robotics, knowledge representation typically focuses on a world model, an internal representation of the external environment. A world model can be as simple as a database of facts. But often, it is useful for a robot to reason about what it perceives, drawing on knowledge both specific to its situation and in general. Work in the ASD group has been with a description logic [5], which supports representation and reasoning about objects and categories. The goal is a world model that can capture spatial, temporal, and semantic information relevant to air and ground systems, plus tools for analyzing, updating, and sharing between intelligent systems.

In general, the more possible it is to express in a representation, the longer it can take to reason [6]; this is a tradeoff between expressiveness and efficiency (or tractability). A description logic strikes a reasonable balance in the tradeoff.

Representation and inference algorithms have been core areas of AI research since the inception of the field, and gradual progress has been made on both expressiveness and efficiency. More specifically, we expect improvements in automated techniques to help integrate separately developed knowledge bases; refine knowledge representations initially constructed by hand; and capture knowledge from interaction with the environment.

> We can expect gradual progress in the ability of robots to explain their decisions and actions.

Hard problems remain. Maintaining the validity of the world model in a dynamic environment over time is closely tied to perception; perceptual change is constant in a mobile system. Failures will be inevitable in determining what is true and which action to take, within time constraints; how to deal with such failures must be dealt with by mechanisms outside of the world model.

Another challenge is commonsense reasoning (which can inform context). Imagine the instruction, “Look for activity in front of the tall building on the corner of the intersection.” A building described as “tall” might be 3 stories or 100 stories, depending on its surroundings. The “front” of the building may depend on the structure of the building, such as an entrance and clear walkways, but also on people’s activities. Human beings carry out such inferences effortlessly, but they require enormous amounts of stored knowledge or computation for a robot to match.

As another example from the convoy scenario, our human planner might imagine debris left along one stretch of the roadway, where usually it is clear. Building materials might be stacked at a point where they could be quickly turned into a barrier. These might suggest an ambush, but other observations might suggest that a building is being constructed nearby. AI systems can generate and evaluate alternative explanations for a given set of observations, but creativity and intuition in the process are not well understood.

Decision-Making for Action

Reasoning, as in the previous section, may reach conclusions about actions, but deciding to act does not always take the form of logical inference based on knowledge. For example, behavior-based robots, inspired by biological organisms, may do little reasoning at all. Their complex behaviors are layered incrementally on top of simpler behaviors. A range of other possibilities exists. Robot decisions can be formalized as Markov Decision Processes, can be the output of AI planning and scheduling algorithms, and be produced by cognitive architectures.

ASD research follows this last avenue. Cognitive processes take information from perception modules and the world model (a proxy for memory) to interpret scenes, objects, and activities in a cognitive and mission context. Interpretation and decision-making, as performed by the architecture, are shaped by what is known about human cognition. Eventually, models of learning, categorization, and analogy will be included. In other words, the approach is cognitive robotics according to the Technical Committee for Cognitive Robots [7]: “Cognitive robots achieve their goals by… paying attention to the events that matter, planning what to do, anticipating the outcome of their actions and the actions of other agents, and learning from the resultant interaction.”

Incorporating cognitive factors into decision-making can potentially bring benefits by taking advantage of what is known about human cognitive processing. The decision process may exploit similar patterns in human cognition related to relevance and familiarity, and the results may be more easily understood by human beings. In the short term, whether cognitive robotics or more traditional AI approaches prevail, we can expect gradual progress in the ability of robots to explain their decisions and actions (e.g., in terms of justifying actions based on internal inferences and a set of percepts); to tailor their decision processes to resource constraints, such as time or computational bounds; and to adhere to constraints imposed by military doctrine.

We should not expect complete solutions in these areas, however, and hard problems will persist in other areas. For example, in some human decision-making, we see elements of intuition, resourcefulness, and even creativity in developing solutions to problems. Only very occasionally is an AI system described in similar terms—this mainly happens in highly structured games and comes as a surprise. Other long-term challenges include generalizing or transferring solutions from one domain to another, determining robustness of solutions across variations in problems, and expanding decision-making to include less understood factors, such as ethics and social norms.

CONCLUSION

We have presented a set of concepts by which problems in AI and robotics can be evaluated—whether and how a robot system can be expected to reasonably deal with problems in its environment. Aspects of the task environment indicate which problems are likely to be harder than others. The harder problems are adversarial, partially observable, stochastic, dynamic, and continuous [1]. A strategic perspective is also needed to evaluate what is known and unknown in the application domain, underlying theory, performance evaluation, and system design. For a specific area within AI and robotics, we see complexities in evaluating salience or relevance, applying context and background knowledge, commonsense reasoning, generating and evaluating explanations of human behavior, and decision-making dimensions outside of logic and utility (e.g., ethics and creativity). AI and robotic systems will continue to improve over time, as well as our ability to understand and predict their performance. ■

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BIOGRAPHIES

ROBERT ST. AMANT is a computer scientist at the U.S. Army Research Laboratory (ARL). He spent 20 years as a professor in the Department of Computer Science at North Carolina State University, where he was recognized with an Outstanding Teacher award in 2013. His current research interests are in robotics, cognitive modeling, and human-computer interaction. He has published over 100 papers and received two best paper awards at the International Conference on Cognitive Modeling and the Behavior Representation in Simulation and Modeling Conference. Dr. St. Amant earned a Ph.D. from the University of Massachusetts in 1996.

MARYANNE FIELDS is a mathematician at the ARL's Vehicle Technology Directorate, serving as the lead for the Intelligent Control Team. Her research interests include planning with uncertain information, semantic spatial understanding, robotic behavior algorithms, and multiagent systems. She recently finished the Autonomous Squad Member project, a multiservice effort funded under the OSD's Autonomous Research Pilot Initiative. Currently a senior editor for the Journal of Intelligent and Robotics Systems, she has served as a reviewer for the IROS and ICRA conferences and written over 20 publications. Dr. Fields received a Ph.D. in mathematics from Clemson University in 1988.

PHILIP OSTEEN is a researcher at ARL's Vehicle Technology Directorate, focusing on developing perception and intelligence algorithms for improved autonomy. He previously worked at the Robotics, Vision, and Control Group at the University of Seville and then at ARL's Autonomous Systems Division. He has published works relating to enabling intelligent systems— temporal world modeling, egomotion estimation, 3-D segmentation, and multisensor calibration for data fusion. Mr. Osteen received his master's degree from the University of Florida, where he participated in the 2007 DARPA Urban Challenge.

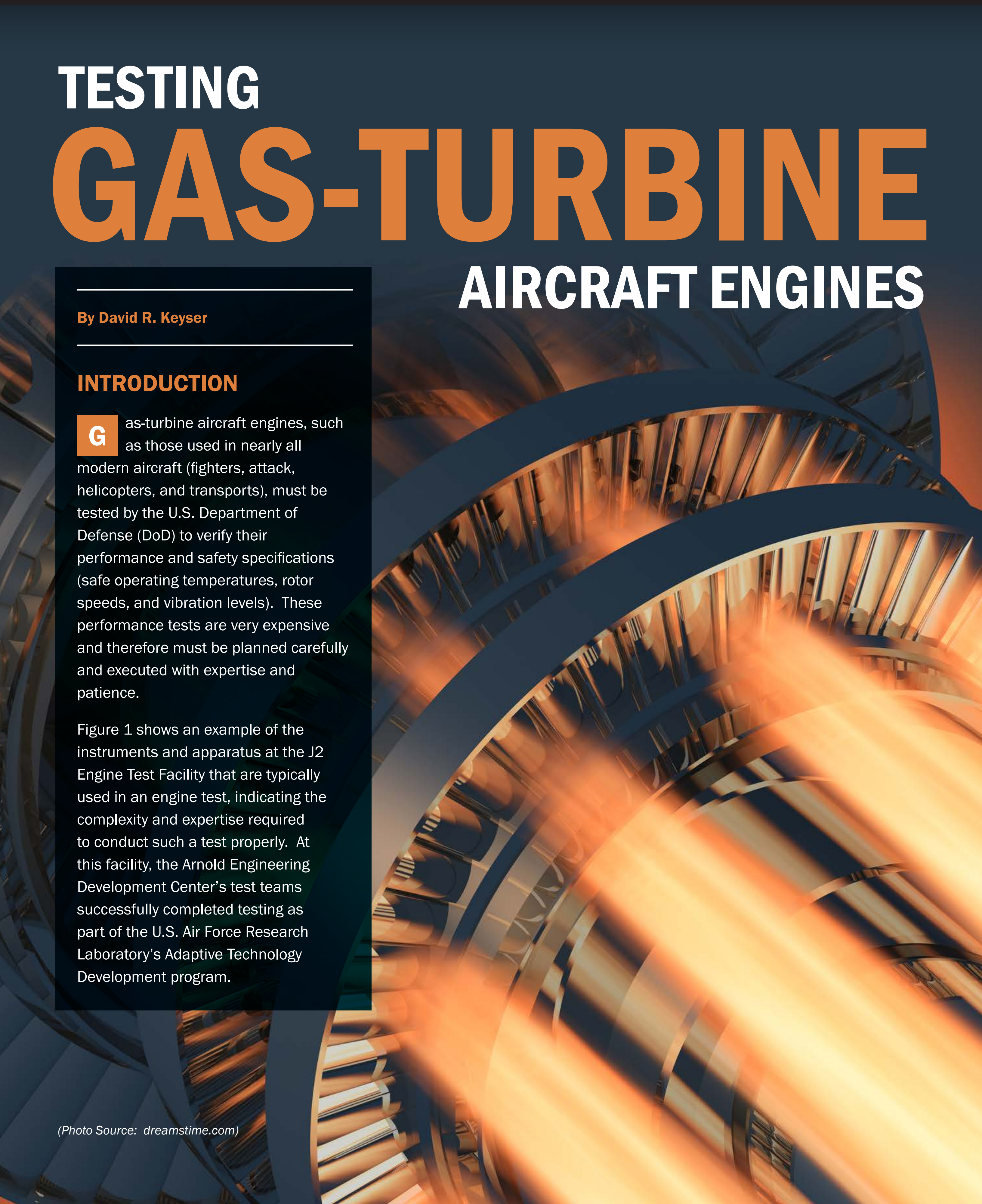
TESTING GAS-TURBINE AIRCRAFT ENGINES

By David R. Keyser

INTRODUCTION

Gas-turbine aircraft engines, such as those used in nearly all modern aircraft (fighters, attack, helicopters, and transports), must be tested by the U.S. Department of Defense (DoD) to verify their performance and safety specifications (safe operating temperatures, rotor speeds, and vibration levels). These performance tests are very expensive and therefore must be planned carefully and executed with expertise and patience.

Figure 1 shows an example of the instruments and apparatus at the J2 Engine Test Facility that are typically used in an engine test, indicating the complexity and expertise required to conduct such a test properly. At this facility, the Arnold Engineering Development Center's test teams successfully completed testing as part of the U.S. Air Force Research Laboratory's Adaptive Technology Development program.



(Photo Source: dreamstime.com)

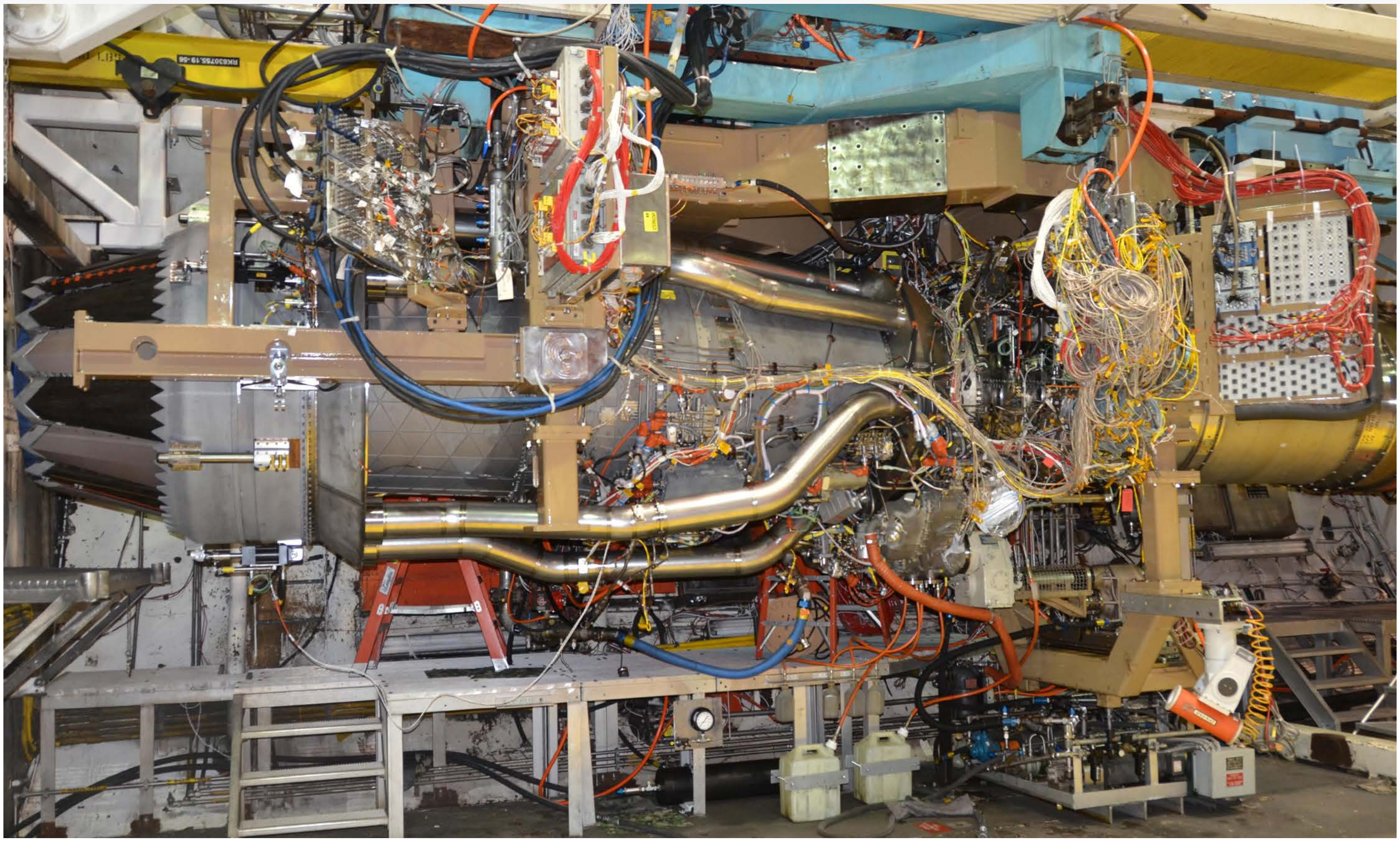


Figure 1: The J2 Engine Test Facility for Pratt & Whitney, Arnold Air Force Base, Tennessee *(Source: Pratt & Whitney).*

Performance testing a gas-turbine aircraft engine is complicated because they come in various configurations, from turbines with single spools to turbines with three spools. It is important in every case to determine the type of engine—from a pure jet, to a fan jet, to a prop jet. In addition, the wide range of testing missions includes standard production, sea-level acceptance testing, and heavily instrumented, altitude-developmental testing. New designs require several different test cells. The test data in virtually every case must be corrected for the differences between the observed and the specified, referenced conditions. The techniques used are based upon the rules of fluid-dynamic similarity and mass and energy conservation.

The prime objective is to determine the performance of thrust and power-producing gas-turbine aircraft engines at ambient test conditions and correct these results to specified standard operating conditions.

PERFORMANCE TESTING GOALS

This article describes testing gas-turbine aircraft engines in steady state, including turbojet, turbofan, turboshaft, and turboprop engines encompassing altitude test conditions and sea-level test conditions. The test results include a myriad of issues to investigate or prove, such as the following:

- Thrust, Power, and Efficiency
- Operating Lines and Stall Margins
- Auxiliary Power Extraction
- Fuel Flow
- Specific Fuel Consumption
- Engine Airflow
- Bleed Airflow
- Vibration Levels
- Pressures and Temperatures
- Humidity
- Rotor Speeds
- Engine Pressure Ratio

Prior to the test, testers, operators, and evaluators should agree in writing on the object, scope, and plan. If possible, the test should be run under the specified conditions, such as thrust and/or power output, pressures, and temperatures, or as close to the specified conditions as possible to avoid applying excessive corrections afterward. Acceptable ranges for atmospheric conditions and appropriate corrections should be determined before the test, as well as appropriate correction methods, models, and formulae. Accurate steady-state engine tests typically result in uncertainties less than ±1.0%, in general, ±5 °F (±2.8 °C) for temperatures and ±0.5% for pressures. With modern data-acquisition systems, direct instrument readings are usually unnecessary. The data can be stored digitally and sampled at intervals. Where necessary, direct observations of instrument readings should be recorded at frequent intervals during testing. A digital data acquisition system capable of steady-state and transient recording is typically used during acceptance tests.

Inputs, Outputs, and Methods of Measurement Under Test

Fundamentally, to measure the power of the air-breathing aircraft engine, we must determine the mass flows of oxygen and fuel being consumed and then the power delivered by the engine, either as thrust or shaft power. Other interesting variables measured during the test include the high-pressure turbine inlet temperature of the gas turbine, the fuel-to-air ratio for the combustor, and the brake-specific fuel consumption, which is the rate of fuel consumed per unit of power. These performance measurements are based on fundamental physical and chemical equations, some of which are modified by empirical factors determined from separate tests (e.g., effects of the unique geometry of the test cell). The primary variables measured and/or computed from the results of the test are those required for input to the equations of physics and thermodynamics so the thrust, power, and efficiency can be determined.

Core Air Flow

As a preface, air is a mixture of gases. Only about 21% of air is oxygen used for combustion of the fuel, while 78% is nitrogen, water vapor (humidity), and a list of more than eight trace amounts of rare, inert gases. There are several measured air flows of interest in testing gas turbines—the mass of air consumed by the engine to produce the thrust or power (core flow), exhaust gas flow, and the amount of bleed air extracted from the compressor section, which is normally specified as a constraining condition. The difference between these flows is the amount of air available for combustion to produce the thrust or power.

> To measure the power of the air-breathing aircraft engine, we must determine the mass flows of oxygen and fuel being consumed.

In a test environment, core airflow entering the engine itself is derived from a combination of test data and analysis. Direct measurement is impractical, but there are several techniques which combine the fundamental equations of flow and thermodynamics corrected by semi-empirical, legacy engineering equations to deduce that flow. These several engine-core airflow techniques are also useful in turboshaft engines, even though direct measurement of inlet airflow is accomplished with an inlet bell mouth, orifice, or Venturi (one method to validate those semi-empirical equations).

Fuel Flow

Fuel flow can be measured with a calibrated orifice or turbine meter, typically in a pipe under 2 inches in diameter. To determine heat (energy) input while operating on liquid fuel, three parametric factors must be known: (1) fuel density at test temperature (with volume measuring flow meters), (2) fuel volumetric flow, and (3) fuel heating value. The total heat input is the product of these factors.

Measuring Temperature

Temperature is measured with a variety of probes to assess aerodynamic performance, cavity conditions, or material temperature (in order of accuracy, they are resistance temperature detectors, thermocouples, and pyrometers). As previously noted, there are manifold loci on the engine, thus creating interest and concern about the strength and life of material components affected by excess temperatures.

Measuring Humidity

Water vapor contained in the air influences the engine and its performance. Although the consequences are complex, they fall into two major categories—engine inlet condensation and changes in gas properties. While the relative humidity is directly related to the extent of condensation on the inlet, the absolute humidity entering the inlet is the main parameter of interest. This is because the absolute or specific humidity affects the gas properties of the engine cycle (incoming air and products of combustion) and, hence, the performance. Therefore, it should be considered when requiring accurate measurements. To minimize those effects, limits on the humidity in the test cell during testing should be imposed.

Since absolute humidity does not change as the air entering from outside is static ambient, absolute ambient humidity outside the test cell can be sampled and the measurement used. This is valid so long as test conditions preclude condensation ahead of the inlet. Humidity transducers or a psychrometer may be used to measure ambient humidity.

Another operational problem is actual condensation in an engine inlet, which depends on a series of factors—relative humidity, air temperature, air pressure, inlet Mach number, and dwell or idling time. For given humidity conditions, the probability for condensation is higher in long inlet ducts and lower in bell mouth intakes.

Measuring Vibrations

The goal of vibration testing is to assure that the engine is free from destructive vibrations at all engine speeds, thrusts, power levels, or torque during steady and transient operations throughout the complete operating envelope of the engine. There are always engine-vibration limits that must be verified during the engine's production, acceptance testing, design assurance, and diagnostic testing. Most of these are purely mechanical and accomplished before the engine enters the cell. However, the test cell subjects the engine to realistic aeroelastic loadings, a prime concern.

The vibration equipment may consist of on-line measuring equipment (transducers to test cell readouts) and off-line analytic equipment (spectrum analyzers). Several of the vibration sensors most often used are as follows:

a. The most common type of transducer used in aircraft engine vibration measurement is the accelerometer. Provisions for determining amplitude and frequency in three mutually perpendicular planes at appropriate locations are part of the test's design. Accelerometers are easily mounted on the casing of the gas turbine. Since they are mounted on the casing, they pick up the vibration problems transmitted from other components. Accelerometers are more reliable than velocity sensors for higher temperatures. The accelerometer is best suited for measurements at high frequencies, such as blade passing, gear meshing, blade flutter, dry frictional whirl, surge, and gear-teeth wear.

> Accelerometers are more reliable than velocity sensors for higher temperatures.

b. Displacement probes measure shaft movement at the probe's location. They cannot be used very successfully to measure shaft bending away from the probe's location. The noncontacting eddy-current sensor is most effective for monitoring and measuring vibrations near rotational and subrotational speeds and is capable of measuring vibration frequencies of more than 2 kHz.

c. Velocity pickups are often used for their flat response of amplitude as a function of frequency as a go/no-go device. Average velocity amplitude is often used as an acceptance criterion because it is sensitive to many important vibration sources associated with gas-turbine aircraft engines.

When any engine exceeds the vibration limits as stated in the manufacturer's specification, the test is stopped until the source of the vibration is determined and eliminated.

SEA-LEVEL TEST CELL

The primary function of the engine test cell is to provide a controlled environment for testing that is compatible with the engine and not hinder its operation. It is therefore necessary to conduct tests in a facility that can provide accurate and consistent measurements of performance. All test facilities have unique characteristics that will affect the testing environment and influence the data obtained. This is particularly true of indoor test cells operating at ambient conditions on the surface. Figure 2 shows one of the typical configurations for sea-level testing of gas-turbine engines [1].

In addition to areas denoted on the figure, there is a test-control room for the instrumentation system, data acquisition and reduction equipment, a measured fuel supply, and an auxiliary power and control system.

Configuration Fundamentals of Engine Test Cells

Test Cell Inlet. The test cell inlet improves the incoming airflow to reduce the effects of external atmospheric wind speed, direction, and extreme temperatures. This system can include flow straighteners, heaters, screens, and noise suppressors. These components create a pressure loss which must be recorded in the test report and analysis. All spaces inside the test cells are designed to produce a uniform velocity profile approaching the engine—much like the engine would experience when

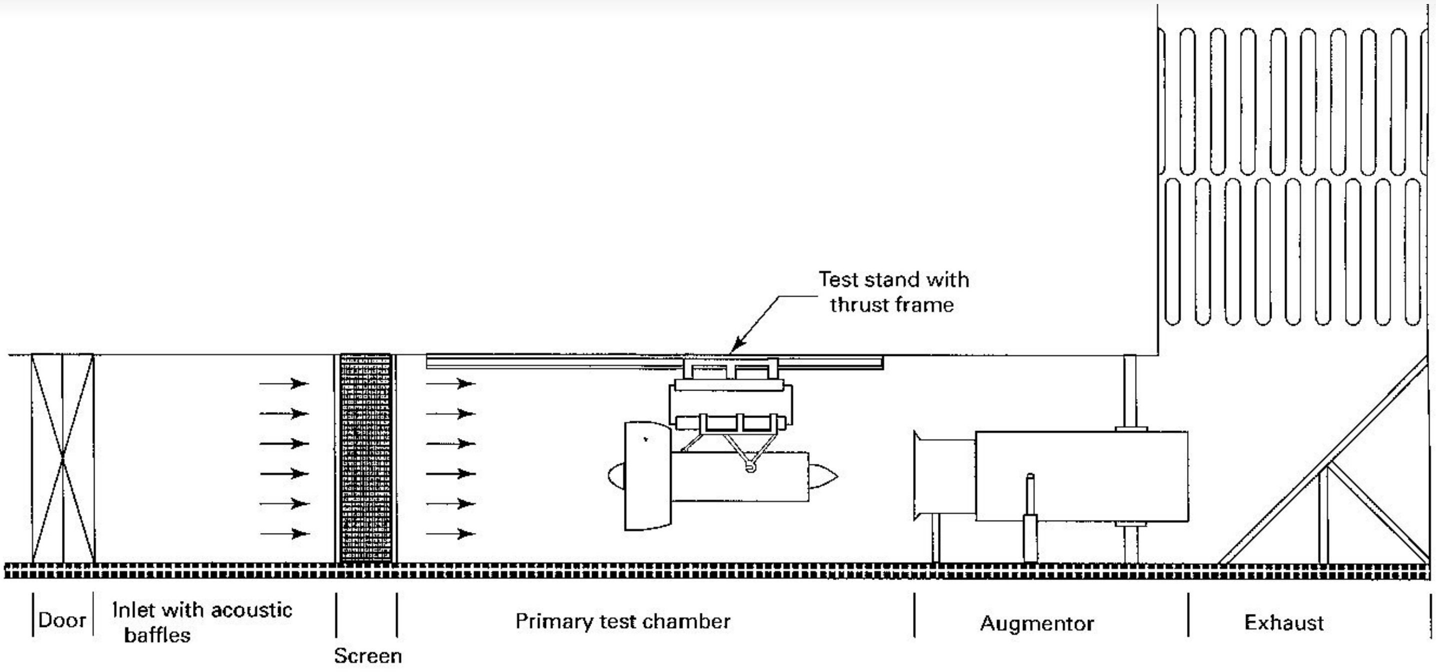


Figure 2: Sea-Level Test Cell for Fan-jet or Turbojet *(Source: American Society of Mechanical Engineers [ASME]).*

flying in clear air; however, this is not simple or easy.

Engine Test Section. The engine test section is the area immediately approaching the engine under test. Generally, this area will be a sufficient cross section so that the air velocity approaching the engine inlet will not exceed approximately 15 m/s (50 ft/s). In this section of a well-designed test cell, the airflow tends to have a uniform pressure distribution. Construction of the test section's design may incorporate tapered or concave corners at the transition where the air flows into the augmenter. Interior walls and ceilings should be smooth and free from protrusions. Vortices, turbulence, and nonuniform temperatures and pressures in the area surrounding the engine can drastically affect engine performance and the test's repeatability. Therefore, all test cells are designed to provide stable testing conditions and minimize turbulent flow by minimizing pressure losses, temperature changes, and pressure variations.

Engine Mounts. The engine mounts support the engine during testing and permit the engine's thrust to be accurately measured. Engine thrust is usually produced at the engine's centerline and transmitted through the mounts to a thrust frame. The thrust frame then pushes or pulls on a load cell, enabling measurement of the reaction. The most common method of engine mounting is overhead suspension. However, at some engine test facilities, the engine is mounted on a pedestal supported by the test cell floor. The overhead mount more closely simulates the mounting in many aircraft and easily accommodates cleaning the engine test section and accessing bottom-mounted engine accessories. The engine mount should be designed to prevent transverse motion, fishtailing, or any type of lateral instability and ensure that the engine's axial alignment is maintained during testing. With turbofans, poor lateral stability caused by the mount's flexibility can result in severe engine oscillations during testing.

Test Cell Exhaust System. In the test cell's exhaust system, the augmenter removes the engine's exhaust gases while inducing the flow of secondary air for cooling, providing some noise abatement. Mixing exhaust gases with the cooling secondary airflow that goes through the augmenter is then directed through an exhaust stack prior to exiting the facility. The following exhaust system features may influence the engine's performance and must be carefully considered:

- The augmenter's configuration (e.g., convergent or divergent)
- The augmenter's tube length and diameter
- Exhaust inlet tube diameter
- Axial distance between engine exhaust and augmenter inlet
- Area ratio of the engine exhaust to the augmenter
- Stack cooling (air or water)

A good test cell will not allow recirculation of engine exhaust gases from exhaust stack into the cell's inlet and must prevent the re-ingestion of exhaust gases into the engine inlet under most environmental conditions.

TURBOSHAFT AND TURBOPROP ENGINE TEST CELLS

The second class of gas-turbine aircraft engines tested is where power is delivered via a drive shaft. Therefore, determining shaft output power for turboprop and turboshaft engines is of prime interest and constitutes the main difference from the thrust-producing engines. Figure 3 shows a typical configuration of a test cell for turboprop engines [1].

The product of torque times speed yields the shaft power of the engine. There are two basic methods for measuring torque: (1) measuring the reaction torque of the absorption device or (2) directly measuring the shaft torque. Dynamometers typically provide controlled torque loading to turboshaft and turboprop engines during testing, as seen in Figure 3. There are several types of dynamometers commonly used for measuring the power, torque, and speed of an engine—a water brake (essentially, a very inefficient water pump), a fan dynamometer (functions like the water brake but uses air as the working fluid), and an electromagnetic absorber (a very inefficient electric generator). These essentially just waste the energy produced by the engine and produce heat with minimal flow.

A good test cell will not allow recirculation of engine exhaust gases from the exhaust stack into the cell's inlet.

Typically, torque is set by the dynamometer's control system while the engine's control maintains the required speed. Typical reaction configurations include a frictionless trunnion support with a load cell or a torsion ring firmly attached to earth. The installation is designed to minimize or eliminate forces from hoses, wires, instrumentation, etc., which can bias the measurement and add to the uncertainty. Usually, shaft-torque measurement is accomplished by directly measuring the shaft torque. This is commonly done by measuring the shaft's strain with a strain gage or by measuring its angular twist with a phase meter.

It is occasionally necessary to test the turboshaft engine on a propeller stand with its intended propeller. If the engine shaft or propeller is equipped with a torque sensor, it can be used to measure shaft power. This sensor must be calibrated using a torque arm and calibrated weights or in a dynamometer test stand prior to propeller-stand testing.

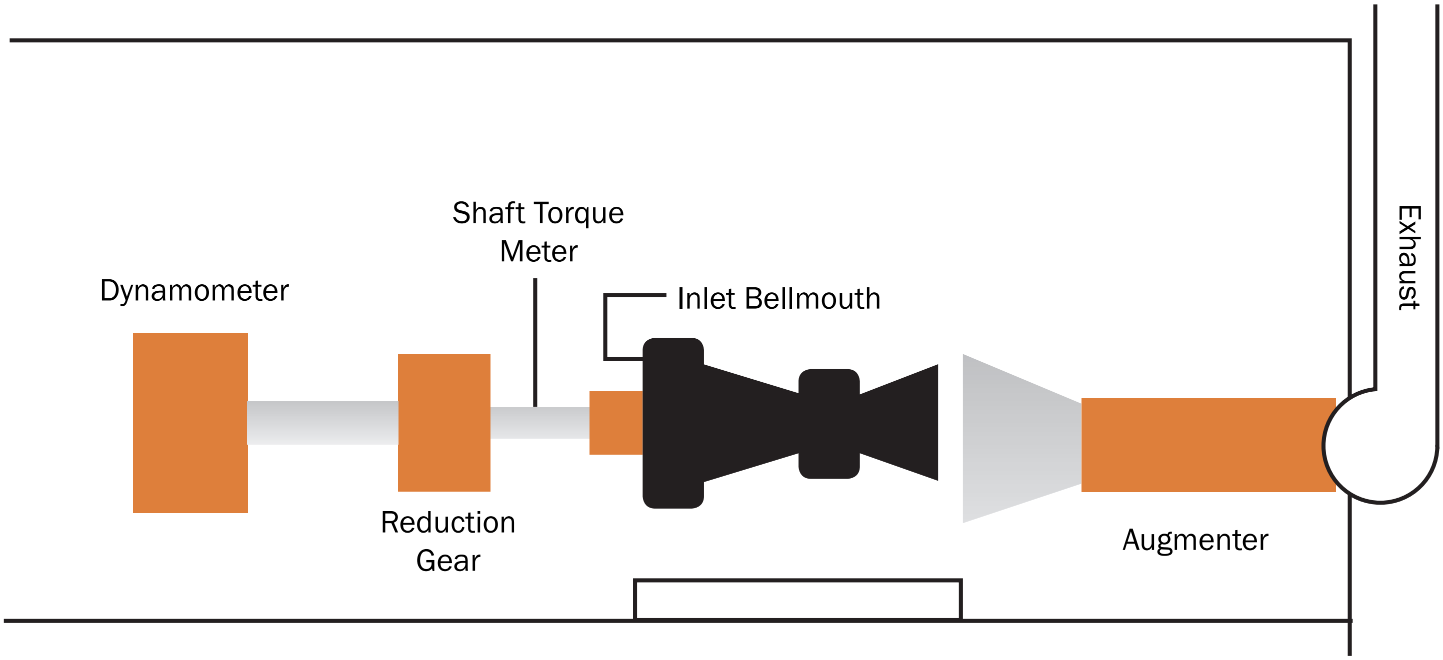


Figure 3: Conceptual Test Cell for Turboprop Engines *(Source: ASME).*

ALTITUDE TEST CELL

The third class of test cell is required to measure the engine's performance as specified at altitudes significantly above mean sea level. To validate such performance, especially for accepting a newly designed gas-turbine engine, it must be tested on the ground in an environment simulating the required altitudes.

An altitude test cell is a vacuum pressure vessel in which a gas-turbine aircraft engine is tested at simulated, high-altitude flight conditions. The chamber is connected to a sophisticated industrial plant of air-supply compressors, temperature conditioning equipment, and exhaust compressors. Altitude test cells may also have inlet air heaters, coolers, and driers or dehumidifiers to condition the incoming air. Altitude is set by "pumping down" the chamber to the lower atmospheric static pressures for the specified altitude. The flight Mach number is set by supplying air at the proper total pressure and total temperature to the engine inlet for the specified Mach number at that altitude. A typical altitude test cell is shown in Figure 4.

The types of testing commonly conducted at simulated altitudes in an altitude test cell are for engine development, qualification, and certification [1].

To measure the inlet air flow to an altitude test cell, the preferred current practice is to use a manifold of sonic flow nozzles upstream of the inlet bell mouth leading to the engine inlet or use the instrumented inlet bell mouth itself to measure the flow. These two methods are interrelated because the calibrated sonic nozzles are used to calibrate the bell mouth. The total pressure of the inlet flow is controlled. Inlet flow is measured by varying the number of nozzles through which flow is allowed and controlling the pressure upstream of these nozzles.

The inlet bell mouth is quite like a large standardized flow nozzle installed in a large pipe. However, each such bell mouth is unique, and its piping configuration and installation to the engine is likewise unique. Consequently, the calibration curve for each bell mouth depends on the peculiarities of its configuration and remains valid only so long as its installed configuration remains unchanged. Since these devices are not in strict accordance with the geometric specifications and tolerances of standardized nozzles and venturis, the generic calibration curves published in Chapter 5 of ASME – Performance Test Code (PTC) 19.5 [2] will not apply. However, once calibrated by the rules specified therein, it becomes a primary flow device. Using a pitot rake or other velocity-sensing instrumentation upstream of the first stage of the engine may also be used to measure the inlet flow.

UNCERTAINTY OF THE TEST RESULTS

Uncertainty analysis plays a very important role in testing gas-turbine engines—from designing the test to interpreting the results—because it defines the quality of the test and if the engine meets the desired performance. The smaller the overall uncertainties, the more accurate the test results. The very nature of the test will be a function of the engine's thermodynamic cycle and the computer model employed to calculate the engine's performance. The best engineering practice is to perform pre-test uncertainty analyses using the known or published values for the sensors intended to be used when

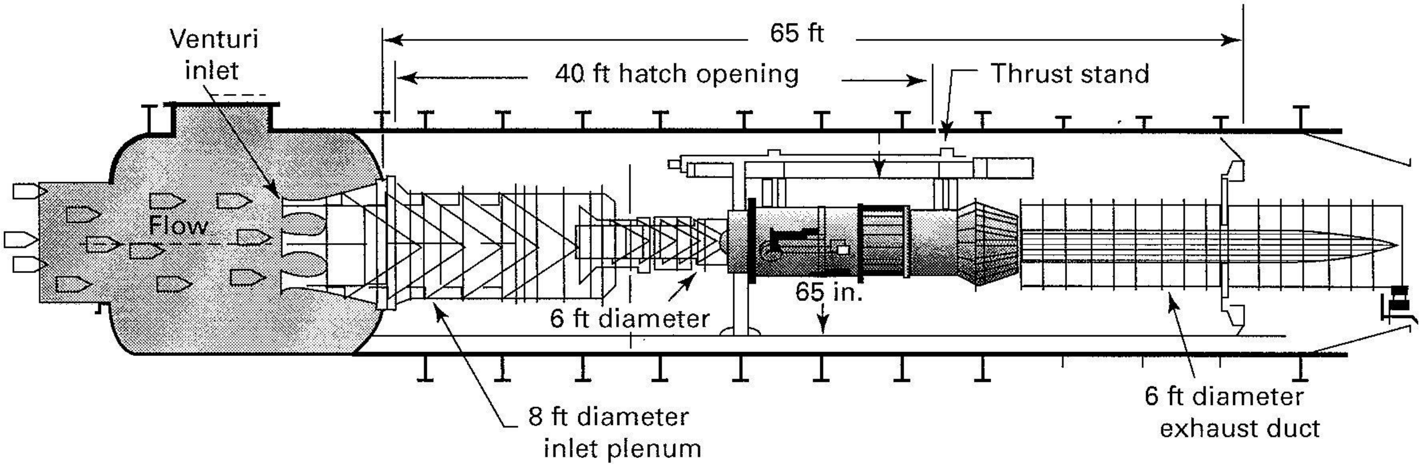


Figure 4: Typical Altitude Test Cell *(Source: ASME).*

applied to nominal, or historic, operating conditions. Then, improvements in the measuring system can be designed into the test plan. During and after the testing program, the observed uncertainties of the measured variables can be examined to see if they meet those predicted. These analyses often take much longer than the reduction of the data and computations of the engine's performance. Several codes and specifications available defining these processes are recommended [3, 4].

CONCLUSION

Testing very expensive aircraft engines in very expensive facilities must be planned carefully and executed with expertise and patience. For those not experienced in such detailed, expert testing, the public availability of rules for such testing, codified by balanced committees of volunteer experts, is an outstanding reference for buyers, contracting officers, and young engineers. Nearly all the original equipment manufacturers and DoD agencies have written their own such test procedures. During negotiations, it is helpful and cost-efficient to have an American National Standard handy for a second opinion.

A well-constituted, standards-development committee includes engineers representing the manufacturers, government, DoD services, and consultants. Such documents should be consulted, as they are designed to be adopted for use or guidance. ■

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[3] International Organization for Standardization (ISO). *Guide to the Expression of Uncertainty in Measurement.* ISO/IEC Guide 98, 1993.

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BIOGRAPHY

DAVE KEYSER is a subject matter expert with SURVICE Engineering Company. For 37 years, he was an engineer throughout NAVSEA and NAVAIR. His work in gas turbines began with the DD-963 Spruance class as the lead propulsion control engineer. During the following 17 years, he supported the tri-services' aircraft on various research and testing projects in fire modeling and protection, survivability, flying qualities, and advanced hydraulic actuators and flight control systems. A Fellow of the ASME, he was awarded the Performance Testing Gold Medal. He initiated and helped develop Performance Test Code (PTC) 55 on testing aircraft engines. Dr. Keyser holds a B.S. and M.S. in mechanical engineering from Swarthmore College and the University of Pennsylvania, respectively. He obtained his Ph.D. in aerospace engineering at the Eurotechnical Research University.

MANUFACTURING AT THE POINT OF NEED USING RECYCLED, RECLAIMED, AND/OR INDIGENOUS MATERIALS


A mine-resistant, ambush-protected (MRAP), all-terrain vehicle, graphically modified *(source: U.S. Marine Corps)*.

By Marc Pepi, Nicole Zander, and Margaret Gillan

INTRODUCTION

The ability to manufacture at the point of need in austere environments is a very important concept for the military. Research at the U.S. Army Research Laboratory (ARL) shows that agile, expeditionary manufacturing could be accomplished using materials indigenous to the location of our operating bases. Indigenous materials include not only the organic and inorganic materials naturally occurring in the area, but also recycled materials from the operating bases (metals, polymers, etc.) and battlefield scrap. This idea could potentially reduce the huge logistics tail needed to conduct wars on foreign soil, saving valuable resources and lives and allowing the Warfighter to perform the mission instead of guarding and securing convoy transports. Having access to technology using locally available indigenous materials would benefit our Warfighters by improving operational readiness, decreasing transportation energy costs, reducing spares inventory needed in-theater, and increasing self-sustainability of our operating bases. This article will describe ARL's efforts towards delivering manufacturing operations to the battlefield using indigenous recycled and reclaimed materials for feedstock.

BACKGROUND

Shrinking the logistics tail is an important benefit of utilizing materials in-theater [1]. The 2013 Army Sustainability Report outlines the Army's desire to reduce the number of convoys required to resupply troops on the battlefield [2]. Reducing vulnerable convoys not only saves materiel and lives, but troops assigned to guard these convoys can be utilized for their intended purpose–engaging the enemy. The charter to reduce the tail in the combat zone is deemed critical to the success of the overall Army transformation, with relevance to Army future missions [3]. The Army's research and development and sustainment communities should consider reducing the logistics footprint a principal goal. As stated in reference [4], "Technology will be one of the primary enablers to reduce the logistic footprint, and the reduction of the logistic footprint is clearly a key element of the future battlefield." In addition, the armed forces are increasingly playing humanitarian roles in assisting citizens who have lost their assets in a natural disaster and/or live in parts of the world where there is no infrastructure for creating buildings, roads, bridges, or manufacture materials that can clean water, create energy, or repair machines. The ability to build and repair items with ingenious materials dually serves the armed forces' and society's needs.

GOAL

The goal of this study is to develop technology to use recycled, reclaimed, and/or scrap resources for in-theatre additive manufacturing to provide value-added products for the Warfighter. This article will briefly describe research being performed by ARL in the following areas: (1) produce additive manufacturing (AM) grade metal powder in a shipping container (intended to supply an operating base with feedstock for metal AM operations) and (2) utilize waste plastics for three-dimensional (3-D) printing applications.

> The charter to reduce the tail in the combat zone is deemed critical to the success of the overall Army transformation.

CHALLENGES

There are many challenges associated with manufacturing indigenous materials in-theater. First, the materials must be readily available and in relatively large amounts to be useful. Next, a manufacturing process capability must exist at the operating base and be robust enough to provide a meaningful and reliable method of production, while retaining a small physical and environmental footprint. Scalability of these manufacturing processes must also be considered. In addition, power and energy requirements will dictate whether these manufacturing processes can be possible on the operating base. A further concern is how do extreme environments (i.e., vibration and thermal and atmospheric conditions) affect raw materials and what equipment is needed for the subsequent processing steps.

IMPACT

Transporting Army materiel to and from theatre is costly not only in terms of the logistic burden, but the time delays associated with replacing, repairing, and upgrading mission-critical equipment, systems, and vehicle platforms. The average Soldier alone generates up to 7-1/2 lbs of waste per day and often has very limited means to remove the waste; as a result, there is a need to address this from an environmental and health perspective. Water bottles are a major problem, representing 200–300 lbs/Soldier/year. Multiple waste streams composed of organic and inorganic materials (including trash from meals-ready-to-eat; cardboard boxes; cellophane and StyrofoamTM packing boxes; used oil and air filters; used motor oil; ammunition dunnage; empty brass cartridge casings; medical waste; used batteries; used steel-belted, off-road tires; etc. [5]) offer an opportunity for novel processing technologies to reuse these materials effectively in-theatre. Such an effort should be focused to offer a safe and environmentally responsible way to reduce disposal requirements by turning specific waste streams into value-added products.

ADDITIVE MANUFACTURING ON THE BATTLEFIELD

The Army has been using 3-D printers in forward areas in Afghanistan since 2012 [6]. These machines come in handy in producing parts made of plastic; however, no metal additive manufacturing equipment has currently made it to the battlefield due to various technical challenges. As Dr. Thomas Russell, former ARL Director, points out with respect to having the capability of having metal additive manufacturing in-theater [7], "Logistically there are benefits. One of our biggest challenges in the Army is that there is a huge logistics burden. If we could forward-deploy manufacturing capabilities, we would have the opportunity to manufacture parts in-theater, or repair parts. This is not just about manufacturing a new part, it's often about how we can repair something that has been damaged. We have the opportunity to do that in-theater and use local materials. It's an exciting area. I don't think we've realized its full potential."

Toward Production of Metal Powder on the Battlefield

One of the challenges associated with metal additive manufacturing on a forward-operating base (i.e., danger that needs to be reduced in risk) is transporting flammable metal powders for use with these processes. To counter this, ARL submitted a Small Business Innovative Research (SBIR) report titled, "Production of AM-Grade Metallic Powder on the Battlefield," which was approved for Phase-I contracts. According to Strauss [8], the problem with traditional metal powder production in-theater (such as gas or water atomization) is that too much infrastructure would be needed, including the equipment, utilities (electric power, water, and inert gas), post-processing the powder, need for cleanliness, etc. Strauss concluded that it would be more practical to stock an inventory of alloy powder for anticipated needs. Although these are legitimate concerns, it was decided to move forward with the AM research to determine whether the operations could be optimized to reduce the burden of these hindrances.

Two companies were awarded a Phase-I contract—American Engineering and Manufacturing (AEM) teamed with the University of Ohio and MolyWorks Corporation. AEM proposed to use Lorenz force levitation and melting, and MolyWorks proposed to produce metallic powder in a mobile foundry. Although the companies were only expected to show a proof-of-concept in the Phase-I effort, MolyWorks used their existing mobile foundry to produce metallic powder, including AISI 4130 steel, titanium 6-4, copper (Cu-101), 316 stainless steel (Figure 1), and 6061 aluminum alloy (Figure 2). This mobile foundry is contained within an International Organization for Standardization (ISO) container. With further research and development, it is anticipated that the ancillary equipment (controller, power supply, gas supply, etc.) could all be contained in an ISO container. The process also needs to be optimized because only a small percentage of the powder currently made falls within the sweet-spot diameter for metal additive manufacturing (approximately -325 mesh/45-μm diameter). Within the mobile foundry, the metal is placed into the crucible, melted, and poured over flowing argon gas. The metal powder is formed and collected through vortex separation into the cyclones at the end of the equipment.

> The average Soldier alone generates up to 7-1/2 lbs of waste per day and often has very limited means to remove the waste.

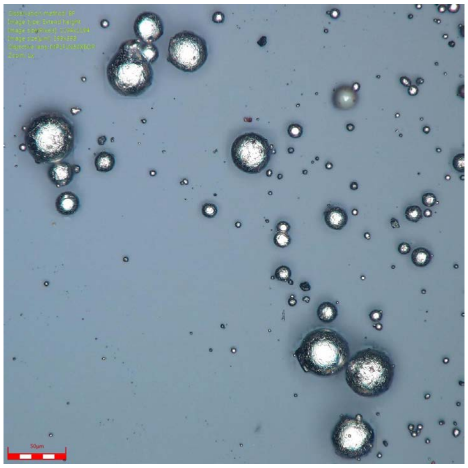

Figure 1: The 316 Stainless Steel Powder (-325 Mesh) Made in the MolyWorks Mobile Foundry Using Certified Alloy Starter Material *(Source: ARL).*

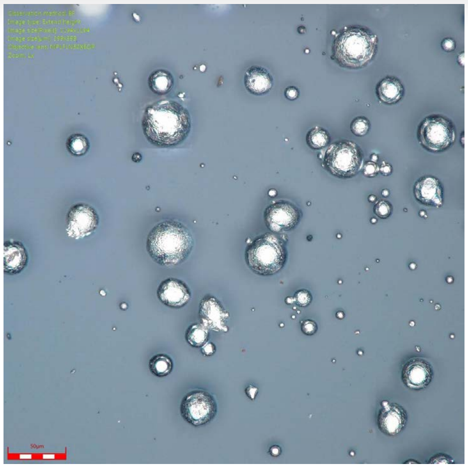

Figure 2: The 6061 Aluminum Alloy Powder (-325 Mesh) Made in the MolyWorks Mobile Foundry Using Certified Alloy Starter Material *(Source: ARL).*

To determine the feasibility of using scrap in this process, ARL furnished MolyWorks with a piece of actual battlefield scrap steel and battlefield scrap aluminum to add to certified steel and aluminum, respectively. MolyWorks was also able to produce aluminum powder made solely from aluminum battlefield scrap (Figure 3). For the most part, the particles are spherical and contain some satellites.

ARL also wanted to determine whether the powder produced in the mobile foundry could be used with the cold gas dynamic spray (cold spray) process. This is important because it would show that AM-grade metallic powder produced on the battlefield could potentially be used with a portable cold spray machine for repairing parts in-situ, extending the life cycle of these components, and reducing the logistics needed to

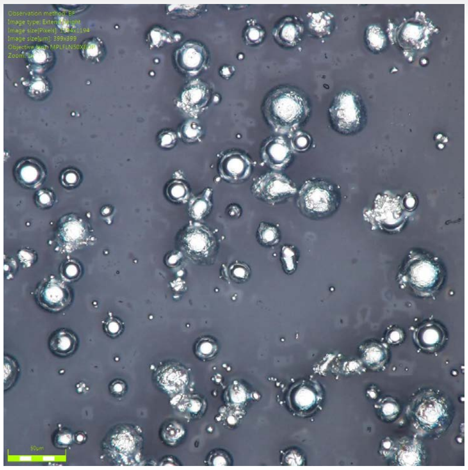

Figure 3: Aluminum Powder (-325 Mesh) Made Entirely From Aluminum Battlefield Scrap Within the MolyWorks Mobile Foundry *(Source: ARL).*

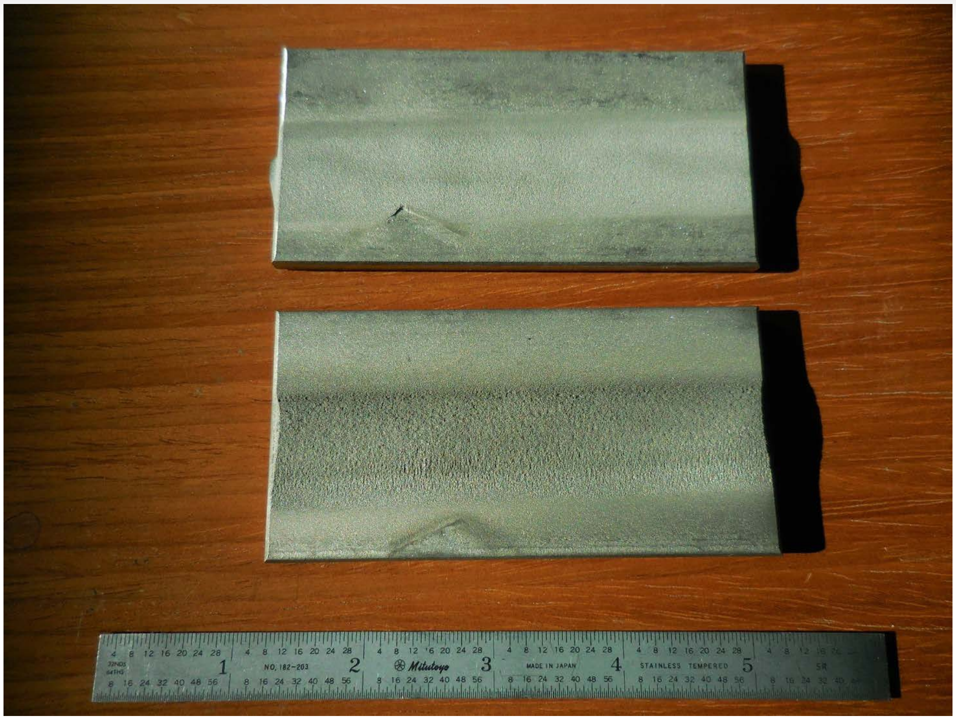

Figure 4: Oblique Lighting Photograph of Cold-Sprayed 316 Stainless Steel Powder (-325 Mesh) Made by Praxair (Top) and the MolyWorks Mobile Foundry (Bottom). Note the Rougher Surface Finish of the Cold Spray Build Using the MolyWorks Powder *(Source: ARL).*

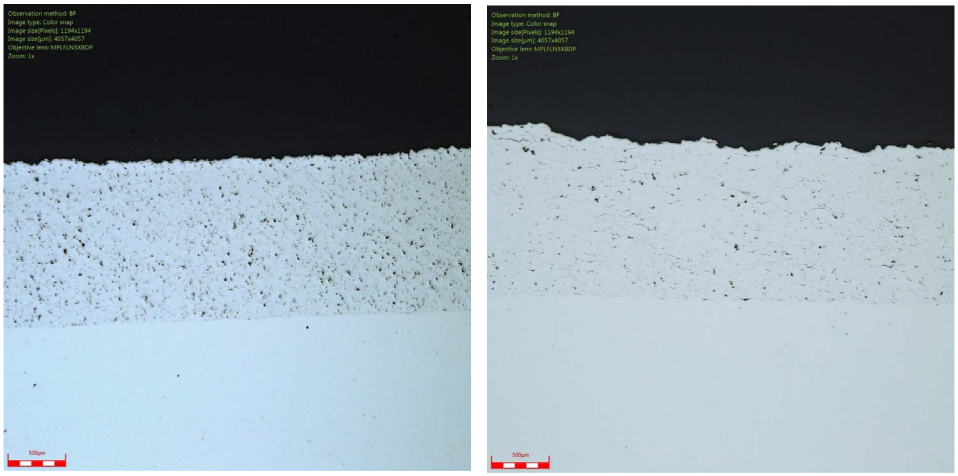

Figure 5: Micrographs of Cold-Sprayed 316 Stainless Steel Powder (-325 Mesh) Made by Praxair (Left) and the MolyWorks Mobile Foundry (Right). Although the MolyWorks Deposit Appeared to Have Less Porosity, It Contained Microcracking *(Source: ARL).*

get a spare part back to the theater of operations. The 316 stainless steel powder was placed within the powder feeder of the VRC Metal Systems Generation II (Gen II) portable cold spray system and sprayed onto 316L stainless steel substrate panels. For comparison, a sample of Praxair FE-101 316 stainless steel powder was also cold sprayed onto a substrate. It took 35 passes to build up 0.10-inch of MolyWorks powder, as opposed to only 25 passes for the Praxair powder. In addition, the surface finish of the cold spray build using the MolyWorks powder was rougher than the Praxair powder (see Figure 4). To determine the reason for this difference, the panel was sectioned and metallographically prepared. Figure 5 shows a comparison of the cross sections of the two cold-sprayed powders. The MolyWorks powder appeared to have less porosity but more microcracks, indicative of higher residual forces within the build. This process would need to be optimized, but it did show that the powder could be cold sprayed with a portable unit. The Praxair powder was analyzed to determine how it compared to the MolyWorks powder. Figure 6 shows that the Praxair powder was water atomized, making “splat” shaped particles, vs. the spherical particles produced from gas atomization.

Particles of 316 stainless steel were mounted and polished and subjected to scanning electron microscopy. Figure 7 confirms that the powder produced by the mobile foundry is mostly spherical, with a smaller amount of spheroidal shapes and very few angular shapes. Some porosity is seen in the cross sections, likely a result of atomization gas becoming trapped in the molten particles during solidification. The microstructure appears to vary from

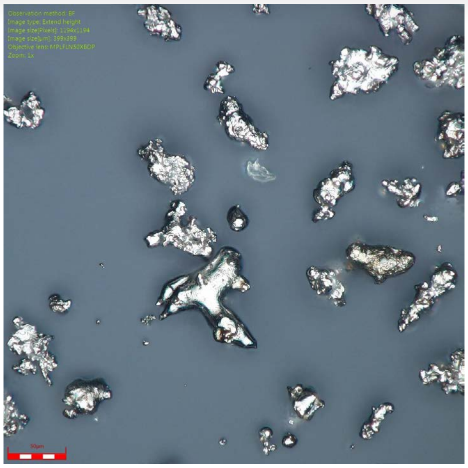

Figure 6: Praxair FE-101 -325 Mesh 316 Stainless Steel Powder Praxair That Has Been Water Atomized, a Contrast to 316 Stainless Steel Powder Made by MolyWorks That Was Gas Atomized (Figure 1) *(Source: ARL).*

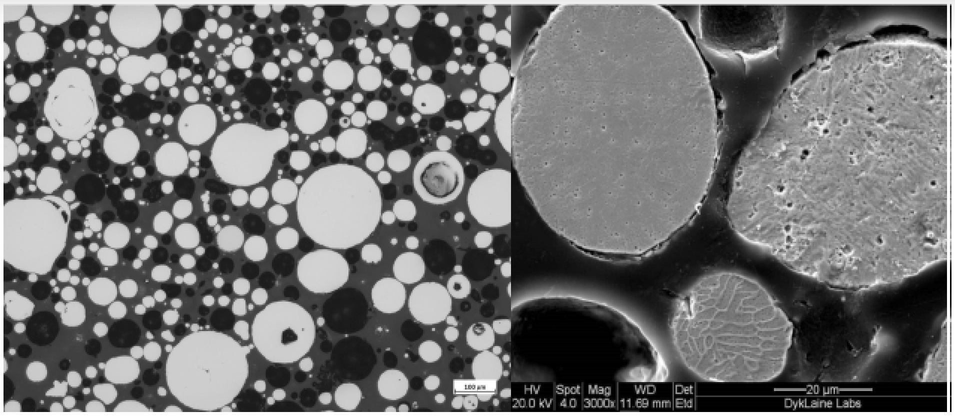

Figure 7: Scanning Electron Microscopy (SEM) Images of the 316 Stainless Steel Powder Produced by MolyWorks in the Mobile Foundry (100x Left, 3000x Right) *(Source: ARL).*

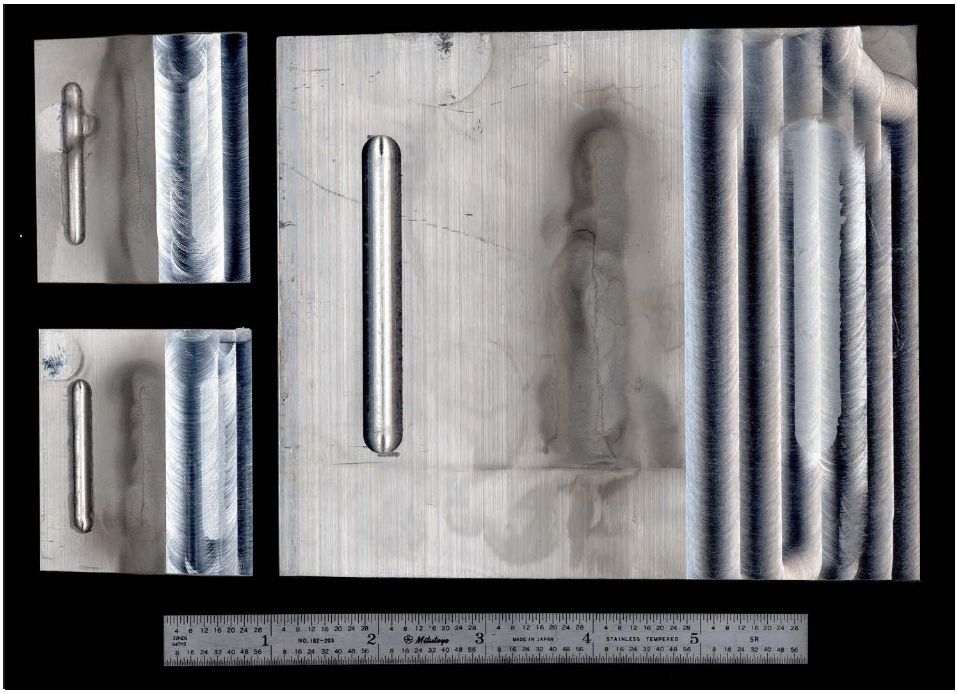

Figure 8: Cold-Spray Deposition of Aluminum Powder (-325 Mesh) Made Entirely From Battlefield Scrap Within the MolyWorks Mobile Foundry Onto Three Panels *(Source: ARL).*

particle to particle for the 316 stainless steel, perhaps due to variability in the manufacturing process.

The aluminum powder made entirely from aluminum battlefield scrap was also subjected to the cold gas dynamic spray (cold spray) process and deposited successfully, as shown in Figure 8. Three grooves were machined onto the test panels. Two grooves were filled with the portable cold spray system, and one was machined back to the level of the substrate. The cold spray deposition machined nicely, and no defects were visually noted. Figure 9 shows the mechanical mixing that was noted at the interface, indicating a strong adhesive bond.

Use of Indigenous Materials on the Battlefield

Historically, the Warfighter has used indigenous materials on the battlefield—from sticks and earth to form gabions and fascines, to sand and rock for sandbags, to expeditionary earth-filled protective-barriers and Hesco-barriers. According to MIL-PRF-32277 [9], this latter family of earth-filled barriers is intended to provide protection from visual detection, small arms fire, indirect fire, and perimeter intrusion. It should be noted that these products are more utilitarian in nature rather than technological innovations.

Three-Dimensional Printing of Casting Molds With Desert Sand

Three-dimensional printing with sand using commercial off-the-shelf printers is possible. However, these printers require original equipment manufacturer (OEM)-provided sand, as well as a binder, to keep the build together. The benefits of using 3-D printed sand molds vs. traditional sand molds include the following:

- Molds can be made in a shorter time, without complex and expensive tooling.
- Molds are generated from computer-aided design (CAD) models.

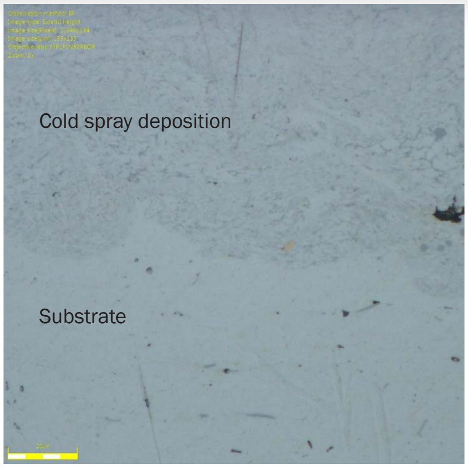

Figure 9: Section Through One of the Small Samples Shown in Figure 8 Exhibiting Mechanical Mixing at the Interface of Deposition and Substrate *(Source: ARL).*

- Complex geometries can be accommodated, with faster design modifications.

In addition, the benefit of using indigenous sand means one less item would need to be shipped to the battlefield.

ARL teamed with the University of Northern Iowa (UNI) on a Defense Logistics Agency (DLA)-funded project to determine whether indigenous sand (such as that found in a desert or beach) could also be used with these machines with the appropriate binder to manufacture appropriate long lead time parts in-theater. The idea is 3-D print molds based on a CAD drawing of a part could subsequently be used to traditionally cast molten materials into the part. This process would yield a part that was not 3-D printed, so it may be more readily accepted by the end user. As a proof of concept, sand from the Defense Training Center at Fort Irwin, CA (Mojave Desert) was sent to UNI to research its potential use with a 3-D printer. The OEM sand that is typically used with these printers is silicon dioxide, shown in Figure 10. For comparison, Mojave Desert sand at the same magnification is shown in Figure 11. Noticeable differences exist, including size distribution (which can be countered through sieving), composition, and the fact that the OEM sand is washed (no dust). The OEM sand looks closer to beach sand than desert sand based on the lack of dust (see Figure 12 for comparison). A CAD drawing of a mock component (Figure 13) was utilized to determine if it could be cast in A356 aluminum using Mojave Desert sand. A mold was made using the OEM powder for comparison. UNI screened the material to eliminate oversize and undersize particles and bond strength tested the sand using conventional foundry resins. Because desert sands may contain materials that affect the curing of conventional resins, various chemical hardeners were investigated. Once the molds were 3-D printed with desert sand, the aluminum was poured and the parts allowed to cool. Figures 14 and 15 show the parts made with OEM and desert sand, respectively. The part made with desert sand appeared to have a rougher surface finish and would most likely need more post-processing than the part made with the OEM sand.

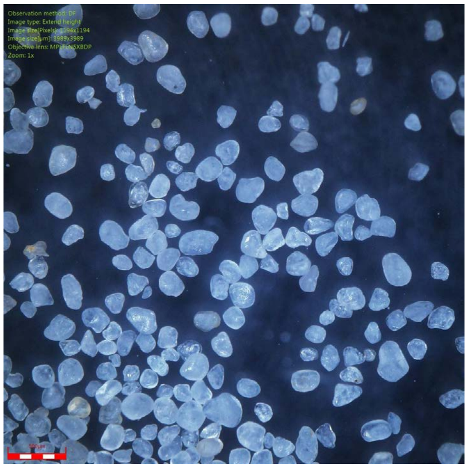

Figure 10: Typical OEM Sand Used With 3-D Sand Printers *(Source: ARL).*

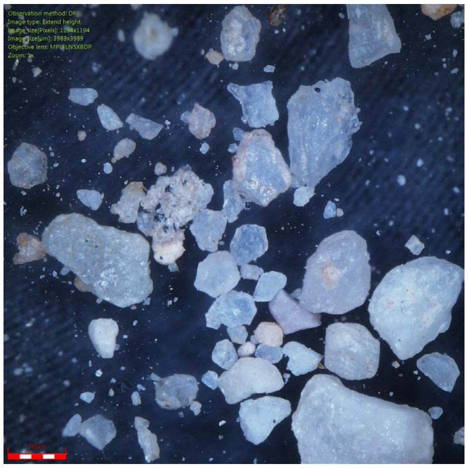

Figure 11: Sand From the Defense Training Center, Fort Irwin, CA (Mojave Desert) *(Source: ARL).*

Figure 12: Sand From Clam Pass, Naples, FL. Aside From the Bits of Shells, etc., the Beach Sand Compares Favorably to the OEM Sand Used With 3-D Sand Printers *(Source: ARL).*

Waste Plastics for 3-D Printing Applications

Although expeditionary AM is a relatively new area for the Army, the Army Rapid Equipping Force has already deployed polymeric AM fused deposition modeling (FDM) equipment to the battlefield as part of the Expeditionary Laboratory (ExLab) [10]. The ExLab contains a Stratasys Fortus 250, which is quite limited in the types of polymer feedstocks it can print, thus limiting applications. The main drawback of this machine is the requirement to use commercial filament from the OEM. Logical supply

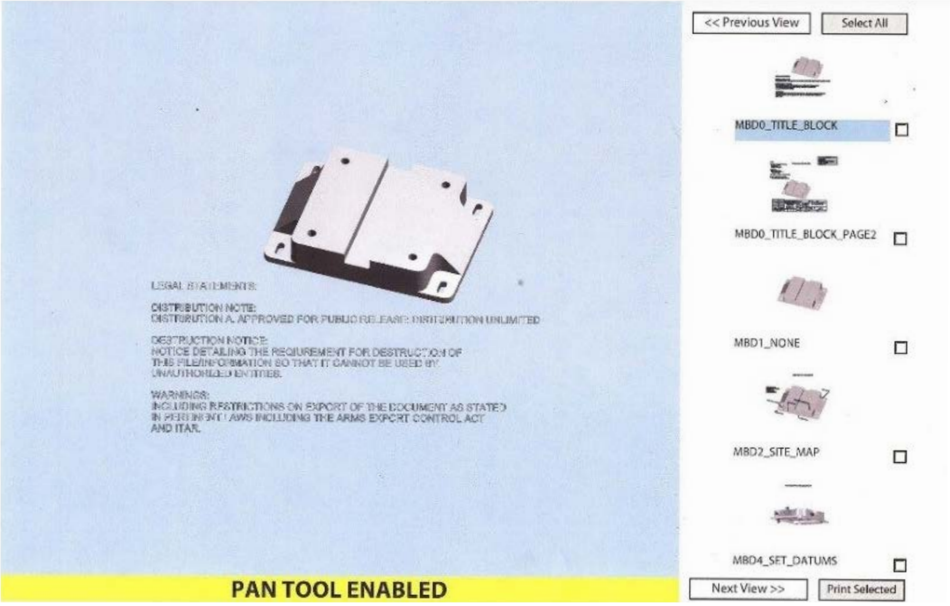

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Figure 13: CAD Drawing of a Mock Component to Be Aluminum Cast Using 3-D Printed Sand Molds *(Source: ARL).*

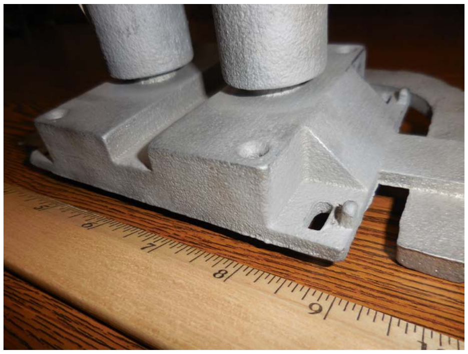


Figure 14: Cast Aluminum A356 Part Using a 3-D Printed Mold With OEM Sand *(Source: ARL).*

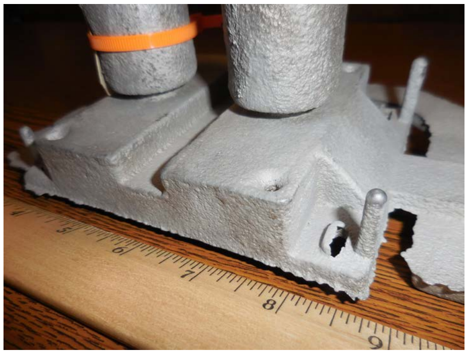


Figure 15: Cast Aluminum A356 Part Using a 3-D Printed Mold With Mojave Desert Sand. Note What Appears to Be a Rougher Surface Compared to the Part Made With the OEM Sand (Figure 14) *(Source: ARL).*

chain issues can again come into play if such filament is unavailable. Figure 16 shows some possible baseline parts made in the ExLab in-theater out of acrylonitrile butadiene styrene (ABS) polymer. Research at ARL was performed to determine the feasibility of 3-D printing using recycled polymers (from an operating base). This included FDM filament feedstocks of polyethylene terephthalate (PET) such as soda bottles; polypropylene (PP) such as yogurt containers; high-density polyethylene (HDPE) such as milk jugs; and polystyrene (PS) such as utensils. The challenges of using recycled materials include the purity of the materials, including additives/fillers/dyes present in many plastic containers and biological and chemical contamination, mixed or unknown feedstocks, and limited power and cleaning materials availability for processing.

Polymer filament was prepared by rinsing plastic containers with ethanol, drying and cutting into pieces that could be fed either through a cross-cutting paper shredder (PET, HDPE, and PP) or a high-speed blender (PS). After shredding, HDPE and PP were mixed in a high-speed blender to form uniform shred sizes. Shredded polymer was fed into a Filabot and/or Process 11 extruder at temperatures ranging from 140 °C to 270 °C to melt the polymers, and the extrudate was collected on a spooler (Filabot). Nozzle diameter was adjusted between 1.75 mm and 3 mm to account for die swell and shrinkage. Target diameter was 1.75 mm and 3 mm.

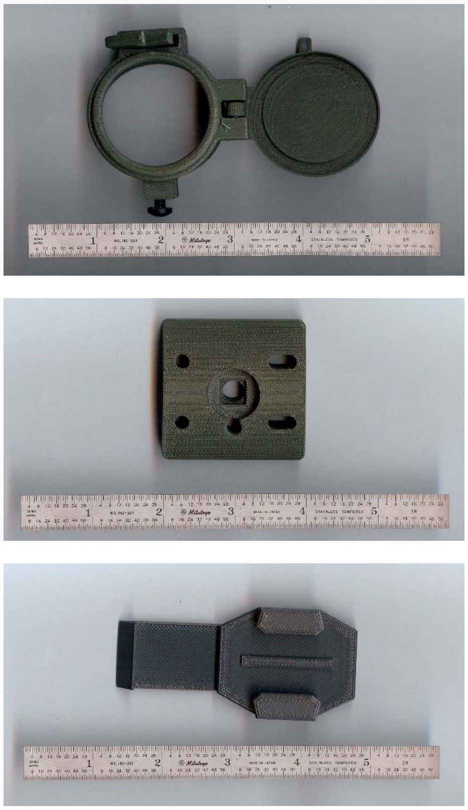


Figure 16: Photos of Items 3D Printed In-Theater (Courtesy of the Army Rapid Equipping Force) *(Source: ARL).*

Filament was printed into tensile bars (Type V, ASTM D638 [11]) on FlashForge Creator Pro and Lulzbot Taz 6 FDM printers. Stereolithography (.stl) files were imported into Simplify 3D to generate toolpaths for the equipment to follow. This program converts the model file (.stl) into a series of toolpaths

(.gcode) that the machine reads to determine where the print head moves and how much filament it extrudes. The bed temperature was varied between 60 °C and 100 °C, while the nozzle temperature varied between 220 °C and 280 °C. The build orientation was in the X direction, with the layer height set to 0.2 mm. The infill density, pattern, and outline overlap were optimized for tensile strength with the commercial Stratasys polycarbonate-acrylonitrile butadiene styrene (PC-ABS) filament.

Thermal properties were measured using differential scanning calorimetry (DSC) with a heat/cool/heat program (TA Instruments). All samples were heated at 20 °C/min to 300 °C, cooled 20 °C/ min to -50 °C, and then heated again at 20 °C/min to 300 °C. DSC data was processed using Universal Analysis software. Chemical analysis was performed by Fourier transform, infrared-attenuated total reflectance (FTIR-ATR) (Thermo Nicolet Nexus 870 ESP) using 256 averaged scans and 4 cm^{-1} resolution over a range of 4000 to 400 cm^{-1}.

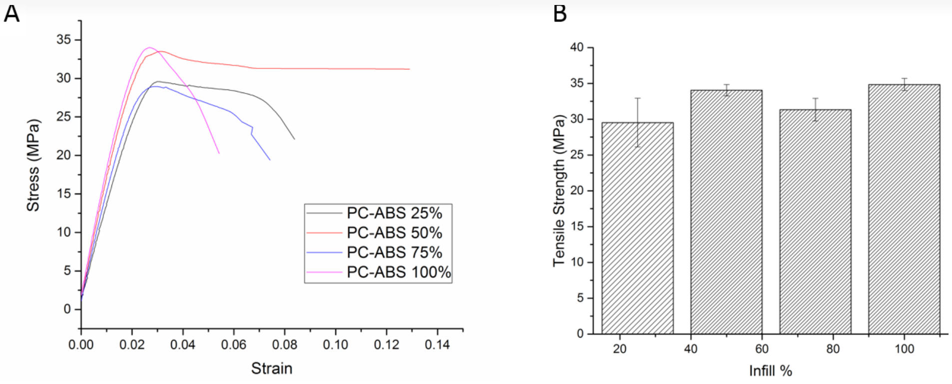


Figure 17: Tensile Test Results on PC-ABS Tensile Bars With Varied Infill Density (A) Stress-Strain Curves and (B) Tensile Strength *(Source: ARL).*

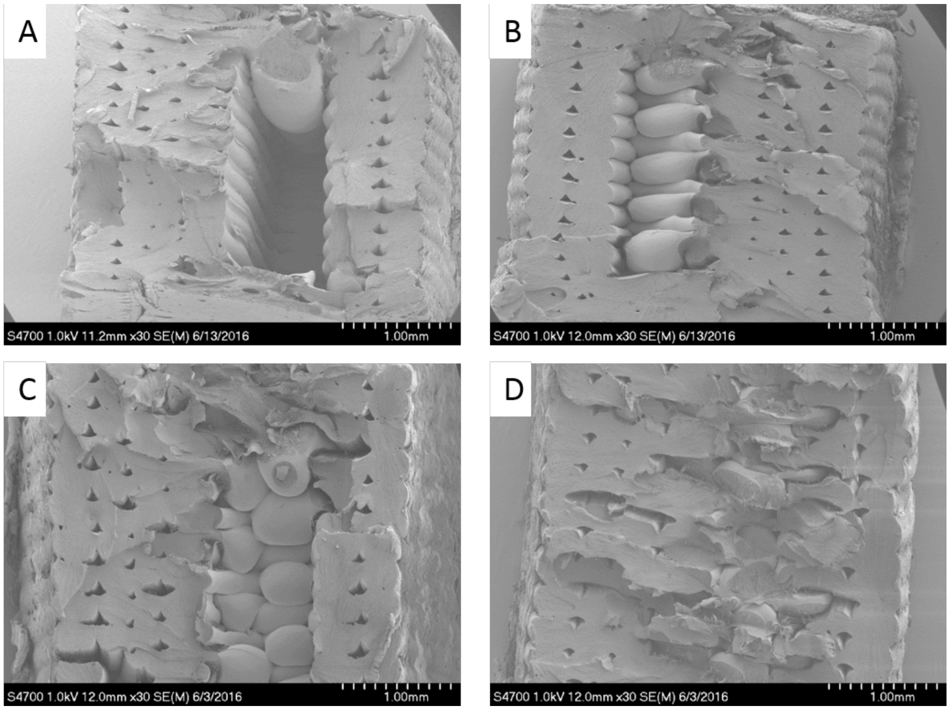


Figure 18: Scanning Electron Microscope Images of Fractured PC-ABS Tensile Bars With Varied Infill Density (A) 25% Infill, (B) 50% Infill, (C) 75% Infill, and (D) 100% Infill *(Source: ARL).*

Select forward-operating bases have Stratasys FDM printing machines which typically use Stratasys PC-ABS filament. To determine the best mechanical properties that could be achieved with this filament, a series of tensile bars were printed in which the infill density, infill pattern, and outline overlap varied. Figure 17 displays the effect of infill density on tensile strength and stress-strain curves for 25%, 50%, 75%, and 100% infill (grid, 30% overlap). Surprisingly, there is little improvement in tensile strength above 50% infill. Tensile strength was higher for the 50% infill, compared to the 75% infill. Figure 18 displays SEM images of the fracture surfaces. All specimens show a printing defect between layers. Filament shape is partially distorted due to melting into the next layer, but filaments are still distinguishable. The breakage occurs for the 25% infill at the void (Figure 18A). There is some filament necking evident in the 50% infill specimen, and the 75% and 100% specimens also show signs of deformation. The effect of the infill pattern was also probed (50% infill, 30% overlap) using four common patterns—grid, fast honeycomb, full honeycomb, and triangular. Figure 19 displays the tensile results and a representative stress strain curve. There was little variation in tensile strength between the different patterns. The triangular and grid patterns had the most reproducibility, while the honeycomb patterns, particularly the fast honeycomb, had high margins of error.

The outline overlap or percentage of overlap of adjacent filaments was also probed at 50% infill (grid pattern). Overlaps of 10% to 75% were probed; there was very little change between 30% and 75% overlap (see Figure 20).

Recycled polymers have a variety of different additives, fillers, and dyes and may have experienced different processing conditions, even for the same polymer type. To get a better understanding of different recycled polymer feedstocks and the best properties to expect from such materials, thermal and mechanical testing was performed. Tensile dogbones were cut out of milk jugs, soda bottles, yogurt containers, and plastic cups (polypropylene) using a die. Plastic water bottles could not be tested due to the ribs in the bottles. Polystyrene materials were too brittle to punch out. (Injection molded parts for all polymers will be compared in future work.) Representative stress-strain curves are displayed in Figure 21, along with the tensile strength and elastic modulus of each material. The soda bottles (PET) had the highest tensile strength, nearly 5x that of the polyolefin materials. The PET bottles had two yield points, with a significant amount of stretching before failure.

Table 1 displays thermal properties from DSC measurements. The two sources of PP examined, PP cups and yogurt containers, have the same melting temperature and similar percentages of crystallinity. However, the crystallization temperatures are 16° apart. This difference may be from the dyes and fillers in the yogurt container compared to the transparent cups and likely had less additives. The thermal characterization of PS only provided glass transition (Tg) information since it is an amorphous polymer, and the Tg's were identical for the two sources of PS. The thermal information for the PET water and soda bottles was markedly different. The PET in the soda bottles had a higher Tg, melting point, and lower crystallization temperature and was more crystalline. Only one source of HDPE was examined.

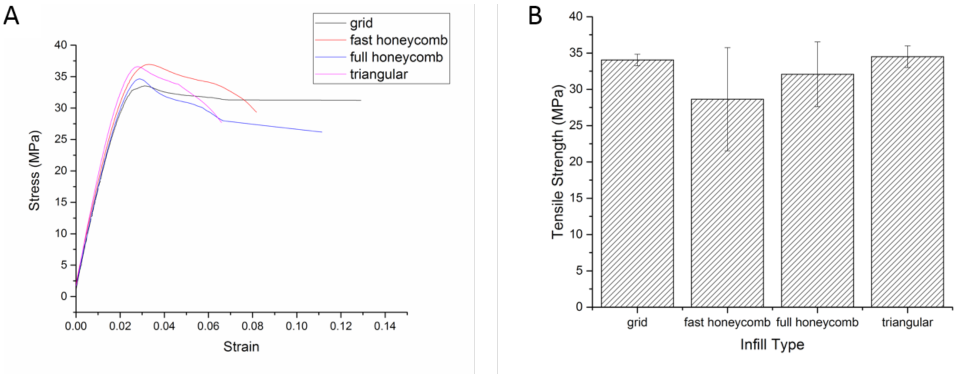


Figure 19: Tensile Test Results on PC-ABS Filament With Varied Infill Pattern (A) Stress-Strain Curves and (B) Tensile Strength *(Source: ARL).*

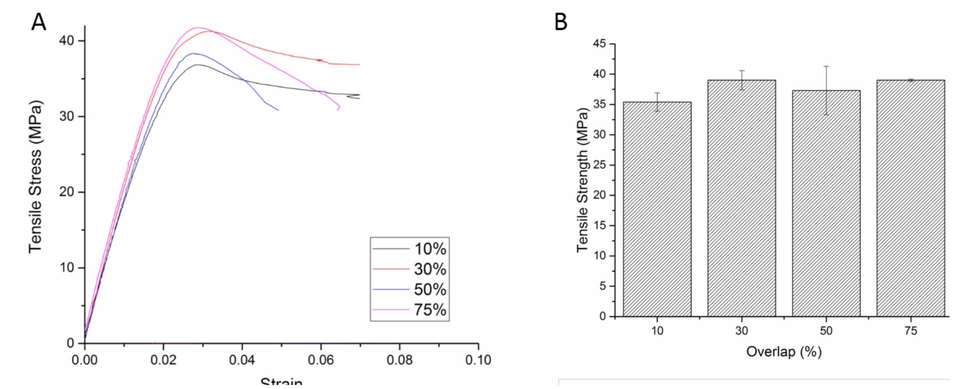


Figure 20: Tensile Test Results on PC-ABS Filament With Varied Outline Overlap (A) Stress-Strain Curves and (B) Tensile Strength *(Source: ARL).*

Chemical characterization was performed using FTIR (Figure 22). The two sources of PS examined (petri dishes and utensils [opaque]) appear chemically identical, even with the presence of fillers in the utensil. The two sources of PET (water and soda bottles) also appear identical. The PP cups and yogurt containers had three regions that were notably different, most likely due to the dyes in the yogurt containers.

Recycled PS, PET, and PP has been fabricated into filament and printed into tensile bars. Tensile bars from recycled plastic were printed using either 50% (PS) or 100% (PP, PET) infill, with a grid pattern and 30% overlap. The PS tensile bars were quite brittle and had a mean tensile strength of 19.9 ± 3.9 MPa or about half of the Stratasys filament (34.0 ± 0.8 MPa). Because the PS filament was so brittle and difficult to spool and feed in the printer, infill and printing parameters were not optimized. PET filament from plastic soda bottles had a tensile strength comparable to the Stratasys PC-ABS filament (36.4 ± 3.1 MPa [PET] vs. 34.8 ± 0.8 MPa [PC-ABS]). PP from yogurt containers had a lower mean tensile strength of 20.1

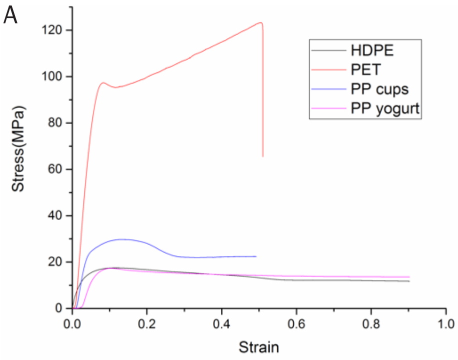
± 2.3 MPa. Printing parameters are currently being optimized to improve tensile strength of the printed parts from recycled filament. Filament has been made with HDPE but not yet printed or tested.

CONCLUSIONS

Reducing the dependence on the logistical supply chain on forward-operating bases will not only increase operational readiness and the self-sustainability of Warfighters in-theater, but also improve the safety of the Warfighter by reducing threat vulnerabilities. The ability to fabricate needed parts on demand, in-theatre in austere environments with available resources, would be game-changing for the military.

With the production of AM-grade metallic powder in-theater, MolyWorks has made great strides in producing powder in a mobile foundry contained within an ISO container. The batches can be made with scrap metal, and the subsequent powder can be cold sprayed and additively manufactured using the Laser Engineered Net Shape (LENS) process. The vision is to have the future capability to produce this powder in-theater for real-time repair of components (e.g., with cold-spray technology) or building spare parts.

UNI has shown that desert sand can be 3-D printed to make casting molds to produce parts via traditional foundry casting. This proof-of-concept showed that locally available sands, with little processing, could be effectively utilized to produce metal casting molds of sufficient strength to cast light metal alloys. This capability may someday allow manufacturing parts in-theater using indigenous sand and recycled/reclaimed battlefield scrap.



B

Sample	UTS (MPa)	Elastic Modules (MPa)
HDPE (milk jugs)	18.6 ± 1.3	577 ± 64
PET (soda bottles)	102 ± 19	1838 ± 258
PP (yogurt containers)	26 ± 6	942 ± 365
PP (cups)	31 ± 1	959 ± 51

Figure 21: Tensile Test Results on Recycled Polymers (A) Stress-Strain Curves of Die-Cut Tensile Bars and (B) Tensile Strength and Modulus *(Source: ARL).*

Table 1: Thermal Characterization of Recycled Polymers Using Differential Scanning Calorimetry *(Source: ARL).*

Polymer	Tg(°C)	Tc(°C)	Tm(°C)	% Crystallinity
rPP (cup)	-6.8	126.6	165.9	53.6
rPP (yogurt tub)	*	110.7	169.9	45.7
rPS (utensil)	91.7	–	–	–
rPS (petri dish)	89.2	–	–	–
rPET (soda bottle)	92.5	188.2	248.4	46.5
rPET (water bottle)	73.3	197.2	243.9	18.5
rHDPE (milk bottle)	**	115.6	137.8	75.5
*Tg not visible, **Tg below instrument minimum (< -80 °C)				

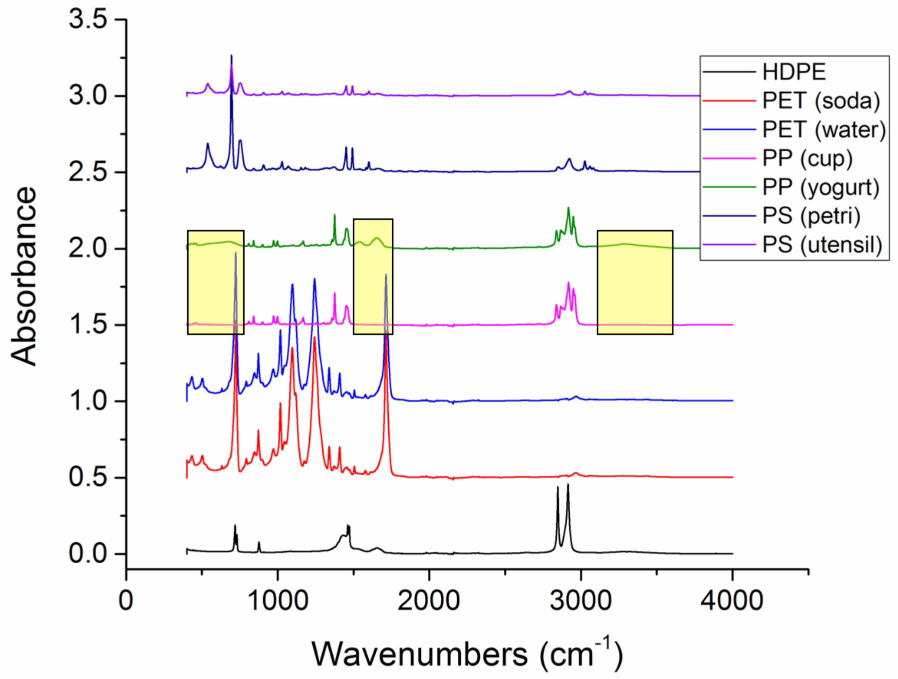


Figure 22: Chemical Characterization of Recycled Polymers Using FTIR-ATR. Yellow Boxes Highlight Different Peaks Between Polypropylene Sources *(Source: ARL).*

> The ability to fabricate needed parts on demand, in-theatre in austere environments with available resources, would be game-changing for the military.

Finally, ARL researched using recycled plastics with 3-D printing applications. Studies were conducted to determine the best print parameters to make the strongest part with the least amount of material. Sources of potential plastic waste were characterized to understand thermal, mechanical, and chemical properties. PET had the highest tensile strength—likely, the best candidate for making strong plastic parts. Tensile bars were printed with recycled filaments and tested. Future work will involve testing tensile specimens from recycled PP, HDPE, and PET filaments.

FUTURE WORK

ARL is interested in all manufacturing processes that can be utilized in-theater with indigenous recycled and reclaimed materials and will pursue paths leading to the ultimate use of AM on the battlefield using these materials as feedstocks. ■

ACKNOWLEDGMENTS

The authors wish to thank the following individuals for their contributions to this work: Chris Eonta and team at MolyWorks Corp.; John Lawmon and team from AEM, Inc. (AM-Grade metallic powder from battlefield scrap); Prof. Jerry Thiel and team from UNI; and Kelly Morris and team from DLA (3-D printing with desert sand for metal casting).

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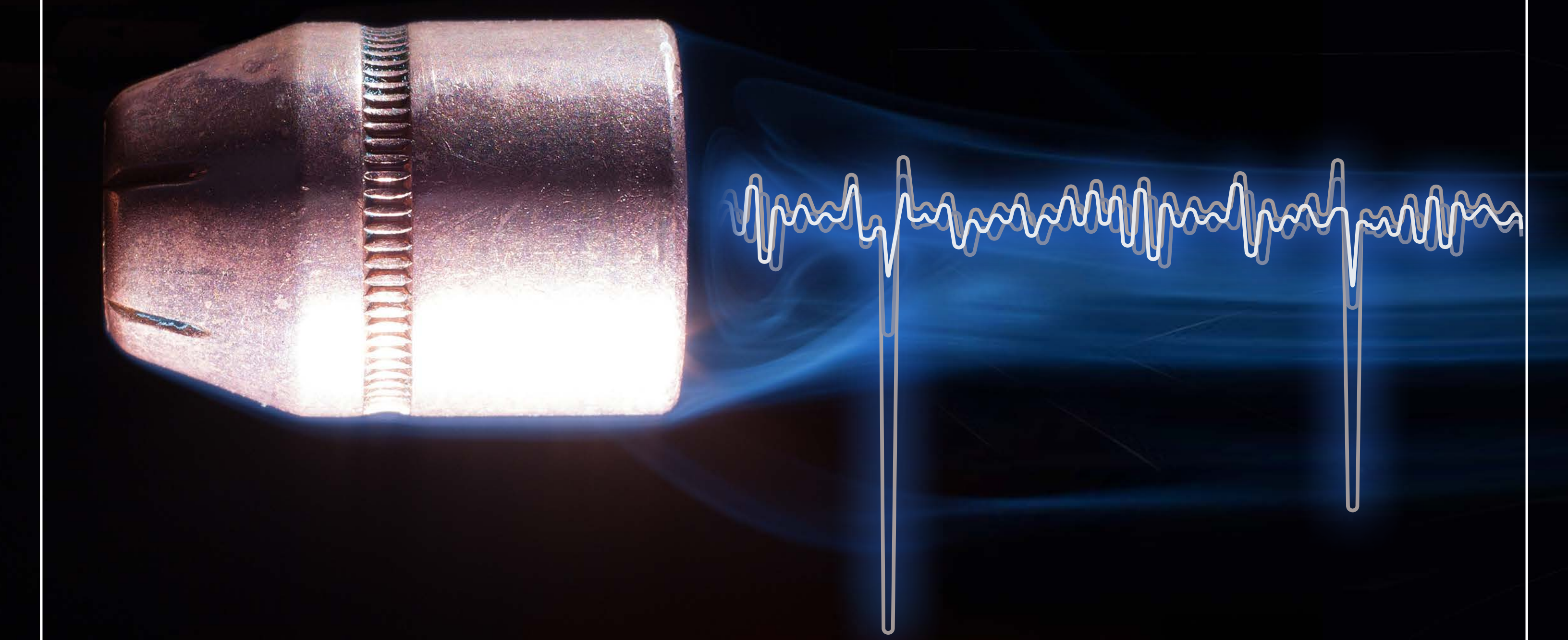
BIOGRAPHIES

MARC PEPI is a materials engineer with ARL and currently the leader of the Hybrid Additive Manufacturing Team. He has worked over 34 years for the Department of Defense in materials behavior and characterization, failure analysis, inorganic coatings, and expeditionary manufacturing. He has an Army Black Belt in Lean Six-Sigma and is a Fellow of the Society for Machinery Failure Prevention Technology. Mr. Pepi holds a B.S. in mechanical engineering and an M.S. in engineering management from Northeastern University.

NICOLE ZANDER is a research chemist in the Polymers Branch at ARL. Her primary research interests are polymer processing, additive manufacturing, and nanofiber research in tissue engineering, antimicrobial materials, and filtration. Her major focus is on recycling waste plastics and other materials into additive manufacturing feedstocks. Dr. Zander is part of a winning Marine Innovation Challenge team in which she is working on building a mobile laboratory that recycles plastics into filament for 3-D printing. She holds a B.A. in chemistry from St. Olaf College and a Ph.D. in analytical chemistry from the University of Delaware, where she explored using electrospun nanofibers to control neurite outgrowth via protein chemistry and contact-guidance.

MARGARET GILLAN is an Oak Ridge Institute for Science and Education (ORISE) Research Fellow at ARL. Her research interests include sustainability in 3-D printing as well as expanding the scope of printable materials. She holds a B.S. in chemistry from the University of Maryland and will begin working toward obtaining her Ph.D. degree in chemical engineering this spring.

DETECTING BULLETS THROUGH ELECTRIC FIELDS



By Yongming Zhang

INTRODUCTION

Imagine detecting a passing bullet and its origination through an electric field (E-field) instead of an acoustic one. This is exactly what the U.S. Army has been investigating—electric-field based bullet detection systems that can identify the presence and range of a passing bullet as well as establish the direction of its origination point.

U.S. Warfighters need a real-time notification system to detect small-arms threat locations. The system must be accurate and effective in ambush scenarios and close-quarters urban combat environments. These include complex firefight environments involving multiple shooters, different weapons (single fire to full automatic, silenced guns, subsonic bullets), background detonations and explosions, and man-made noise/interference.

Existing first-shot detection systems are mainly based on acoustic sensing. Although arrays have demonstrated the ability to locate bullets relatively precisely, they may become saturated or degraded by reverberation and multipath propagation, multiple threat scenarios, high levels of acoustic noise, and/or vibration on vehicles. In addition, the systems do not detect the presence of subsonic bullets or bullets fired from "silenced" weapons. Their largest weakness for the U.S. Department of Defense (DoD) is that they may lose operational capability on the battlefield because of the high levels of background acoustic noise from tanks, planes, and munition explosions.

In addition to acoustic-based detection, it is possible to detect the muzzle flash of a bullet being fired with an optical array. In some instances, a very sensitive array under ideal conditions may even be able to detect the presence of a passing bullet by the friction it generates as it moves through air. However, the performance of such systems requires line of sight to the bullet and degrades in situations with multiple intense light sources, such as a battlefield environment. In addition, accuracy can be affected by suppression devices designed to change the character of the muzzle flash, like an acoustic silencing device.

E-FIELD-BASED BULLET DETECTION

When a projectile travels in space, triboelectric charges build up on its surface, and the moving charge creates an E-field that can be detected and tracked by a small array of E-field sensors. A traveling projectile very quickly rises to a significant electric potential due to combustion and triboelectric (frictional) static electric charging [1]. Since 2005, the U.S. Army Armament Research, Development and Engineering Center (ARDEC) and Army Research Laboratory (ARL) have been investigating E-field technology for bullet detection capability. ARDEC and ARL have performed extensive tests of this technology for accurate bullet detection of single and multiple gunshot events at different ranges with full automatic rapid fire, silencers, and subsonic rounds [2, 3].

> U.S. Warfighters need a real-time notification system to detect small-arms threat locations.

The magnitude of the E-field signal on projectiles scales with increasing size of the projectile and the amount of initial combustion. The response of the sensor depends upon the distance of the closest approach and the relative angle between the sensor axis of symmetry and the path of the projectile. As a result, mutually orthogonal E-field measurements can be used to track the direction of the projectile and thus identify the origination point. Although the current research focus has been on bullets, an E-field-based system can also detect other projectiles such as rocket-propelled grenades (RPGs). Researchers at ARL have collected E-field signals from in-flight RPGs [4]. As expected, the projectiles were easily detected with the larger signal resulting from their bigger size.

The technology's utility can be seen in Figure 1. The left is an acoustic measurement of a shot. The middle shows a second shot, but with the gun silenced. The microphone can no longer acquire clear information about the event. (Note that silencing Shot 2 does not impact measurement.) The right figure, however, shows E-field measurements of the two shots. The E-field sensor can acquire adequate data about the silenced shot to make it clearly detectable.

Until recently, limitations of sensing technology have constrained the usefulness of this technique. Recent advances in E-field sensing technology have enabled the development and demonstration of a research-grade, Army-funded bullet detection system

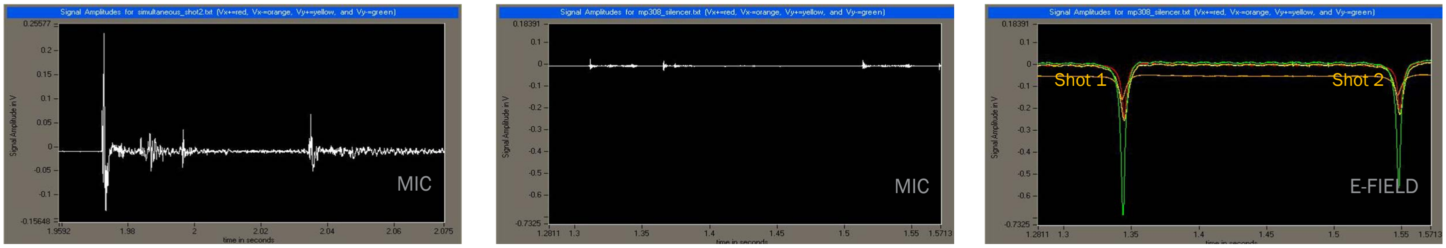


Figure 1: E-Field Measurement Sensing Silenced Bullets: (Left) Shot 1—Acoustic Detection, No Silencer; (Middle) Shot 2—Acoustic Detection, but Silenced Bullet; and (Right) Both Shots With E-Field Detection *(Source: QUASAR Federal Systems).*

whose capabilities fill gaps left by the acoustic-based gunshot detection systems currently used. The system can not only detect bullets that are passing by its sensing apparatus but also has a direction indication display that tells the user where the shot originated. The system can function in noisy areas, including in the presence of multiple gunshots; in urban environments, where acoustic-based systems can be confounded by effects created as sound encounters multiple tall buildings; and with silenced firearms and subsonic bullets, which may evade acoustic detectors.

ARDEC research personnel have used E-field sensors to detect signals from a wide variety of small arms fire, from 5.56 North Atlantic Treaty Organization rounds to .50-caliber Browning machine gun fire [4]. In some of these experiments, the sensors were mounted on a high-mobility, multipurpose wheeled vehicle (HMMWV – commonly known as a Humvee). Some of this work was conducted using high-sensitivity sensors from QUASAR Federal Systems (QFS) [5].

> The system can not only detect bullets that are passing by its sensing apparatus but also has a direction indication display that tells the user where the shot originated.

RECENT WORK

In December 2015, a complete prototype system built by QFS (Figure 2), including E-field sensors, a compact commercial-off-the-shelf DAQ/processor, and embedded software, demonstrated a detection capability of 98% for AR-15 gunshots passing the sensor node between 1 and 3 meters, with a 0% false alarm rate at a local live-fire range. The E-field gunshot location (EGL – eagle) system had a local LED display and remote LCD monitor displaying the detected hostile gunshot direction (angle of arrival) in real time. The EGL also detected rapid fire, crossfire, and subsonic rounds.

Researchers are also working on combining acoustic and E-field detection capabilities because the shockwave

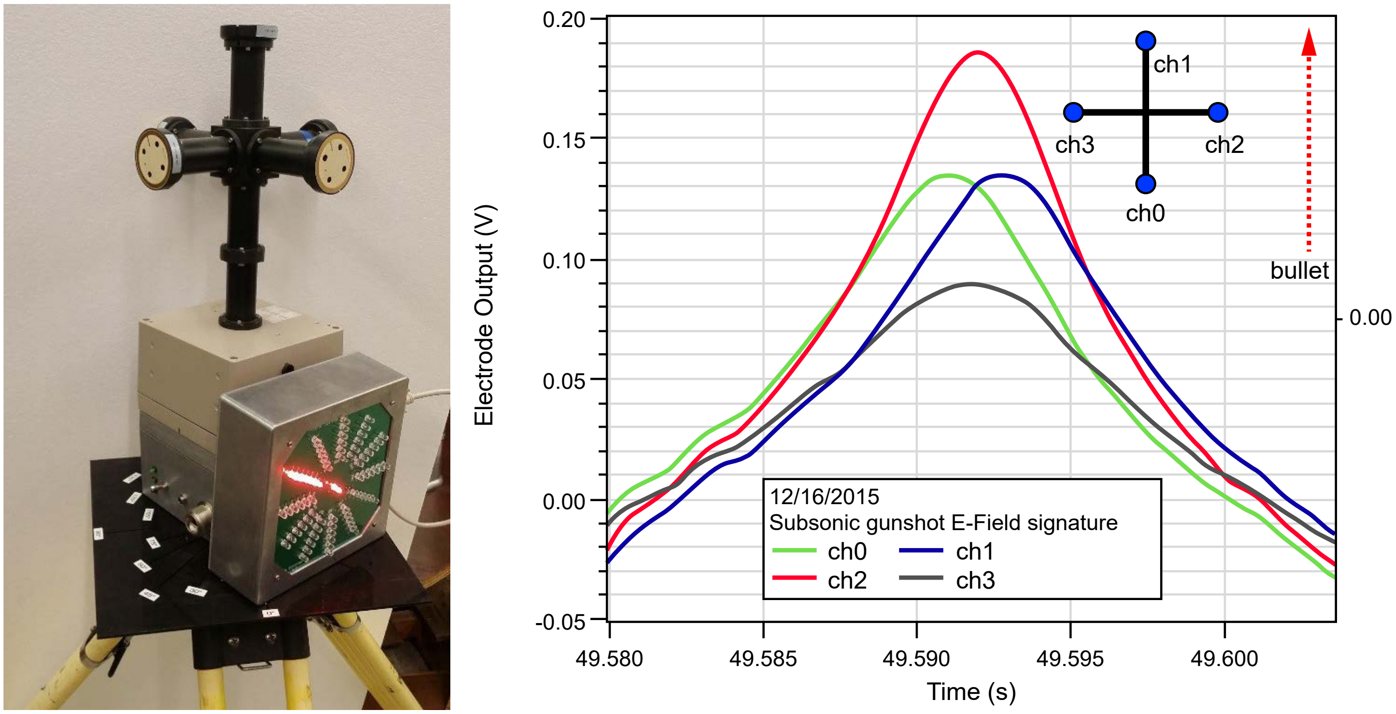


Figure 2: EGL system: (Left) E-Field Sensor Module With Five Electrodes for Gunshot Detection. The Circuit Modules and Power Are Enclosed. The LED Display Indicates the Direction of Bullet Origination in a Clock-Face Modality. (Right) E-Field Signatures on Four Electrodes Generated by a Passing Bullet *(Source: QFS).*

generated by a passing bullet arrives at a time delay equal to the passing distance/sound speed. It is therefore possible to use the shockwave to confirm that detected E-field pulses above the threshold are from bullets, thus lowering the false alarm rate. It is also possible with an acoustic-based system to use the shockwave to detect the bullets and an E-field measurement to confirm detection, again lowering the false alarm rate. This measurement modality combination can dramatically improve the performance of both types of gunshot detectors.

The algorithms, software, and hardware developed under this effort will have dual-use applications for all levels of law enforcement and other government agencies for Homeland Defense, with platforms such as vehicles, boats, helicopters, and on outposts. This system will be extremely useful in urban environments where high background noise may be encountered. Local and county police organizations that supported ARDEC in testing this technology have expressed great interest in its development and availability for police vehicles as well as for individual officers.

The eventual product can be used for military, law enforcement, and other government agencies for Homeland Defense. Since the product will be developed for shooter-bearing detection in a worst-case sensing scenario, it should be easily adaptable to many other scenarios. The product series is envisioned to include a system designed for mounting on a Humvee, one for a "defensive outpost," and prototypes for man-portable applications. The compact nature and standalone capability of the eventual product means that it could later be used as a module in a large system, providing detection and reporting incoming bullets.

ADDITIONAL MODALITIES

In 2011, remote voltage sensors the size of two stacked pennies were mounted on a vehicular Objective Gunner Protection Kit (a type of gunner's turret mounted on an armored vehicle), and tests to simulate close-quarters ambush conditions were performed. Detection accuracy for fired bullets was within a few degrees. Establishing that functionality can be obtained with small sensors enables mounting wearable modalities on a Warfighter's torso and/or helmet. The Army has funded preliminary work mounting a helmet with sensors on a tripod and firing Airsoft pellets nearby to establish that signal fidelity from the helmet mock-up is adequate for the application (Figure 3). Measurements were also taken with the system on a walking person to establish that noise levels would not be too high for acquiring bullet signals in this modality. These tests established that the helmet configuration had adequate signal to detect bullets and noise in measurements on a walking subject would not prevent the system from functioning.

> Establishing that functionality can be obtained with small sensors enables mounting wearable modalities on a Warfighter's torso and/or helmet.

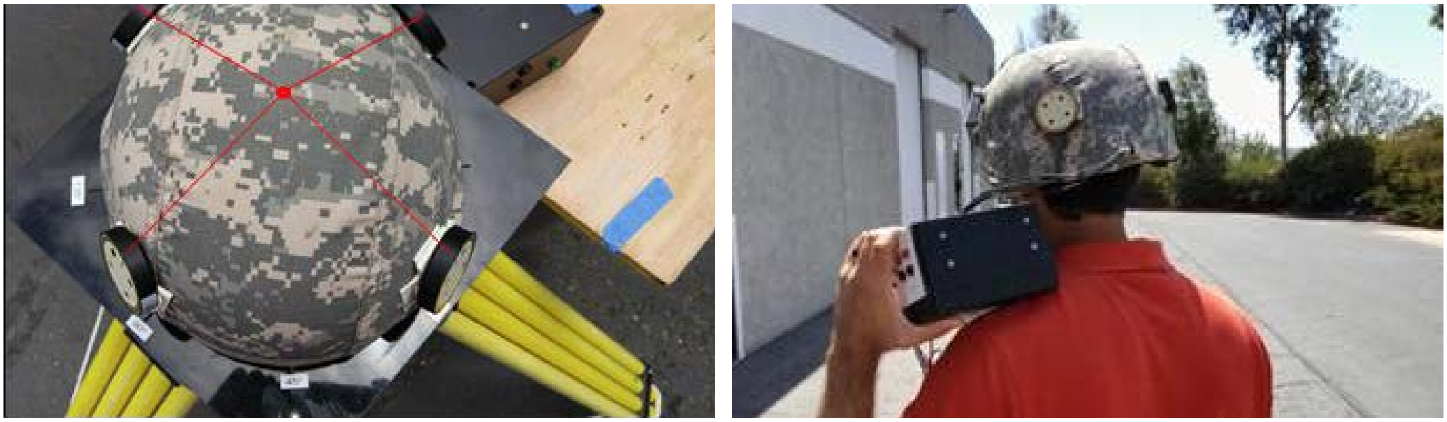


Figure 3: Body-Worn System Concept Testing: (Left) Sensors Mounted on a Helmet and (Right) Noise Measurement Setup *(Source: QFS).*

Table of Contents

CONCLUSION

The DoD uses a variety of technologies for bullet detection and location, but the systems are all subject to certain areas of weakness. High battlefield activity/urban environments can confound acoustic and optical systems, impairing their accuracy. Silencing/light damping devices can disguise the bullet's signature to the point where systems cannot detect it. E-field based sensing offers an alternative detection/location method that can overcome these weaknesses, serve as a standalone system, and complement and enhance existing technology. ■

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BIOGRAPHY

YONGMING ZHANG is the CEO of QUASAR Federal Systems and has more than 10 years of research and development experience in low-noise electronics, including electric and magnetic field sensors, superconducting devices, GaAs devices, low-noise microwave amplifiers, microwave filters, and fiber-optic devices. He is an IEEE senior member and has published more than 40 articles in referenced journals. Dr. Zhang has served as the principal investigator of more than a dozen DoD-funded research projects for diverse applications such as underground facilities detection, semiconductor manufacturing process monitoring, lightning detection and localization, and bullet detection capability. He holds a Ph.D. in physics from Chalmers University of Technology in Sweden.

CONFERENCES AND SYMPOSIA

DARPA Launch Challenge (DLC)
16 April 2018–31 December 2019
http://www.darpalaunchchallenge.org ▸

SOFWERX TeamWERX Challenge: Amplifier-Repeater
5 July–10 September 2018
SOFWERX Facility
Tampa, FL
https://www.teamwerx.org ▸

SEPTEMBER 2018

SOFWERX Next Generation Information and Identification Awareness (NGIA) Collaboration Day
5–6 September 2018
SOFWERX
Tampa, FL
https://www.sofwerx.org/ngia ▸

2018 JASP Susceptibility Reduction Work Group
5–7 September 2018
Seneff Building
Fort Rucker, AL
https://www.dsiac.org/events/2018-jasp-susceptibility-reduction-work-group ▸

Building More Survivable Defense Systems and More Effective Weapons: A Short Course on LFT&E - Fall 2018
11–13 September 2018
SURVICE Engineering Company
Belcamp, MD
https://www.dsiac.org/events/building-more-survivable-defense-systems-and-more-effective-weapons-short-course-lfte-fall ▸

JAS FY18 Program Review
18–20 September 2018
Threat Training Facility
Nellis AFB, NV
https://www.dsiac.org/events/jas-fy18-program-review ▸

Directed Energy Systems Symposium
24–28 September 2018
Renaissance Portsmouth-Norfolk Waterfront Hotel
Portsmouth, VA
https://protected.networkshosting.com/depsor/DEPSpages/DEsysSymp18.html ▸

Fundamentals of Random Vibration and Shock Testing
24–26 September 2018
Clark Testing Laboratory
Jefferson Hills, PA
https://equipment-reliability.com/training-calendar/fundamentals-random-vibration-shock-testing-september-24-26-2018 ▸

Future Indirect Fire
26–28 September 2018
Hilton Garden Inn Lawton-Fort Sill
Lawton, OK
https://futureindirectfires.iqpc.com ▸

DARPA Subterranean (SubT) Challenge Continues
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Louisville, KY
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OCTOBER 2018

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Portland, ME
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NDIA Augmented Reality Workshop 2018
3 October 2018
The Waterford Reception Center
Springfield, VA
http://www.ndia.org/events/2018/10/3/9843---ar-workshop ▸

SOFWERX - Aviation Maintenance Modernization Capability Assessment Event
4–5 October 2018
SOFWERX
Tampa, FL
https://www.sofwerx.org/aviation ▸

2018 Mechanical Design Reliability Course
16–18 October 2018
SURVICE Engineering Company
Belcamp, MD
https://www.dsiac.org/events/2018-mechanical-design-reliability-course ▸

21st Annual Systems Engineering Conference
22–25 October 2018
Grand Hyatt
Tampa Bay, FL
http://www.ndia.org/events/2018/10/22/21st-systems-engineering-conference ▸

HELMOT XVIII
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Hampton Roads Convention Center
Hampton Roads, VA
https://vtol.org/events/helmot-xviii ▸

NOVEMBER 2018

The 2018 OSA Laser Congress
4–8 November 2018
The Westin Boston Waterfront
Boston, MA
https://assl.osa.org/home/about-assl ▸

Aircraft Survivability Symposium 2018
6–8 November 2018
Naval Postgraduate School
Monterey, CA
http://www.ndia.org/events/2018/11/6/9940-2018-aircraft ▸

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