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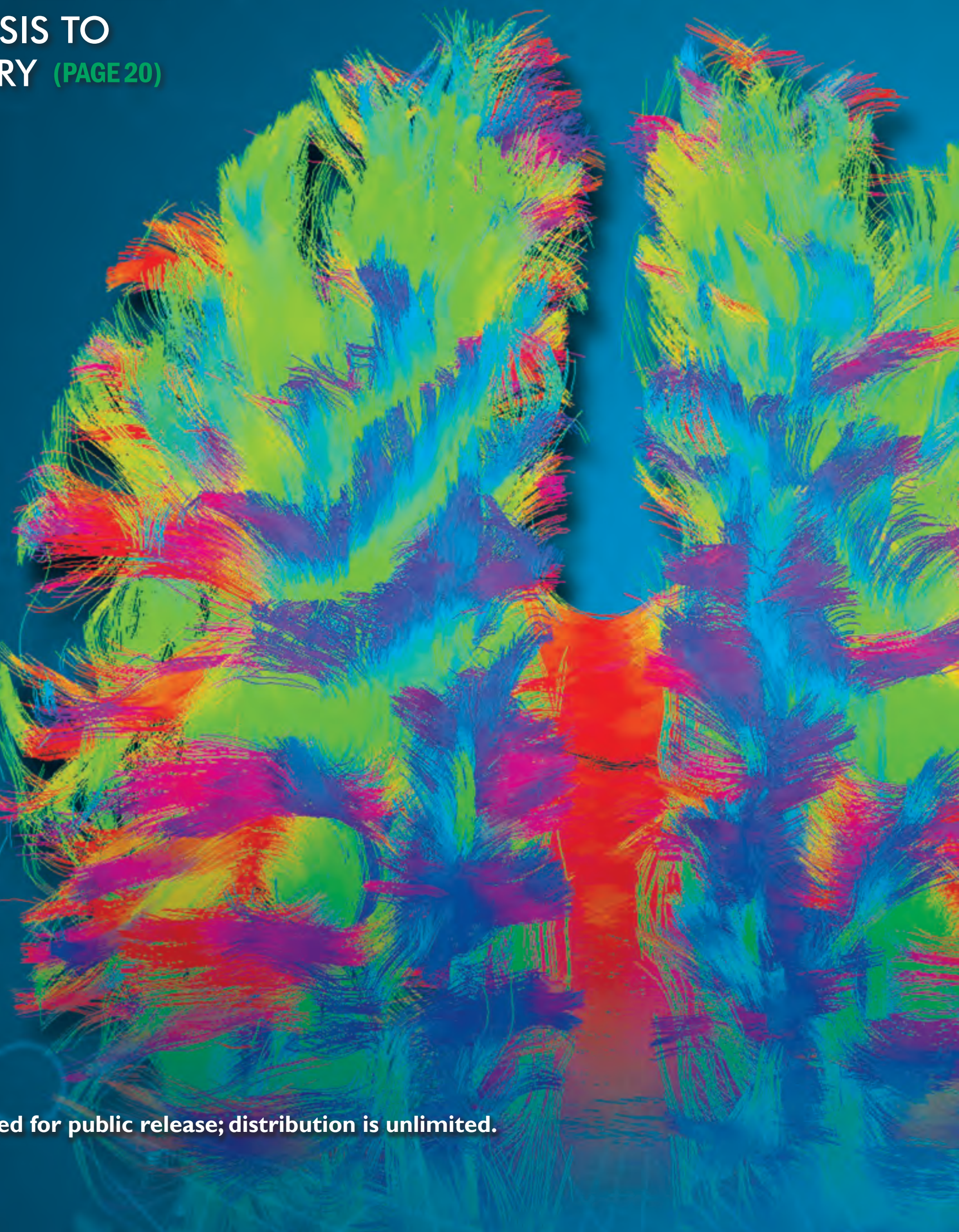
MODELING THE MIND

USING FINITE ELEMENT ANALYSIS TO PREDICT TRAUMATIC BRAIN INJURY (PAGE 20)



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Editor-in-Chief: Eric Fiore

Contributing Editor: Eric Edwards

Art Director: Melissa Gestido

On the Cover:
The underlying structure of the brain's white matter attained through Diffusion Tensor Magnetic Resonance Medical Imaging (DT-MRI).

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Department of Defense Information Analysis Centers

CONTENTS

CONTACT DSIAC

Thomas L. Moore, PMP
DSIAC Director

Eric M. Fiore, CSEP
DSIAC Deputy Director

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

WPAFB SATELLITE OFFICE
96 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

NEW YORK OFFICE
100 Seymour Road
Suite C101
Utica, NY 13502-1311
Office: 315.351.4200

DSIAC CONTRACTING OFFICER REPRESENTATIVES

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

Peggy M. Wagner (ACOR)
96 TG/OL-AC
2700 D Street, Building 1661
Wright-Patterson AFB, OH 45433-7403
Office: 937.255.6302
DSN: 785.6302

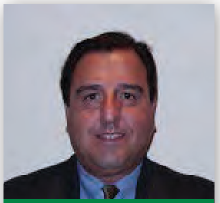
DSIAC PROGRAM MANAGEMENT ANALYSTS (PMAs)

Philippe A. "Phil" Guillaume
Office: 703.767.9180
Email: philippe.a.guillaume.ctr@mail.mil ▸

Marisiah Palmer-Moore
Office: 703.767.9109
Email: marisiah.v.palmer-moore.civ@mail.mil ▸

IAC Program Management Office (DTIC-I)
8725 John J. Kingman Road, Suite 0944
Fort Belvoir, VA 22060-6218

MESSAGE FROM THE EDITOR



ERIC FIORE

The widespread detrimental effect of traumatic brain injury (TBI) to military personnel—and, to a similar extent, professional athletes—has become increasingly evident, largely due to increased media coverage on this topic. While such coverage has certainly helped the public understand the nature of TBI, it is often still unclear how this phenomenon is affecting the general population. In reality, the clinical treatment of TBI has become so widespread that it is akin to treating an epidemic. In this winter edition of the *DSIAC Journal,* our feature Survivability and Vulnerability article by David Powell focuses on cutting-edge research that could lead to the development of methods with greater TBI predictive capability. Powell discusses empirical TBI modeling that could ultimately provide the means to predict not only the amount of cellular damage within the brain but also the cognitive effects that damage may have on an individual.

In a companion article, Brian Wessel briefly discusses one testing lab's extension of its test technology/methodology, which has been used primarily to support military personal protective equipment (PPE) development and certification, to likewise support the design and improvement of protective athletic equipment.

Also, with the Department of Defense (DoD) ranking as the federal Government's largest federal consumer of energy (by far), the desire to reduce the military's dependence on fossil fuels and increase the use "greener" renewable sources of energy is becoming a national imperative. In our Advanced Materials article, Alex MacDiarmid addresses the topic of biofuels and their impact on system reliability, availability, and maintainability (RAM) by examining the U.S. Navy's plan to incorporate the use of biodiesel in the fleet.

Composites have long been another material of choice for Defense systems, especially aircraft, which require high strength-to-weight ratios. However, because of the intrinsic composition of composite materials, reparability remains an issue that must be considered for the system's entirelife cycle. In our Reliability, Maintainability, Quality, Supportability, and Interoperability article, Madeline McAuley discusses contemporary methods and considerations for implementing, maintaining, and repairing common composite structures.

In Joe Zinecker's Autonomous Systems article, we learn how autonomous ground vehicles are navigating their way onto the battlefield, and we get an update on much of the recent progress that Lockheed Martin has made with unmanned vehicles, as well as a glimpse of some of its future plans.

Methods for finding the proverbial "needle in the haystack" is the subject of our Military Sensing article, wherein Chris Kennedy et al. describe ongoing efforts by the Georgia Tech Research Institute to improve the nation's Multi-Disciplinary Intelligence (MINT) system and to develop a method for prioritizing massive amounts of intelligence, surveillance, and reconnaissance (ISR) data.

Finally, our Survivability and Vulnerability article by Jefferson Amstutz and Christian Gribble on graphics processing units (GPUs) presents a novel architecting approach for configuring GPUs to improve blast simulation and visualization processing. ■

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BIOFUELS IN THE DoD:

Impact on System Reliability, Availability, and Maintainability

By Alex MacDiarmid

The growing concern over U.S. energy security has prompted a number of Government initiatives intended to reduce the nation’s dependence on fossil fuels. Regardless of one’s stance on the scientific feasibility of using biofuels as an economical alternative to traditional petroleum-based fuels, the Navy’s ambitious goals to power the Great Green Fleet carrier strike group on a biodiesel-petroleum blend require an analysis of all potential effects on the system’s operation. This article identifies specifics of the Navy’s plan, as well as noted effects and challenges associated with the use of biodiesel, including those impacting the reliability, availability, and maintainability (RAM) of the system.

FUELING THE DoD

U.S. dependency on fossil fuels, as well as the subsequent vulnerability to the effects of geopolitical conflicts on the supply of foreign oil, has raised serious questions and concerns regarding the nation's energy security. These concerns have led to an increased interest in, and demand for, energy produced by/from renewable sources. The U.S. Government's support of these efforts is widely publicized and includes examples such as tax incentives for those who own/operate renewable-energy systems (to offset the initial investment costs), as well as funding for universities, manufacturers, and consortiums that research and develop renewable-energy technology and equipment. While this type of support is invaluable to the growth of this technology, it is only one part of the Government's broader approach to a cleaner, more secure energy strategy.

> The DoD accounts for 80% of the Federal Government's energy consumption and is believed to be the largest organizational user of petroleum in the world.

As the nation's largest energy consumer, the U.S. Government not only is a major contributor to our energy dependency but is also at high risk should the availability of a particular source become compromised. More specifically, according to the Navy's "Strategy for Renewable Energy" [1] (shown in Figure 1), the Department of Defense (DoD) accounts for 80% of the Federal Government's energy consumption and is believed to be the largest organizational user of petroleum in the world [2]. This incredible demand reflects the DoD's overwhelming dependency on fossil fuels and subsequent vulnerability to a number of factors that can potentially affect the supply of these resources. Together, these factors have led to increased efforts to implement similar "green" strategies within the DoD as those that are being employed within the private sector and by the general public.

DoD AND RENEWABLES

Over their relatively brief history, energy systems powered by renewable sources have seen limited use within the DoD. Installations that have incorporated alternative-energy technologies have traditionally involved small-scale implementations. Some of the most notable examples include solar panels and wind turbines, which have essentially become the poster children of the green movement. These technologies continue to play a larger role in the nation's domestic power production and have more recently been used in various capacities to support U.S. military facilities. Applications include anything from small-scale systems employed at remote operating bases to large-scale megawatt systems, such as the turbines in use at the U.S. Naval Base at Guantanamo Bay. As the technology has matured, the size and energy-producing capacity of these systems have increased, and, even more importantly, the system availability has improved. It should be noted, however, that these facilities are usually supported by the electrical grid and, thus, have a redundant power supply (often a carbon-based backup) should the renewable source and/or system become unavailable.

Defense systems (with the exception of nuclear energy systems) are similar in the sense that they have predominantly relied on carbon-based fuels. The critical difference is that most of these systems are petroleum-fueled and do not have the luxury of a redundant power supply. Thus, they have far less tolerance for a loss of power from a renewable source.

The aforementioned improvements to solar and wind energy systems are the result of the successive advances over the course of the technologies' history, as well as the significantly renewed interest and demand over the past decade. Though vegetable oils were used to power diesel engines as early as 1893 [3], the science involved in the large-scale production of petroleum alternatives is not nearly that mature. Nonetheless, the nation's growing reliance on foreign oil suppliers

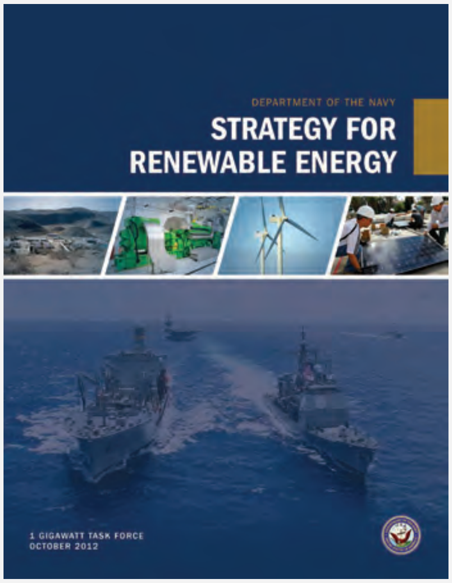

Figure 1: The Navy's "Strategy for Renewable Energy" (2012).

is such that petroleum-based products have become one of the primary targets for renewable, environmentally friendly replacements. This fact is reflected in some of the more recent policies adopted by the DoD.

One specific example of a green DoD initiative is the strategy outlined by the Secretary of the Navy, which set the following goals [1]:

- By 2020, 50% of the total Department of the Navy (DoN) energy consumption will come from alternative sources.
- By 2020, the DoN will produce at least 50% of shore-based energy requirements from alternative sources; 50% of DoN installations will be net-zero.
- By 2015, the DoN will reduce petroleum use in the commercial vehicle fleet by 50%.
- By 2012, the DoN will demonstrate a Green Strike Group in local operations and will sail it by 2016.
- Evaluation of energy factors will be mandatory when awarding contracts for systems and buildings.

This plan represents a considerable undertaking by the Navy because it not only is the DoD's most ambitious energy strategy to date but it also addresses a broad range of energy-producing alternatives.

RENEWABLE PETROLEUM ALTERNATIVES

A key element of the Navy's strategy is the introduction of biofuels as an alternative means to power the various Defense systems within the fleet. Biofuels are alternative fuels produced from biomass. The two most popular biofuels are ethanol, which is commonly blended with gasoline, and biodiesel, which has the greatest potential for DoD applications. Biodiesel, also known as fatty acid methyl ester (FAME), is produced through a transesterification process of one of many different feedstocks. The byproduct is a nontoxic, renewable fuel that is capable of powering diesel engines.


U.S. Navy

Figure 2: The USS Princeton Participating in the Great Green Fleet Demonstration at the RIMPAC 2012 Exercise. [4]

These advantages make biodiesel an attractive candidate for the Navy's Renewable Energy Strategy, particularly because of the vast quantities of jet fuel and maritime diesel that are used to fuel the Navy's expansive fleet of aircraft and marine vessels. In fact, one of the first steps in the implementation of the Navy's strategy involves the aforementioned Great Green Fleet, a Carrier Strike Group fueled by nuclear power and biofuel blends (50/50 biodiesel and petroleum-based marine diesel or aviation fuel). In anticipation of its scheduled deployment in 2016, the fleet constructed a demonstration at the 2012 Rim of the Pacific (RIMPAC) exercise (shown in Figure 2), successfully evaluating the performance of "drop-in" replacement biofuel blends with all systems performing at full capacity.

An expansion of this program, as a result of the renewable goals and the success of this initial evaluation, could represent a considerable reduction in the Navy's demand for petroleum. This potential reduction is further supported by the recent Defense Logistics Agency (DLA) solicitation to companies capable of supplying 37 million gallons of drop-in biofuels as part of the Bulk Fuel requirement for DLA Energy's customers located in the Inland/East/Gulf Coast regions of the United States [5].

Admittedly, some experts continue to question the scientific feasibility of using biofuels as an economical alternative to traditional petroleum-based fuels, as well as the true environmental impact tied to the production of biofuels. The Navy's plan nonetheless indicates a clear intention to move forward with these renewable alternatives. As such, it is important to consider all potential effects on the systems' operations, especially when considering the importance of their mission.

BIODIESEL

One of the key advantages of using biodiesel is that it can be produced from a diverse collection of oils and animal fats, including waste oil and both edible and nonedible vegetable oils. This variety of biodiesel feedstocks, which can be found all over the world, helps to mitigate issues with the availability of raw materials. More importantly, the variety provides for a number of options that can help to minimize production costs, as well as the potential impact on a nation's food supply, by targeting nonedible biomass, feedstocks that require the least agricultural inputs (i.e., have the smallest environmental impact), and/or plants that can thrive in environments otherwise unusable for (consumable) agricultural farming. However, feasibility studies must also consider the feedstock's effect on certain biodiesel properties, including those that affect engine performance, in addition to the aforementioned factors.

> The main advantage of biodiesel is its ability to be used as a replacement for petroleum diesel without engine modifications.

The main advantage of biodiesel is its ability to be used as a replacement for petroleum diesel (petrodiesel) without engine modifications as a result of the fuels' similarities in physical properties (e.g., cetane number). Biodiesel may also be blended with conventional diesel in varying proportions. For example, the biofuels sought in the aforementioned DLA solicitation could be blended in a range of 10 to 50% with conventional petroleum products.

While sharing similar material properties with conventional diesel, biodiesel has the advantage of being nontoxic. Furthermore, biodiesel emits fewer pollutants into the environment, with significant reductions in unburned hydrocarbons, carbon monoxide (CO), and particulate matter emissions (though it does emit a greater quantity of nitrogen oxides [NO_x]) [6]. Traditionally, marine diesel has been a lower-quality bunker oil fuel with high levels of pollutants (e.g., sulfur). With pure biodiesel, sulfates are essentially eliminated, while biofuel blends also reap similar benefits based on the percentage of biodiesel present.

A number of additional advantages (having a higher lubricity, being biodegradable and safer to handle, etc.) are mentioned in the alternative fuel literature. While important to the conversation, the primary advantages described previously are the main factors supporting the production and use of biodiesel as a viable petroleum alternative.

BIOFUEL RELIABILITY

As often is the case for new and evolving technologies, there can sometimes be an overemphasis on the positive characteristics of biofuels and biodiesel (such as those noted previously), while the potential shortfalls can be overlooked. From a reliability perspective, flaws and vulnerabilities are incredibly important to the task of predicting and/or identifying possible causes of failure, such that they can be mitigated and/or corrected to prevent future failures from occurring. Along those lines, we must evaluate the impact that these alternative fuels, specifically biodiesel, can have on engine performance, longevity, and maintainability.

Though similar enough to be used in the same diesel engine, the properties that separate biodiesel from its petroleum-based counterpart are responsible for both the aforementioned advantages and other unique characteristics that would be considered disadvantages. One example is the different behavior that is exhibited under colder temperatures. Petrodiesel typically starts to freeze or "gel" at temperatures well below freezing, while similar effects on biodiesel are observed at much warmer temperatures. In fact, biodiesel's cloud point, a cold weather property that represents the temperature at which crystals begin to form, can be more than 20° F higher than that of petroleum diesel [7]. Below these temperatures, the continued crystal growth can eventually plug the system's fuel filter and ultimately prevent fuel from reaching the engine. Such events are a serious threat to the operational availability of a Defense

system and, worse yet, a possible cause for engine damage. The significant difference in cold weather performance generally necessitates that a biodiesel blend (e.g., B20 – 20% biodiesel, 80% petrodiesel) be used to limit the temperature increase for these cold weather properties. For more extreme temperatures (e.g., below -20° F), special low-temperature diesel fuels and/or flow additives may be required to prevent the possibility of gelling and any subsequent engine damage.

Biodiesel's unique properties are also responsible for a number of material compatibility issues that complicate the use of this renewable alternative. These incompatibilities are especially important because some of the materials are commonly used in fuel storage and handling systems. Elastomers and rubbers commonly used in seals, hoses, and gaskets are susceptible to degradation from extended contact with biodiesel, with effects ranging from a general softening to complete failure. The broken-down material can clog filters and potentially ruin fuel pumps; or, in more extreme cases, a failed hose could leak fuel onto a hot engine. Use of natural rubber, buna-N, nitrile, and polypropylene should be avoided for systems operating with biodiesel, although many of these materials have been, or are in the process of being, phased out of use.

Compatibility issues also extend to copper-containing metals, such as brass and bronze, as well as lead, tin, and zinc galvanized surfaces, which can also be found in fuel storage systems. The reaction between these materials and the chemical compounds in biodiesel not only introduces sediments into the fuel supply but can also cause the storage tank to corrode. Another common cause of clogs in the fuel system results from biodiesel acting as a solvent, allowing other substances to dissolve into solution. Though seemingly unimportant, biodiesel will often clean out deposits left behind from the use of petrodiesel, eventually clogging the system when the sediments reach the fuel filters. For this reason, thorough fuel system cleaning and regular inspection of fuel filters are recommended when switching to a biodiesel fuel supply.

Cold-weather performance and clogging of the fuel lines, filters, and injectors are two of the most commonly cited issues with regard to biodiesel-powered systems. The noted disadvantages are most severe for pure biodiesel (B100) and tend to be less severe with a growing percentage of petrodiesel in a blended fuel. In fact, the most common blend used for road vehicles in the United States is B20, which satisfies the minimum blend percentage for renewable/environmental requirements while also limiting the impact of the negative effects of biodiesel's use. The Navy's plan indicates that it intends to use a 50/50 blend (B50), which will likely exhibit more of biodiesels' characteristic behavior. A B100 (100% biodiesel) standalone drop-in replacement typically requires engine modifications.

An anticipated challenge to the Navy's plan involves the storage and/or availability of biodiesel or biodiesel blends. With a global operation, procuring the necessary resources, including fuel, may be difficult. While biodiesel can be produced from a number of previously discussed feedstocks, the biomass used in the production of the fuel affects its relevant properties. Furthermore, there is no international marine-grade biodiesel standard, with the current U.S. and European standards (ASTM D6751 and EN 14214, respectively) relating to road vehicles and land-based systems [8]. Storage of biodiesel also presents a challenge, as noted in the discussion of compatibility issues with common storage materials. Some biodiesels will also break down when stored for extended periods of time as a result of reacting with atmospheric air in high temperatures. Additional additives are recommended to prevent or limit oxidation degradation of the fuel and inhibit corrosion, both in the engine and the fuel-handling system.

BIOFUEL R&D

The renewed interest in renewable energy has also led to the recent release of a number of new policies and initiatives from various Government agencies. While some include pilot study evaluations, such as the Navy's Great Green Fleet Carrier Strike Group, others have more of a research and development (R&D)-based focus. One of the leading agencies for such activities is the National Renewable Energy Laboratory (NREL), which the Department of Energy (DoE) selected to co-lead the National Advanced Biofuels Consortium (NABC). This national program is tasked with the development of advanced biofuels that follow a sustainable, cost-effective production process while maximizing the use of existing refining and distribution infrastructure.

While biofuels have been proven capable of powering automobiles and various internal combustion engines, the extent of their use and acceptance as a viable petroleum replacement will ultimately be determined by a number of relevant factors, such as cost, availability, and performance. In other words, demonstrating that engines can run on this fuel is one part; the second is to ensure that a petroleum alternative does not compromise performance or introduce a new set of problems (i.e., trading one problem for another). Unfortunately, observations from early biofuel (biodiesel in particular) implementations have suggested that there are issues with which to contend (identified in the previous section) based on the unique biofuel properties. Mitigation of these issues continues to be an important goal of ongoing research efforts.

While not alone in this effort, NREL (as its name suggests) is one of the leading laboratories for the R&D of renewable energy technology. NREL's efforts extend across a myriad of alternative-energy technologies, including wind, solar, geothermal, hydropower, and hydrogen fuel, as well as across materials and computational and structural engineering disciplines for energy efficiency. With respect to biofuels, research activities address a wide range of topics, from performance and emissions to storage and stability. Certain efforts involve the testing and evaluation of biofuels to quantify specific performance metrics. The results of these analyses are used to develop mitigating strategies for the aforementioned challenges of biofuel use, through materials selection considerations and the biochemistry investigations for the development of fuel additives and stabilizers.

In addition, NREL's biofuel research extends well beyond biodiesel and ethanol, the two most well-known renewables for diesel and spark-ignited engines. The organization has several forward-looking research efforts in a variety of fuel types (cellulose-derived oxygenates, hydroisomerized fats and oils, butanol and long-chain alcohols, etc.). These efforts are considering a number of potential alternatives to traditional petroleum-based products. Much of this research involves biomass characterization. The sustainability of these alternatives is heavily dependent on both their economic and environmental costs. Accordingly, it is essential to develop an understanding of the different biomass properties to determine the environmental requirements and the necessary processing steps and byproducts, as well as the energy and quality-related properties (e.g., cetane number and energy content) of the resultant biofuel. Ultimately, these are some of the most important factors for long-term sustainability.

While the investigations into a number of different biofuel feedstocks continue, one category of biomass that has gained popularity for its numerous advantages is algae biofuels [10]. Algae (plural for alga) biofuels have a significantly greater yield and, in addition to the high energy and lipid content (used in biodiesel), also produce byproducts that can be used as fertilizers and ethanol feedstocks. Typically cultivated in large man-made ponds (as illustrated in Figure 3) or commercialized photobioreactors, algae biofuels are not competitive with agriculture and require limited input (water, sunlight, and CO_2). The challenge, however, lies in the costs associated with the commercialization of algae production. NREL is currently engaged in a number of R&D efforts to overcome these challenges, including the following:

Figure 3: Artist Rendition of Algae Cultivation Ponds. Photo Credit: Pacific Northwest National Laboratory [9].

- The development of metabolic models and related software tools to model and optimize algae behavior based on parameter manipulation.
- The isolation, characterization, and assessment of scale-up potential of microalgae from samples taken from a variety of northern marine and freshwater habitats.
- The identification and development of microalgal strains that can be cost-effectively harvested and processed into biofuels.
- The investigation of the biochemical conversion of algae into biofuels and the analysis of the physical chemistry properties of subsequent algae fuels.

Partnered with a number of like-minded organizations, NREL and its continued R&D efforts are vital to the economic feasibility of biofuels as a replacement to petroleum products.

> Thorough fuel system cleaning and regular inspection of fuel filters are recommended when switching to a biodiesel fuel supply.

CONCLUSIONS

The use of renewable alternatives provides a promising outlook for the nation's future and security, especially as the country continues to work to wean itself from its long-time dependency on fossil fuels. However, the implementation of this continuously emerging technology will require researchers and developers to consider all possible effects and challenges on system operations so as not to overlook potentially critical flaws that may have a considerable impact on the reliability, availability, and/or maintainability of the systems being considered. ■

BIOGRAPHY

ALEX MACDIARMID is a reliability and materials engineer at Quanterion Solutions, Inc., supporting the DSIAC core operations. He specializes in a number of reliability services (reliability predictions, modeling, and analysis) while also performing material investigations and general research. Mr. MacDiarmid holds an M.S. in reliability engineering from the University of Maryland and a B.S. in mechanical engineering from Rensselaer Polytechnic Institute.

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DTIC SEARCH TERMS:
Biofuel(s) or Alternative Fuel(s)

RESULTS: 116,000

- Fuels (1,211+)
- Logistics, Military Facilities & Supplies (670+)
- Theses (580+)
- Test & Evaluation (547+)
- Military Operations, Strategy & Tactics (510+)
- Government & Political Science (500+)
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- Economics & Cost Analysis (450+)
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***See page 3 for explanation ▸**

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Figure 1: Graphical Processing Unit with Massively Parallel CPUs and Coprocessors.

LEVERAGING GPUs FOR BALLISTIC SIMULATION

By Jefferson Amstutz and Christiaan Gribble

INTRODUCTION

Ballistic vulnerability can be difficult to understand in a timely and accurate fashion. Interactions between threats and targets are complex and unwieldy—and so are the codes used to simulate such events on an analyst's behalf. Typical analysis is conducted on large clusters, environments for which interactive simulation is not feasible. As such, analysts often spend large amounts of time creating inputs, large amounts of time waiting for simulations to execute, and even larger amounts of time sifting through output data to identify results of interest.

Meanwhile, high-performance computing architectures have been changing such that existing software is unable to trivially take advantage of the newest advances and features: program execution has progressed from being exclusively serial on the central processing unit (CPU) to being parallel both on the CPU and on massively parallel coprocessors, such as the graphics processing unit (GPU) pictured in Figure 1.

Parallel processing provides the ability to execute multiple computations in the same time-cost of a single computation.

Modern computing systems exhibit several types of parallelism, including bit-, instruction-, and data-level parallelism, as well as task parallelism. Our target hardware architecture, the GPU, dictates that data parallelism be exploited to fully leverage hardware resources. In this article, we describe a software architecture for ballistic simulation that leverages data-level parallelism, and we discuss a prototype implementation on the GPU. Our results demonstrate that, when programmed carefully with a full understanding of the underlying hardware constraints, GPUs can execute the computations necessary to complete ballistic simulations at interactive rates on a single workstation.

BALLISTIC SIMULATION

Vulnerability analysis consists of running one or more ballistic simulations to better understand the relationship between threats and targets. Ballistic simulation, in turn, involves the interaction of a nontrivial number of input parameters and results in system-level probability of kill (*pk*) outcomes between a target and a set of threats.

Analysts seek insights regarding effects on various system *pk* values from a particular threat. Input traditionally comes from various description files that combine during a simulation run. Output of a shotline instance is a set of requested *pk* values. While numeric values suffice for some questions analysts seek to answer, visuals that depict the results of a collection of shotlines can also be of value in understanding simulation outputs. This basic process is illustrated in Figure 2.

> GPUs provide computational resources not yet exploited by modern vulnerability analysis applications.

Existing ballistic simulation codes employ a depth-first approach: each stage of simulation is computed from start to finish in a sequential manner (as illustrated in the top panel of Figure 3). Until a decade or so ago , this computational model excelled by taking advantage of rapidly increasing CPU clock rates. However, massively parallel coprocessors, such as GPUs, typically operate as data-parallel devices: using the large volume of available cores, one task is executed across multiple data elements [1]. To maximize utilization of these devices, computations must be grouped in a breadth-first manner, executing only a few distinct instruction streams on the largest possible volume of data at any one time (as illustrated in the bottom panel of Figure 3). This approach requires a significantly different organization of both data and computation compared to existing codes.

SYSTEMS ARCHITECTURE

GPUs provide computational resources that have not yet been exploited by modern vulnerability analysis applications. With additional computational power, new application use-cases are possible. The software architecture described in succeeding text not only best leverages modern massively parallel hardware architectures but also provides performance sufficient to enable both real-time vulnerability analysis and interactive visualization of all shotline

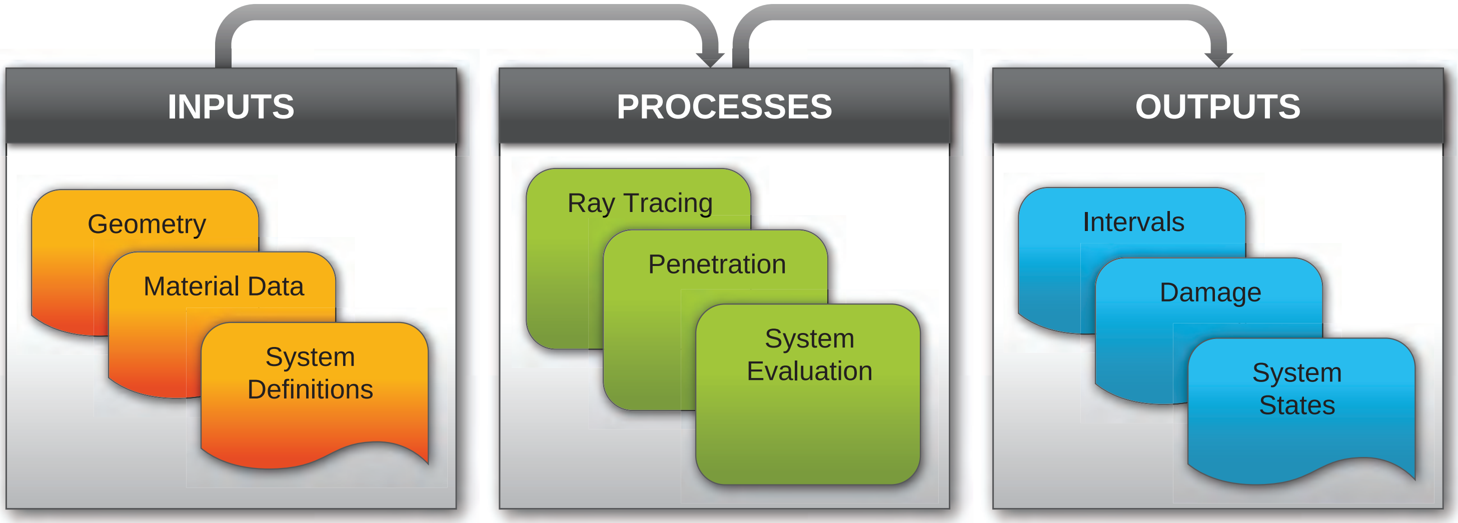

Figure 2: Stages in a Typical Ballistic Simulation, Involving Various Input (e.g., Target Geometry, Material Properties, and System Definitions) and Output/ Visualization Forms.

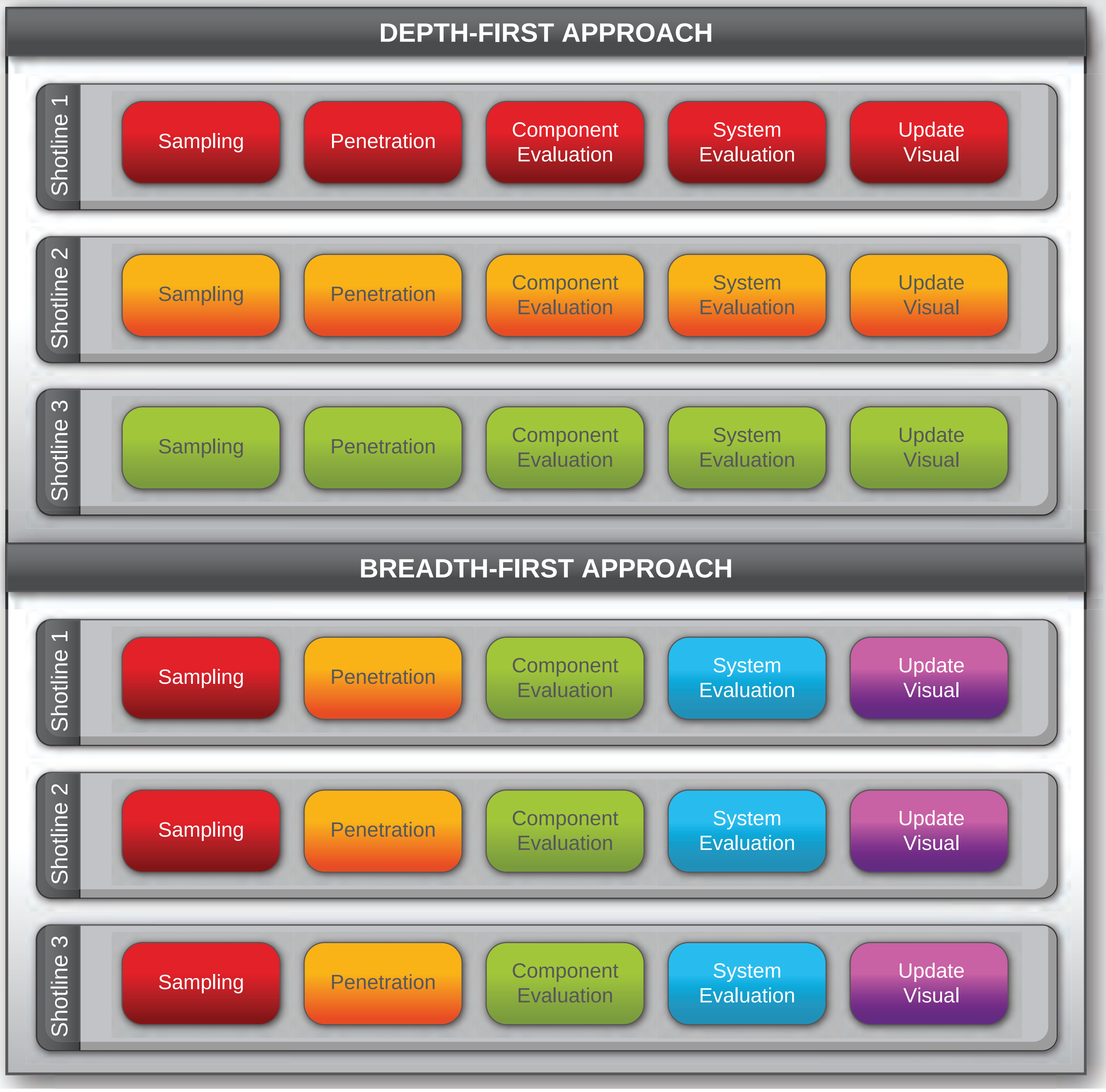

Figure 3: Depth-First vs. Breadth-First Computation (Note: Color Indicates Operation Grouping and Order of Execution).

simulation stages, both of which are features not common to existing codes.

GPU Hardware Architecture

GPUs provide significant performance gains when algorithms are designed to exploit their underlying hardware configuration. While several implementations of massively parallel coprocessor architectures are available, many share a common computational model: data-level parallelism. The single instruction, multiple data (SIMD) model is one approach to data-level parallelism in which a single instruction stream executes across multiple data streams simultaneously, as illustrated in Figure 4. To exploit the benefits of data-level parallelism, programmers must understand and use these SIMD coprocessor architectures carefully and correctly.

SIMD architectures impose the constraint that all vector units associated with a single control unit execute the same instruction across a group of data elements. Most implemented SIMD architectures support wide memory fetch operations that fill an entire SIMD vector unit in a single fetch. These memory operations take several orders of magnitude longer to execute than a SIMD arithmetic

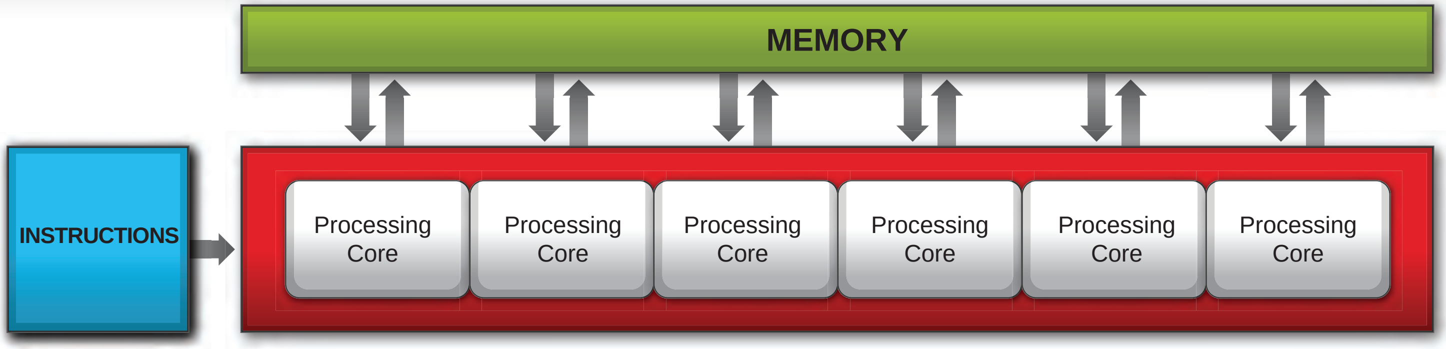

Figure 4: SIMD Hardware Architecture.

operation, so arranging data elements in a manner that minimizes memory fetches per SIMD unit in turn maximizes simulation data throughput, ultimately leading to higher performing code. A GPU's underlying SIMD architecture thus dictates that computations be arranged as stages spanning the range of simulated shotlines.

Simulation Pipeline

We decompose the fundamental computations necessary to execute ballistic simulation into logical subcomputations that map directly to modern GPU architectures. The fundamental computations are:

- Threat Initiation
- Geometry Sampling
- Threat Penetration
- Component Damage Evaluation
- System Evaluation
- Visualization.

Each stage takes input data, executes a set of operations on those data, and creates a result set of data that serves as input to the next stage. The progression of data elements through each stage creates a simulation pipeline that has a defined initial configuration and expected form of output, as illustrated in Figure 5.

This configuration has two distinct advantages. First, data between each stage can be transferred from the GPU and visualized in their entirety, thus providing the ability to communicate trends showing not only what data are computed but also how they are computed, thereby illustrating interactions between pipeline stages. Second, this configuration ensures that GPUs execute the same instructions on local data, which is critical to performance.

Due to the massively parallel nature of GPUs, executing simulation operations at high volume is necessary to fill the

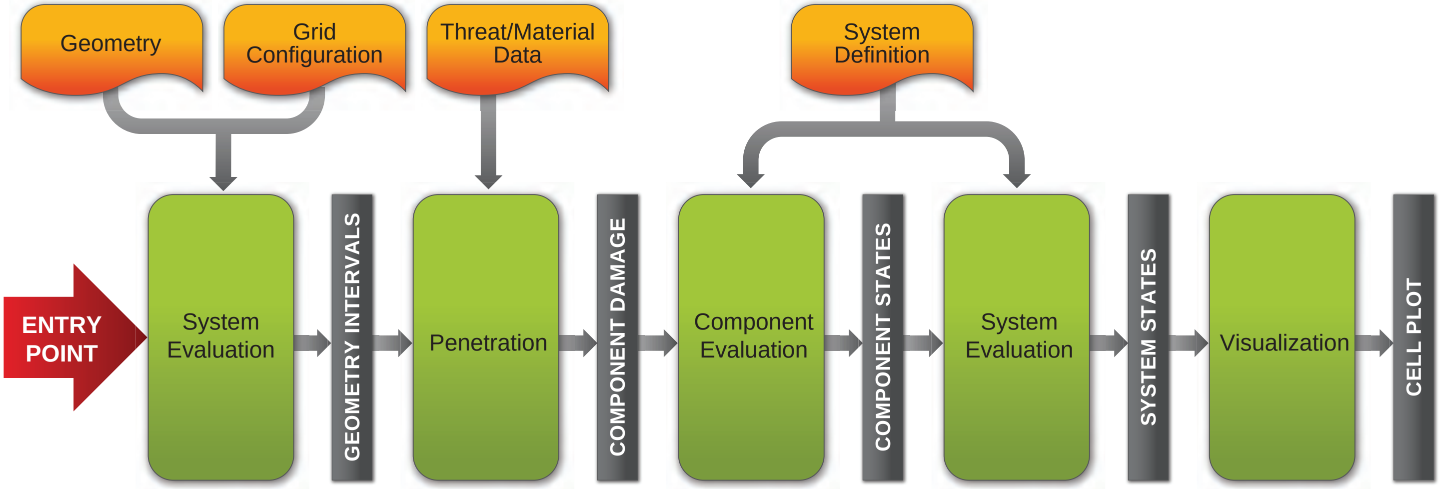

Figure 5: A GPU Ballistic Simulation Pipeline, With Each Stage of Computation Comprising an Individual GPU Kernal.

computational cores and memory of a device. We thus assume that a full simulation executes a set of many individual shotlines simultaneously—for example, all shotlines in a high-resolution grid layout with a particular view of the target.

Threat Initiation. The first stage of our pipeline is threat initiation. Threat initiation refers to the process of discovering the location and orientation at which the main weapon is fused. Ballistic simulation packages handle the arrival of threats at their fusing location differently because weapons are evaluated by analysts in different ways. In our pipeline, this relatively low-cost computation is either provided directly as input or is itself physically simulated, depending on requirements. The result is an initial origin and direction at which the weapon has fused.

Geometry Sampling. The next stage takes weapon configurations and samples target geometry to generate intervals according to that configuration. Weapon configurations are sets of data to initialize the threat state before penetration begins. Sampling geometry on a massively parallel architecture can proceed in many different ways; we chose ray tracing. Each ray trace operation follows the path of a single threat, such as a shaped charge jet or artillery fragment. While the details of this process are not within scope, there are issues that the interval construction process must be able to handle, such as tolerance for geometric overlap and correctly handling in-plane ray/geometry intersection [2]. Our ray tracing subsystem handles these issues correctly and robustly. The resulting interval data correspond to objects with which a given threat might interact during penetration.

Threat Penetration. Penetration follows geometry sampling and, in addition to initial threat and material information, takes intervals as input. The computation selects one penetration model from a collection of such models and loads corresponding material data. The bulk of a simulation's computation follows, as threats are propagated along intervals. Threat propagation creates a collection of component damage information and a collection of secondary threat information, such as armor spall fragments.

> Due to the massively parallel nature of GPUs, executing simulation operations at high volume is necessary.

Damage Evaluation. After the penetration stage completes, damage information is evaluated for each component in the target. Component damage evaluation may require additional information about the correspondence between damage to a given component and the resulting *pk*. This additional information is called an evaluation mode, and different evaluation modes can be used in a single simulation to explore different types of results. As an example, one mode may determine if a threat simply hits a component, while another may determine if the threat creates damage above some threshold, thereby resulting in a killed component.

System Evaluation. The system evaluation stage takes *pk* values from the component evaluation and aggregates new *pk* values based on system definition inputs. Similar to the component evaluation, the system evaluation may have various modes of evaluation.

Visualization. The visualization stage typically operates with system *pk* values to generate a visual representation of the simulation results. An example is found in shaped charge jets arranged in a grid—the visualization may be a plot of colors representing output *pk* values with one color per shaped charge instance.

Secondary effects may be computed at various points during simulation, depending on application requirements. For example, if only the impact of a grid of shaped charge jets—and not secondary spall fragments—is of interest, the pipeline architecture completes computation on the main penetrator and generates a visualization before the pipeline for spall is computed. However, only after all primary and secondary effect pipelines are complete is the simulation itself considered to be finished.

Prototype Implementation

We implement a prototype simulation pipeline using the software architecture described previously to demonstrate both the capability and performance of ballistic simulation on modern GPUs. Our implementation is written in C++ and uses NVIDIA CUDA C/C++ for GPU computations [3].

The CUDA programming model exposes GPUs as multi-thread processors in which all threads execute a single *kernel*, or common code entry point.

Threads are grouped in so-called *blocks* and run on top of SIMD groups, called *warps*. Warps execute in SIMD fashion, but CUDA allows threads to *diverge*. Divergence measures differences among a series of instructions executed across a collection of independent threads. Divergence within a warp introduces instruction-level overhead and can also introduce extra, often highly expensive, memory fetches. Both instruction-level overhead and additional memory fetches are likely to have significant impact on performance, so careful attention must be given to these issues during implementation. Each kernel is called by the host application asynchronously and runs until all threads complete.

> The combination of real-time simulation and visualization enables users to adjust input parameters as simulations execute.

Our implementation receives necessary simulation inputs from the host application, which provides the following general capabilities:

- Loading and Viewing Geometry in 3-D
- Annotating Geometry with Material Data
- Creating, Loading, and Editing System Definitions
- Creating and Modifying Initial Threat Parameters.

Each stage of computation described in the preceding Simulation Pipeline section comprises an individual CUDA kernel, as illustrated in Figure 5. Inputs to any one stage are subdivided if the data (including inputs, outputs, and temporary values) are larger than device memory. Output buffers are therefore transferred back to host memory when available. This approach not only allows large simulations to execute within the sometimes-limited memory of GPU devices, but it also facilitates flexibility. For example, data in host memories are easier to inspect and therefore debug. Moreover, data in host memories can be easily transferred to downstream computations executing on devices other than the GPU.

The threat initiation kernel converts a view configuration from a 3-D geometry viewer to the initial set of shotlines, with one shotline per display pixel. These shotlines are used to launch rays that sample the target and generate intervals during geometry sampling. Rays are traced with Rayforce, an open-source high-performance GPU ray tracing engine (see **http://rayforce.survice.com**).

The penetration kernel calculates threat penetration along interval output from Rayforce. This kernel takes data about an initial threat for a selected penetration equation as input. We currently implement both THOR [4] and Line-of-Sight (LoS) penetration equations. The LoS equation simply aggregates material thickness penetrated by the threat and records whether or not components are located within an input threshold. The output damage buffer contains information about threat state and damage information for each component along the shotline.

The component and system evaluation kernels take input data and generate *pk* values as output. The component evaluation kernel calculates *pk* values for each component along the shotlines from damage information. We optimize memory consumption by storing only component *pk* values for components that appear in the final output. The system evaluation kernel then aggregates component *pk* values according to the current system definition.

Finally, the visualization kernel maps system *pk* values to pixel colors for each shotline according to a single top-level system selected by the user. Pixel colors are then displayed as an image that is the same resolution as the original 3-D geometry viewer window.

We benchmark our prototype implementation, which is part of the Visual Simulation Laboratory (an open-source simulation and visualization framework [see http://www.vissimlab.org]), on a workstation with two 8-core 2.66-GHz Intel Xeon CPUs, 16 GB of host memory, and a single NVIDIA GTX Titan GPU with 6 GB of device memory. To demonstrate the implementation in a nontrivial scenario, the target geometry contains 1,167,791 triangles, as shown in Figures 6a and b. The results, depicted in Figure 6c, are generated from a 1,024 x 1,024 grid of shotlines, where more than 500,000 shotlines actually intersect target geometry (rather than empty space). The entire image is computed in 0.333 s, resulting in more than 1.5 million shotlines completed per second.

IMPACT AND FUTURE WORK

Breadth-first ballistic simulation, when implemented according to the architecture discussed previously, enables various advantages over depth-first approaches. First, using the computational power of the GPU enables single-view analysis to be computed in

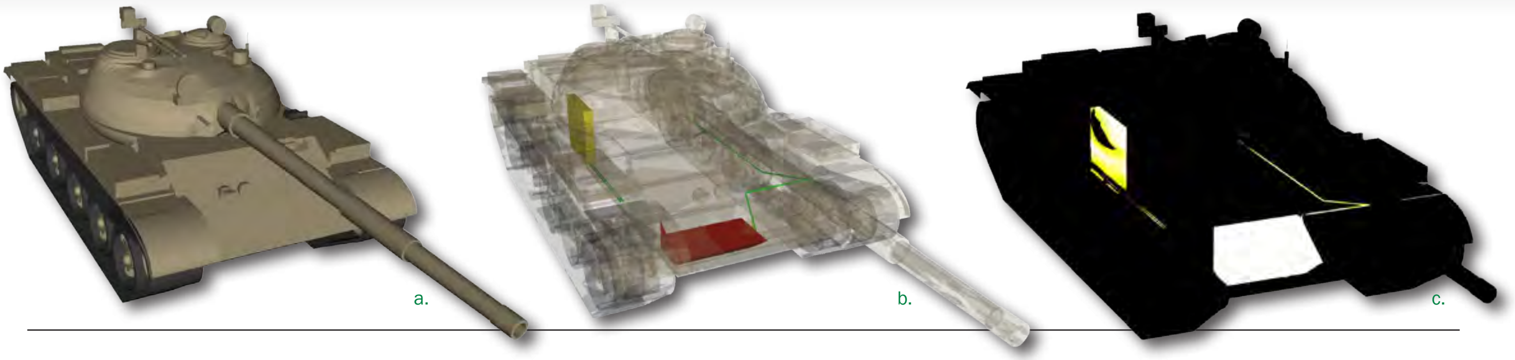

Figure 6: Ballistic Simulation on the GPU.

real-time on a single GPU. Second, data of interest to a user can be visualized immediately, without waiting for other results in the simulation to complete. Thus, analysts can begin to understand the results of one pipeline iteration while other, potentially more expensive, iterations are computed.

The combination of real-time simulation and visualization enables users to adjust input parameters as simulations execute. Traditionally, minor changes to input data introduce large workflow time-cost because all shotlines must complete before trends present in any output can be assessed. However, in our architecture, only certain stages of simulation need to be re-executed when parameters change. Thus, trending results from minor input changes can be visualized and understood immediately, enabling analysts to answer questions concerning vulnerability that were previously inaccessible.

While real-time, single-instance simulation provides new vulnerability analysis capabilities, large-volume batch simulation is still important to certain analyses. The simulation architecture presented herein, combined with modern massively parallel coprocessors, can drastically increase batched simulation volume. This effect itself is beneficial because larger computed datasets enable higher-fidelity answers as a result of higher-resolution inputs and results.

Going forward, the subject architecture will be implemented and demonstrated in a complete, end-to-end ballistic simulation application on a single workstation. Additionally, trends in the capability and programmability of low-power CPUs and GPUs suggest that an implementation of this architecture on mobile devices is well within reach, so the exciting possibilities enabled by such a system will continue to be explored. ■

BIOGRAPHIES

JEFFERSON AMSTUTZ is an Associate Research Scientist in the SURVICE Engineering Company's Applied Technology Operation. His work focuses on support to the U.S. Army Research Laboratory via the development of high-performance simulations in the Visual Simulation Laboratory framework. Mr. Amstutz has a B.S. in computer science with a minor in mathematics from Grove City College.

CHRISTIAAN GRIBBLE is a Principal Research Scientist in the SURVICE Engineering Company's Applied Technology Operation. He is also the Principal Investigator leading SURVICE's NVIDIA CUDA Research Center. Dr. Gribble's research explores the synthesis of interactive visualization and high-performance computing. He holds a B.S. in mathematics from Grove City College, an M.S. in information networking from Carnegie Mellon University, and a Ph.D. in computer science from the University of Utah.

ACKNOWLEDGMENTS

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DTIC SEARCH TERMS:

Computer Processing Ballistic Simulation

RESULTS: 43,800

- Export Control (2,600+)
- Computer Programming & Software (2,500+)
- Computerized Simulation (2,120+)
- Test & Evaluation (2,111+)
- Antimissile Defense Systems (2,103+)
- Military Operations, Strategy & Tactics (2,000+)
- Computer Programs (1,981+)
- Simulation (1,758+)
- Guided Missiles (1,647+)
- SBIR (1,600+)

***See page 3 for explanation ▸**

FINDING NEEDLES IN THE ISR HAYSTACK

MINT PROGRAM HELPS PINPOINT THREATS CONTAINED IN INTELLIGENCE DATA

By Chris Kennedy, Alan Nussbaum, and Shane Carleton

INTRODUCTION

Everyday, U.S. military and security units receive vast amounts of data collected by intelligence, surveillance, and reconnaissance (ISR) sensors. Human analysts constantly review these data, searching for possible threats. To aid in this effort, researchers from the Georgia Tech Research Institute (GTRI) are helping to improve the capabilities of the nation's Multi-Disciplinary Intelligence (Multi-INT or MINT) system, which monitors incoming data.

A key to improving the U.S. MINT system involves bringing "actionable intelligence"—information that could require immediate response—to the attention of human analysts as quickly as possible. But finding actionable intelligence is a challenge; it must be identified from a myriad of raw data gathered by intelligence sources, including optical and radar sensors, communications sensors, measurements and signatures intelligence (MASINT), and others.

"The number of analysts is limited, and they can only perform a certain number of actions," said research analyst Chris Kennedy, who leads the MINT effort. "So out of a huge set of information, which could involve millions of data points, you need to find the most valuable pieces to prioritize for investigation and possible action."

ACCLERATING THE SYSTEM

The MINT work addresses two related challenges in the field:

- Network bandwidth and workstation processing power sometimes cannot keep up with incoming data sets that contain terabytes—and sometimes even petabytes—of raw information.
- Human analysts need to stay on top of incoming data by concentrating on the most significant information.

Metadata are small amounts of information that contain the key elements of a data point, which is an individual piece of data. For example, in the case of a car moving down a road, its metadata might consist of the make, model, color, location, speed, and number of passengers. Those attributes are highly informative, yet much easier to transmit and process than, say, a video of the car, which would involve large amounts of data.

The MINT approach (illustrated in Figure 1) creates metadata fields, or leverages existing ones, thereby characterizing each data point with minimal overhead. Then only the metadata are transmitted to the main system for immediate processing; the rest of the raw data are retained in an archive for potential use at a later time.

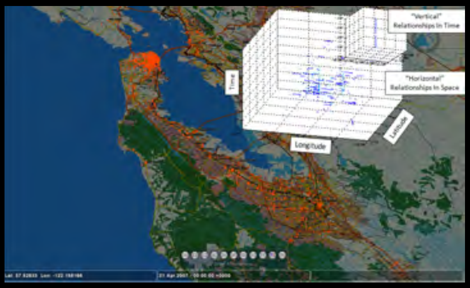


Figure 1: Brightkite Checkins in and Around San Francisco Bay Over a 3-Year Period. MINT Operates on These Data in 23 Minutes.

The metadata technique results in much smaller amounts of information being relayed from ISR sources to computers. That reduction, in turn, reduces processing loads, which helps computers and networks keep up with incoming data. The raw data are also stored and can be examined if necessary.

"Obviously, under this data-reduction approach," Mr. Kennedy said, "there are information losses that could affect how our program makes decisions, which is why our system is only a tool for, and not a replacement for, the human analyst."

INFORMING THE ANALYST

The second challenge—supporting human analysts—is addressed by methods that improve the system's ability to identify, compare, and prioritize different types of information. First, the gathered metadata are converted into a single uniform format. By creating one format for all incoming metadata, data points from many different sources can be more readily identified and manipulated. This uniform format is independent of the data source, so different types of ISR data can be processed together.

Then, using the identity-bearing metadata tags, researchers use complex machine-learning algorithms to find and compare related pieces of information. Powerful concurrent-computing techniques allow problems to be divided up and computed on multiple processors. This approach helps the system perform the complex task of determining which data points have been previously associated with other data points.

Other metadata approaches have been used in the past but only for a single intelligence technology, such as a text-recognition program that identifies keywords in voice-to-text data. The MINT program differs from these approaches because it integrates metadata from a variety of intelligence disciplines into a single technology that prioritizes corroborative relationships from multiple sources.

> We need to be able to say to the analyst, "OK, you've got a million data points, but look at these 10 first."

One set of potentially significant signals can be quickly compared to others in the same vicinity to form an in-depth picture. For example, in a disaster relief scenario, one aircraft-mounted ISR sensor might detect information that indicates abandoned vehicles. However, if another sensor detected a functioning communications device in one of the vehicles, that detection would indicate a higher likelihood of finding a survivor, potentially prompting a rescue reconnaissance effort.

The relationship found between the communications device's signal information and the vehicle's imagery information would be prioritized against other found relationships and displayed to the analyst on mapping software, such as GTRI's FalconView program.

ONGOING IMPROVEMENTS

Recently, the MINT team began working with other researchers involved in the development of the Stinger graph-analysis software. Stinger's capabilities could aid MINT efforts in recording and analyzing information about long-term patterns of observed relationships, such as a type of vehicle and a specific communications device being frequently observed together by independent sensors. This information would then be sent to an analyst through a web-based portal, giving the analyst access to alerts regarding specific kinds of relationships identified by MINT.

The MINT team is presently focused on improving the program's capacity to process many data points quickly, using three primary sets of testing data involving potentially millions of data points over lengthy time spans. The researchers' goal is to achieve real-time or near-real-time processing capability, so analysts can be alerted to abnormal information almost instantly.

"We want to get to the point where, as the latest data are coming in," Kennedy said, "they are being correlated against the data we already have. We need to be able to say to the analyst, 'OK, you've got a million data points, but look at these 10 first.'" ■

DTIC SEARCH TERMS:

MINT and ISR

RESULTS: 1,240

- Military Operations, Strategy & Tactics (104)
- Information Science (89)
- Military Intelligence (84)
- Computer Programming & Software (80)
- Foreign Reports (80)
- Symposia (69)
- Computer Programs (68)
- Aircraft (59)
- Military Forces & Organizations (57)
- Test & Evaluation (52)

***See page 3 for explanation** ▸

MODELING THE MIND

Using Finite Element Analysis to Predict Traumatic Brain Injury

By David Powell

INTRODUCTION

Traumatic Brain Injury (TBI) is a serious concern for both the military and the general civilian population. In particular, blast-related TBI has been prevalent in recent military conflicts [1]. During Operation Iraqi Freedom, a study of casualties requiring level V care at Walter Reed Army Medical Center reported that 29% of those screened had a TBI. Blast and explosion were the most common cause, accounting for 78% of those found to have a TBI [2]. Likewise, in the civilian population, approximately 1.4 million people in the United States sustain a TBI each year. Of that number, 50,000 die, 235,000 are hospitalized, and 1.1 million are evaluated, treated, and released from the nation's emergency departments [3]. When one also includes concussions (often called mild TBIs) in the discussion, it is also possible that the largest proportion of patients is never even seen in an emergency department. But perhaps the most concerning aspects of TBI are the residual effects, with at least 5.3 million Americans—almost 2% of the population—estimated to have current long-term or lifelong disabilities from TBIs [4].

TBI associated with closed head injuries, also referred to as nonpenetrating head injuries, can be caused by blast, blunt force impact, or sudden acceleration.

In cases such as these, diffuse axonal injury is one particular injury mechanism that has been cited as a signature injury of TBI neural damage [1, 5]. Deformation of the brain tissue can induce misalignment in the cytoskeletal network or axolemma permeability, inducing a cascade of subcellular events and culminating in the severance of the axon [6, 7]. It is these axon fiber bundles that make up the structural network that allows neurons to communicate with one another. Injury to the axons leads to degraded structural connectivity, which may be responsible for the cognitive deficits that are characteristic of mild, moderate, and severe cases of TBI [8]. Concussion, or mild TBI, is thought to be a less severe type of diffuse axonal injury, where axons are damaged to a minor extent from stretching. Postmortem studies of brains with concussions have found axonal damage; however, because of other factors, such as restricted blood flow, it is not possible to isolate the cause of this damage and solely link it to concussions.

NUMERICAL APPROACH

Finite element (FE) simulations are often used to better understand the mechanical response of the brain and investigate the potential for neurotrauma during a blast or impact event. Magnetic resonance imaging (MRI) scans can provide valuable detail on the geometry of the head, skull, and brain. The data from these scans can be used to create accurate, patient-specific FE meshes that can then be used in these blast or impact simulations. Tissue damage is computed using empirically based damage models. Modeling axonal injury mechanisms within the white matter of the brain has been the focus of many recent efforts. Various biomechanical and physiological injury thresholds for neurotrauma have been proposed, including those based on intracranial pressure [9] and those based on axonal strain [10, 11, 12]. Simulations using strain-based injury criteria have shown that the degree of injury predicted is highly dependent on the incorporation of the axonal orientation information and the inclusion of material anisotropy into the constitutive model for white matter.

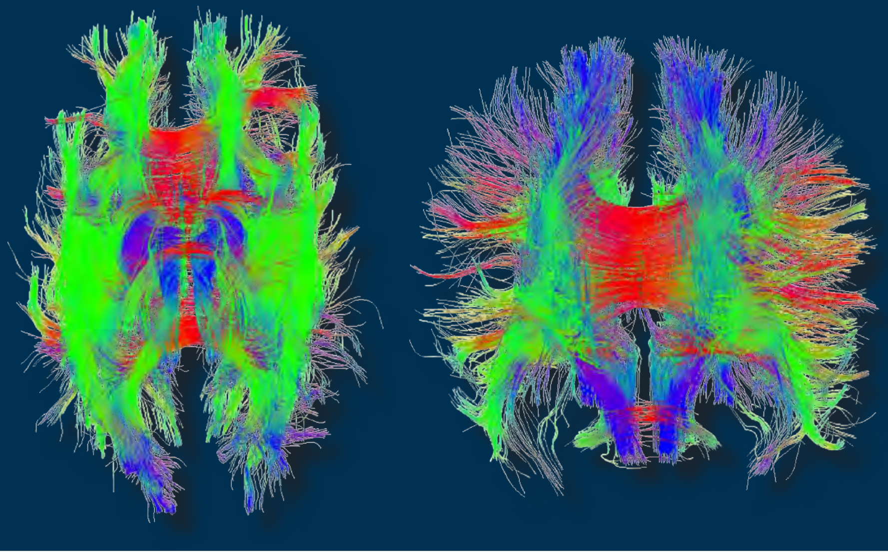


Figure 1: Dorsal (a) and Posterior (b) Views of DTI-Produced Axonal Fiber Tractography.

Traditional MRI scans are not able to provide the requisite detail at the microstructural level to generate the orientation vectors needed in the anisotropic material models. To obtain data on the axonal fiber orientation, a relatively new noninvasive tool called Diffusion Tensor Magnetic Resonance Medical Imaging (DT-MRI)—or Diffusion Tensor Imaging (DTI)—is used to capture the structural organization of the white matter. DTI is based on the principle that within biological tissue, water diffuses more rapidly in the direction aligned with the internal structure and slower in the perpendicular directions. The resulting images can be used to generate the diffusion tensor, from which diffusion anisotropy measures, such as the fractional anisotropy, can be computed. The principal direction of the diffusion tensor can be used to estimate the white matter connectivity of the brain. As shown in Figure 1, DTI allows the axonal fiber tracts to be charted and then imported into an FE model so that they can influence the mechanical response of the brain. These models can then be used to calculate the strains and damage in these fibers to create a prediction of diffuse axonal injury [10, 13].

The general process to create a biofidelic FE simulation begins with an MRI scan of a human subject. The subject undergoes both a Magnetization-Prepared Rapid Acquisition with Gradient Echo (MP-RAGE) scan and diffusion-weighted imaging. From the MP-RAGE scan, segmentation algorithms delineate the 3-D brain volume into brain regions to create a volume mesh. Data from the diffusion-weighted imaging are used in a reconstruction algorithm to estimate the streamlines that provide the structural connections between the regions of the brain. The reconstructed fiber tracts and the brain regions are then combined within an FE model.

The anisotropic material model, which is described in the next section, requires a unit vector for each element to identify the fiber orientation, $\underline{a}_0$. This task is complicated due to the unstructured nature of the FE mesh and the differences between the DTI scan resolution and that of the FE mesh. Fibers may begin and end in different elements, and a single element may contain multiple fibers. An algorithm is used to take the DTI data and assign an orientation vector to each element within the FE mesh. To begin, each fiber is subdivided into a number of smaller straight-line segments. The algorithm determines if any fiber segment overlaps with a given FE. If no fibers overlap an element, then that element is treated as an isotropic material. Depending on the fiber density and the element size there may be multiple fibers or multiple fiber segments within a single element. In this case, an averaging scheme is used to assign a single orientation to that element. The scheme adds all of the fiber segment vectors (from the same fiber) that are contained within the element. The resulting vector is normalized to create an average orientation. Note that the fiber segment vectors are not unit vectors, so their physical length acts as a weighting function in the averaging scheme. If multiple fibers pass through the element, the process is repeated for each fiber, after which all of the resulting averages are summed and normalized. There is the potential to include multiple fiber families, each with their own orientation, by expanding upon the following material model. This expansion would be of the greatest potential use when combined with Diffusion Spectrum Imaging (DSI), which is capable of describing fiber crossings. An example of the discretized axon fiber tracts along with the FE mesh is shown in Figure 2.

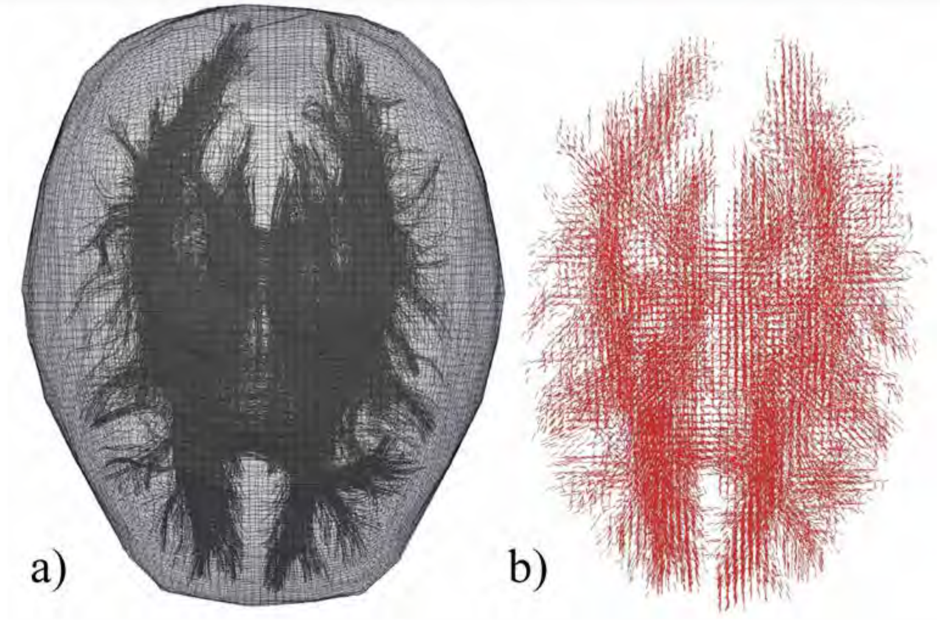


Figure 2. DTI Data Overlaid Onto a Brain's FE Mesh (a) and Discretized Orientation Data Assigned to Each Mesh Element (b).

> This modeling provides not just a means to predict the amount of cellular damage but also the cognitive effects that damage may have on an individual.

With an anatomically accurate mesh of the head, skull, and brain, along with constitutive equations informed by diffusion-weighted imaging, FE simulations of blast and impact can be carried out. These simulations produce a spatio-temporal description of the tissue deformation. The resulting strains and pressures can be compared to experimentally based injury thresholds for white matter, relating how the simulated blast or blunt impact forces translate to cellular death in neural tissue. Using high-performance computing clusters, we are then able to probe these forces at spatial scales matching our neuroimaging efforts. However, reliable predictions of tissue deformation are highly dependent on accurate constitutive equations describing the stress-strain response of the various biological materials.

We now consider one of the material models that will be used to describe the white matter and its axon fiber bundles.

TRANSVERSELY ISOTROPIC MATERIAL MODEL

In many biological tissues, fibers or bundles of cells are aligned in uniform directions. As a result, isotropic materials models are insufficient for capturing the mechanical behavior. For the white matter within the brain, axon bundles form complex fiber tracts as they connect and facilitate communicate between different regions in the brain.

These axonal fiber tracts have been reported to be approximately three times stiffer than the surrounding matrix material [14] and thus play an important role in the mechanical response of the brain. To model the white matter, we use a transversely isotropic hyperelastic material, where the fiber tract directions are determined from DTI data. A viscoelastic material model can be employed to include rate effects; however, for the sake of simplicity, rate effects are not discussed here.

To describe the material model, we must first define some basic kinematic concepts. The deformation gradient is defined as:

$$\underline{\underline{F}} = \frac{d\underline{x}}{d\underline{X}},$$

where $\underline{X}$ is the position of a material point in the reference (undeformed) configuration and $\underline{x}$ is the position of the same material point in the current (deformed) configuration. The ratio of the deformed volume to the undeformed volume is given by the Jacobian, the determinant of the deformation gradient:

$$J = det\left(\underline{\underline{F}}\right).$$

It is often beneficial to perform a multiplicative decomposition of $\underline{\underline{F}}$ into volume-changing (dilational) and volume-preserving (distortional) parts to separate the bulk and the shear response. To accomplish this decomposition, a deviatoric deformation gradient in which the volume change is eliminated is defined as:

$$\overline{\underline{\underline{F}}} = J^{-1/3}\underline{\underline{F}}.$$

We can then define a modified right Cauchy-Green tensor:

$$\overline{\underline{\underline{C}}} = \overline{\underline{\underline{F}}}^{T}\,\overline{\underline{\underline{F}}}.$$

The modified principle invariants of the right Cauchy-Green deformation tensor are defined as:

$$\bar{I}_1 = tr\overline{\underline{\underline{C}}},$$

$$\bar{I}_2 = \frac{1}{2}\left[\left(tr\overline{\underline{\underline{C}}}\right)^2 - tr\left(\overline{\underline{\underline{C}}}^2\right)\right],$$

and

$$\bar{I}_3 = det\overline{\underline{\underline{C}}} = \left(det\overline{\underline{\underline{F}}}\right)^2 = 1.$$

For the modified right Cauchy-Green tensor, because the volume change has been eliminated, the third principle invariant will always be 1. To capture the anisotropic nature of the white matter, we introduce a unit vector, $\underline{a}_0$, assigned using DTI data, that describes the direction of the fiber in the undeformed reference configuration. We can then define two additional invariants based on the fiber direction:

$$\bar{I}_4 = \underline{a}_0 \cdot \underline{\overline{\underline{C}}\underline{a}_0},$$

and

$$\bar{I}_5 = \underline{a}_0 \cdot \overline{\underline{\underline{C}}}^2\,\underline{a}_0,$$

where $\bar{I}_4$ and $\bar{I}_5$ arise from the anisotropy and describe the deformation of the fiber family. Should it be necessary to include multiple fiber directions, we can define additional invariants for each new fiber family ($\bar{I}_6 = \underline{b}_0 \cdot \underline{\overline{\underline{C}}\underline{b}_0}$, and so on). It should be noted that

$$\bar{I}_4 = \underline{a}_0 \cdot \underline{\overline{\underline{C}}\underline{a}_0} = J^{-2/3}\underline{a}\cdot\underline{a} = J^{-2/3}\lambda^2,$$

where $\underline{a} = \underline{\underline{F}\underline{a}_0}$ is the direction of the fiber in the current configuration and λ is the stretch in the fiber bundle. Thus, $\bar{I}_4$ will also be useful in evaluating strain-based injury criteria for the axon fiber bundles.

The strain energy, Ψ, of the transversely isotropic hyperelastic material can be written as a function of the modified principle invariants along with the Jacobian, which describes the change in volume. Assuming that the responses of the fibers and the matrix material are not strongly coupled, we can choose to separate the strain energy into a linear combination of the isotropic and anisotropic components [13, 15, 16]:

$$\Psi(I_1, I_2, J, I_4, I_5) = \Psi_{\mathrm{iso}}(I_1, I_2, J) + \Psi_{\mathrm{aniso}}(I_4, I_5),$$

where $\Psi_{\mathrm{iso}}\left(\bar{I}_1, \bar{I}_2, J\right)$ describes the response of the isotropic matrix and $\Psi_{\mathrm{aniso}}\left(\bar{I}_4, \bar{I}_5\right)$ describes the directional contribution of the reinforcing fiber bundles. We can then select an appropriate isotropic strain energy function for the matrix component, such as a Neo-Hookean or Mooney-Rivlin material model. For the anisotropic response, it is suggested to select a Fung material model that includes the exponential behavior characteristic of most soft tissues [16]:

$$\Psi_{\mathrm{aniso}}\left(\bar{I}_4\right) = k_1\left[exp\left(k_2(\bar{I}_4 - 1)\right) - \bar{I}_4\right],$$

where k_1 and k_2 are material constants obtained from a parameter fit to experimental data. This example is a relatively simple example of a Fung material. Depending on the available data, a more complex constitutive model for the fibers may be preferred.

NUMERICAL SIMULATION

A 3-D finite element model of the human head can be constructed using MRI data [17, 18]. The work described here used a Lagrangian, 3-D, explicit transient dynamic code called Presto within the Sierra Solid Mechanics suite of codes from Sandia National Laboratories. While this article is focused on modeling the white matter, the full simulation requires constitutive descriptions and properties for all of the components, including the skull, cortex, brain stem, cerebrospinal fluid, and skin and muscle (usually represented together as a soft tissue mixture). Within each volume element in the white matter region of the mesh, an algorithm assigns a fiber direction based on the DTI data. The model can be exposed to a variety of loading conditions, such as an applied blast pressure or an impact, both potential causes for TBI. Within the simulation, the axonal strain is calculated and compared against an injury threshold. The literature contains a wide range of such injury thresholds, from 0.05 to 0.21 [19, 20]. Bain and Meaney [11] have shown an electrophysiological impairment at axonal strain levels of 0.28 (liberal), 0.13 (conservative), and 0.18 (optimal) in tension.

In one series of simulations, a blast pressure was applied based on a charge detonated 3 m in front of the body at mid-thoracic height. The size of the charge was chosen so as to produce a peak incident pressure of 210 kPa and a positive duration of 2.8 ms. This loading is survivable with ballistic protective body armor and falls below the 50% survivability threshold for lethal head injury [21]. The largest axonal strains produced during this loading exceeded 0.17 and increased at the center of the brain throughout the simulation. Elements on the surface of the brain and near the ventricles also exhibited large amounts of axonal strain. Peak axonal strains occurred approximately 10–15 ms after the initial contact of the blast wave. Simulations were run with the head fixed and with the head permitted to rotate. When head rotation was prohibited, axonal strains did not exceed even the conservative threshold

FROM THE BATTLEFIELD TO THE SPORTS FIELD: BALLISTICS TEST LAB SUPPORTS TBI R&D

By Brian Wessel, Communications Manager Chesapeake Testing

Traditionally a provider of ballistic and nondestructive testing of military and law enforcement equipment, Chesapeake Testing is a Maryland-based independent test lab that is now extending its reach into the sports testing market. The lab is leveraging its extensive expertise in personal body armor (including helmet and armored vest) testing, as well as its state-of-the-art equipment and facilities, to test safety equipment designs intended to help prevent/reduce sports-related injuries, including traumatic brain injuries (TBIs).

The lab's efforts are in accordance with the National Operating Committee on Standards for Athletic Equipment (NOCSAE), which regulates the safety of all sports equipment used by professional athletes, youth organizations, and recreational sports enthusiasts.

"We are determined to meet standards that employ the latest technology, rather than just doing the same old thing," said Cameron Showell, the head of Chesapeake's Sports Testing Department. "This work is really part of a new generation in thinking and not what was done 20 years ago."

Among the advanced equipment that the lab is using in its sports testing efforts are an in-house monorail blunt impact tower (Figure 1), a twin-wire drop tower (Figure 2), and an air cannon, which can launch baseballs, hockey pucks, and various sports projectiles at speeds exceeding 200 mph.

The lab also offers specialized x-ray computed tomography (XCT) services, allowing manufacturers to get a detailed look at the inside of their products in support of pre-production quality control and post-test analysis. The large walk-in bay, 450-kV micro-focus XCT system is one of the most powerful XCT systems in use today, enabling objects up to 37 inches in diameter to be imaged with extremely high resolution. The system can also be combined with Chesapeake's other XCT systems and processing and visualization tools to support not only athletic equipment manufacturers but also customers throughout the DoD and other industries. ■

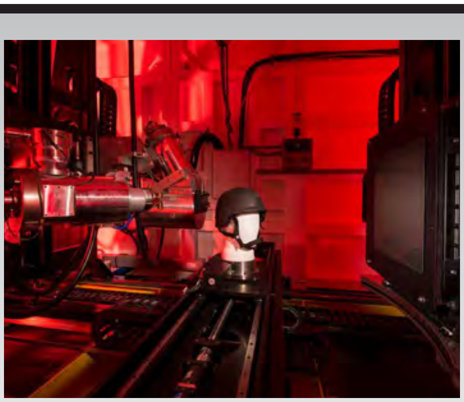
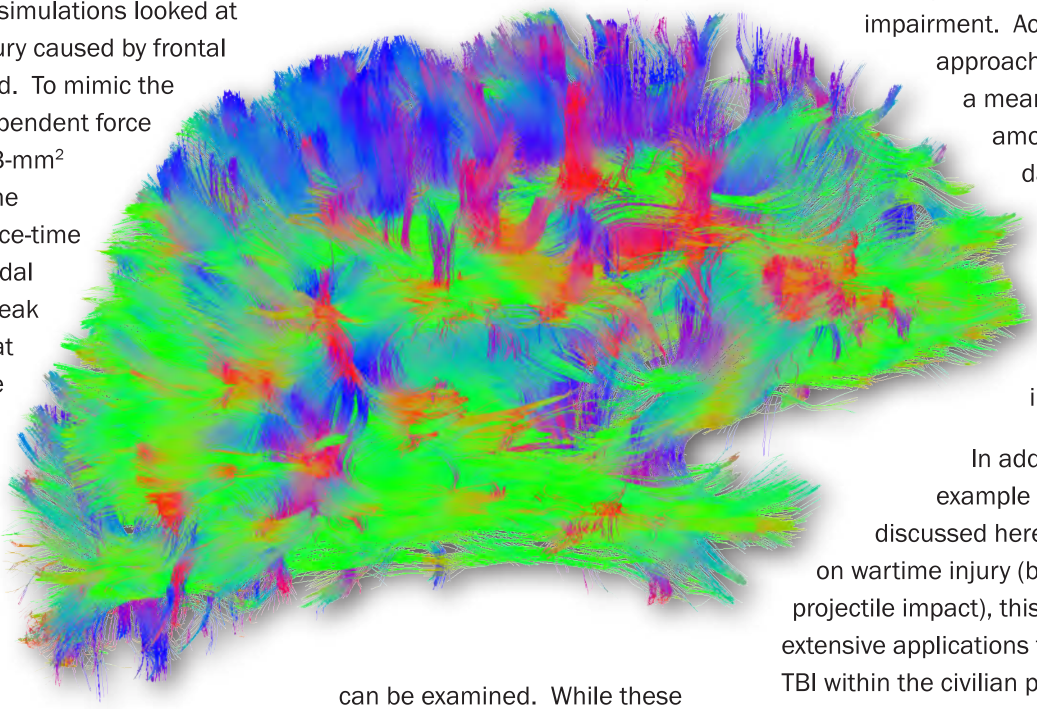


Figure 1: Chesapeake Testing's Monorail Blunt Impact Tower.

Figure 2: Chesapeake Testing's Twin-Wire Drop Tower.

for electrophysiological impairment. Allowing the head to rotate in response to the blast wave and the associated angular acceleration plays a significant role in the calculation of axonal strains and contributes to the severity of the TBI [22]. In further studies, frontal blast loading was compared to side blast loading. The side blast led to a higher concentration of axonal degradation in the occipital region, while frontal blast produced a more evenly distributed axonal damage [23].



Another series of simulations looked at diffuse axonal injury caused by frontal impact to the head. To mimic the impact, a time-dependent force was applied to a 3-mm^2 circular area on the forehead. The force-time curve was sinusoidal in shape, with a peak force of 7,000 N at 2.7 ms. While the highest pressures were seen in the frontal region of the brain, the largest axonal strains occurred in the temporal and occipital regions. In these areas, the axonal strain exceeded the 0.18 threshold for electrophysiological impairment [18].

CONCLUSION

The modeling efforts discussed herein have focused on the use of noninvasive DTI techniques to, in effect, provide a signature of TBI. In addition, these efforts have potential for even greater predictive capabilities investigating the structure-function relationship within the brain and the neurological impact of the axonal damage. The brain's gray matter contains most of the neuronal cell bodies involved in decision-making, memory, sensory perception, and muscle control; the white matter, made up of the bundles of axons, is responsible for communication between the different regions of gray matter. Using DTI, the paths of the fibers can be charted; regions of the brain associated with specific roles can be identified by subject-matter specialists or through scans (such as a Functional Magnetic Resonance Imaging [fMRI]); and the fiber tracts connecting these regions can be examined. While these simulations are not at a level of detail needed to map every connection within the brain (the current goal of the Human Connectome Project), we can still (using graph theory) look at what regions are connected and measure the strength of those connections, both through the number of fibers and the length of the connections.

A map of the neural pathways can be generated where specific regions of gray matter are represented as nodes with connections based on the axon fiber paths. Connections passing through the regions where strain is above a certain threshold, as predicted by the FE simulation, are degraded. The strength of the communication in this neural network can be calculated both before and after the simulation. Network science provides the means to calculate the global and local efficiency of these networks, as well as their capability to transfer information between nodes. By comparing these measurements both before and after the traumatic event, the reduction in the brain's capacity for communication can be calculated, thus providing a measure of mental impairment. Accordingly, this approach provides not just a means to predict the amount of cellular damage within the brain but also to predict the cognitive effects that damage may have on an individual.

In addition, while the example simulations discussed herein have focused on wartime injury (blast and projectile impact), this approach has extensive applications for modeling TBI within the civilian population as well. As mentioned previously, concussions are a mild form of TBI that are a major concern in both amateur and professional sports. There is considerable public pressure to increase the safety of athletes, especially at the high school and college levels. Also, the accelerative loading to the head during an automobile crash is another common cause of TBI within the United States. Thus, this approach to modeling diffuse axonal injury could help in evaluating new designs for protective sports gear and automotive safety measures (as discussed in the inset article).

Not surprisingly, validation of these simulations remains a challenge. Human experiments have been limited to cadaveric testing, where pressures, displacements, and strains can be measured. These measurements, when available, have shown good agreement with the simulation; however, experimental measurements of axonal damage and cell death (the quantities of greatest interest) are not possible through cadaveric testing. Qualitative comparisons can be made from medical scans, but true validation would require scans both before and after the head trauma. The geometry of the brain and the white matter fiber tracts are patient-specific, so without pre-injury DTI data, comparison with post-injury data is approximate at best. The use of animal testing as a human analog is one possible alternative; however, there are ethical implications of animal testing which must also be taken into consideration. Hopefully, long-term comprehensive studies of both soldiers and athletes will be published and will provide repeated DTI scans to investigate changes in the white matter tracts over time. For example, pre- and post-game DTI scans of football players could be combined with in-helmet accelerometers to record loading and identify axonal injury. Studies such as these have the potential to provide further insight to fine tune and validate the numerical models. ■

DTIC SEARCH TERMS:

Traumatic Brain Injury

RESULTS: 7,420

- Medicine & Medical Research (3,924)
- Wounds & Injuries (1,736)
- Anatomy & Physiology (1,364)
- Psychology (1,112)
- Trauma (1,054)
- Brain (992)
- Military Personnel (846)
- Traumatic Brain Injuries (826)
- Medical Services (790)
- Military Medicine (653)

***See page 3 for explanation ▸**

BIOGRAPHY

DAVID POWELL is a mechanical engineer with the SURVICE Engineering Company. He earned a B.A. in engineering from Dartmouth College and a Ph.D. in mechanical engineering from the University of California at Berkeley. He also held post-doctoral research positions at Stanford University and at the University of California, San Francisco, where he worked with a neurosurgery group at San Francisco General Hospital and developed numerical models for cerebral arteries. Dr. Powell was also a principal investigator for Soft Armor and Fiber Composite Modeling for Soldier Protection at the U.S. Army Research Laboratory and worked closely with the biomechanics modeling group on projects involving the spine and brain.

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STI ALERT

Interested in learning more about TBI? To assist with your research and development needs, DSIAC retains subject-matter experts who are available for consultation. These experts are on hand to provide the latest information on emerging trends and the current state-of-the-art in TBI research. For additional Scientific and Technical Information (STI) on this subject, please contact DSIAC.

CONTEMPORARY METHODS FOR REPAIRING COMPOSITE MATERIALS

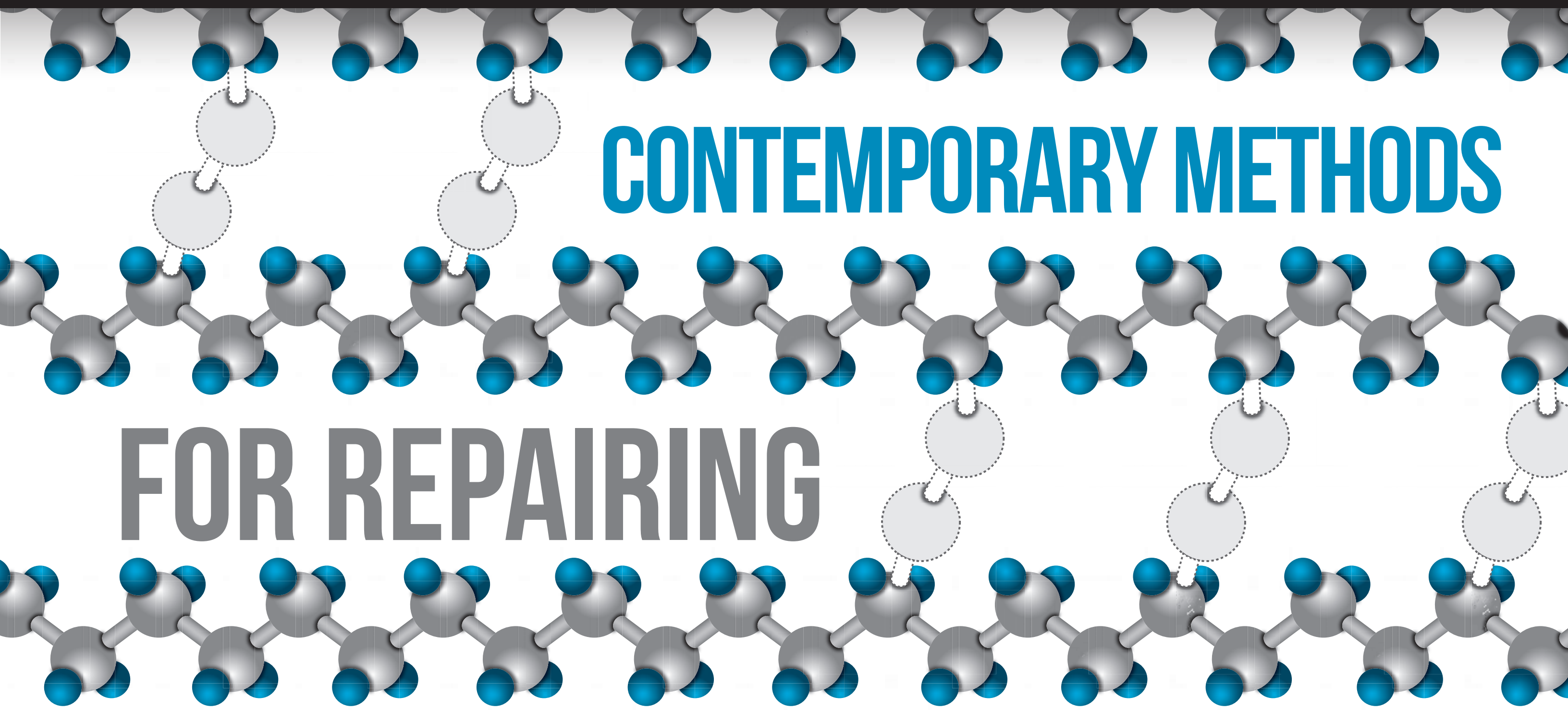

Figure 1 (illustrated above): Repeating Crystalline Polymer Chains with Strong and Weak Interchain Bonds.

By Madeline McAuley

INTRODUCTION

Composite materials, especially those that exhibit high strength-to-weight ratios and thermal stability, continue to be of increased interest to the Defense industry. Materials researchers, vehicle designers/manufacturers, and other industry stakeholders are recognizing the potentially significant cost savings (among other benefits) that could result from the lighter weight and correspondingly improved performance and fuel efficiency associated with incorporating composites into vehicle designs and a myriad of other applications. That said, the complex interaction between composite materials and the respective system requires careful design, especially in structural applications. One issue in particular is the failure to design for reparability, while striving to minimize up-front costs, which could ultimately burden the customer with high system life-cycle costs [1]. This article discusses contemporary issues and considerations associated with structural composite composition, failure, inspection, and repair.

COMPOSITE COMPOSITON: A CLOSER LOOK

A structural composite consists of matrix material and load-carrying reinforcement material. Matrix materials include plastic, ceramic, metal, and glass. Reinforcement materials include fiber, chopped fibers, flakes, particles, and whiskers.

The most common composite matrix materials are some form of plastic. Plastics can be categorized in two groups: thermoplastic and thermoset. Thermoplastics can be further categorized into their degree of crystallinity (i.e., amorphous, semi-crystalline, or crystalline). Amorphous polymers consist of completely random-ordered chains. Crystalline polymers consist of completely ordered three-dimensional chains, further oriented with weak interfacial bonds, as illustrated in Figure 1. Semi-crystalline polymers reside somewhere in between amorphous and crystalline polymers. Amorphous polymers are impact-resistant and elastic while crystalline polymers are harder, stiffer (more brittle), and more thermally stable than amorphous polymers. The degree of crystallinity depends on several factors, including viscosity and the number of side groups of the polymer chains. The weak interfacial bonds between chains of a thermoplastic fade with the application of heat. As the chains ebb, the material softens, allowing it to be reformed. Common thermoplastic materials include polyetheretherketone (PEEK) and polyphenylene sulfide (PPS).

A thermoset polymer is one large cross-linked molecule that is held together with strong covalent bonds. If one were to heat a cured thermoset, the cross-links would prevent displacement of the chains and the material would degrade. Consequently, thermosets cannot be reshaped like thermoplastics after curing, and repairs require a liquid state catalyzer for cross-linking the repair material into the cured material. Commonly used thermoset materials include epoxy, polyester, silicone, and bismaleimides.

Typically, thermoplastics exhibit increased toughness when compared with thermosets. However, it is important to note that the increased addition of fillers or fibers to thermoplastics reduces its impact strength to levels comparable to thermosets [2]. A comparison of thermoplastic and thermoset properties is provided in Table 1.

COMPOSITE FAILURE

Composite failures can largely be attributed to a material fracture or physical damage. Composite fractures typically result from material breakage at a fundamental level. The interface between the fiber and matrix is crucial for stress transfer. Fracture damage can be the result of breakage of atomic bonds, fiber breakage, debonding between the fiber and matrix, and delamination [4, 5]. In this context, damage refers to the distributed irreversible change that results from external physical or chemical loading. The most common damage types include core damage, intralaminar matrix cracks, delamination, and fiber fracture [6]. Delamination, one of the more common forms of fracture damage, is the separation of plies caused by interlaminar cracking between two adjoining plies in a laminate [4].

Inspection Techniques

The extent of composite material damage cannot be easily assessed by visual inspection alone. For example, low-energy impacts often leave no visible marks on the surface, yet can result in extensive underlying delaminations, commonly referred to as barely visible impact damage (BVID). Accordingly, there are several nondestructive inspection (NDI) techniques for composites, such as tap testing, ultrasonic inspection, X-ray inspection, and thermography, which can be used to detect hidden damage.

Tap testing (which is performed manually or with a special tap hammer) is one of the simplest methods that can be used in the field on composites with up to five or six plies. Such testing is often performed by tapping the surface of a structure and discriminating good areas from bad by analyzing differences in sound resonance. Experienced testers need only their ears to discern the good areas, which tend to reverberate

Table 1: Qualitative Comparison of Current Thermoplastics and Thermosets [3]

Characteristic	Thermoplastics	Thermosets
Tensile properties	Excellent	Excellent
Stiffness properties	Excellent	Excellent
Compression	Good	Excellent
Compression strength after impact	Good to excellent	Fair to excellent
Bolted joint properties	Fair	Good
Fatigue resistance	Good	Excellent
Damage tolerance	Excellent	Fair to excellent
Durability	Excellent	Good to excellent
Maintainability	Fair to poor	Good
Service temperature	Good	Good
Dielectric properties	Good to excellent	Fair to good
Environmental weakness	None, or hydraulic fluid	Moisture
NBS smoke test performance	Good to excellent	Fair to good
Processing temperatures, °C (°F)	343–425 (650–800)	121–315 (250–600)
Processing pressure, MPa (psi)	1.38–2.07 (200–300)	0.59–0.69 (85–100)
Lay-up characteristics	Dry, boardy, difficult	Tack, drape, easy
Debulking, fussing, or heat tacking	Every ply if part is not flat	Typically every 3 or more plies
In-process joining options	Co-fusion	Co-cure, Co-bond
Postprocess joining option	Fastening, bonding, fusion	Fastening, bonding
Manufacturing scrap rates	Low	Low
Ease of prepregging	Fair to poor	Good to excellent
Volatile-free prepreg	Excellent	Excellent
Prepreg shelf life and out time	Excellent	Good
Health/safety	Excellent	Excellent

and ring from the bad areas, which tend to thud [7]. Alternatively, special tap hammers can be used in noisy environments, such as an airfield, to provide greater objectivity. In either case, the tester must have a good understanding of the underlying structure, as the difference in tones from internal doublers and stiffeners could lead to a false interpretation [8].

One of the most popular NDI techniques for composites is ultrasonic inspection [9, 10]. Pulse-echo ultrasonic equipment can be used to determine the depth of defects. However, this equipment does not work well when inspecting composites with a core material. Alternatively, through-transmission ultrasonics overcome the core limitation of pulse-echo ultrasonics but require access to both sides of the item under inspection [11]. Additionally, through-transmission equipment is typically fixed in a dedicated facility and not generally field deployable.

X-ray equipment can provide the most detailed information to inspectors [11]. However, the major limitation with this type of equipment is detecting delaminations parallel to the image plane. Similar to ultrasonic equipment, X-ray equipment is also generally fixed in a dedicated facility and requires well-trained inspectors [8].

REPAIR

Repairing a damaged composite component to its original mechanical properties is extremely challenging. The characteristics of the repaired composite are generally never the same as the original. Consequently, there are typically three tradeoffs to consider when implementing a composite repair: strength, stiffness, and weight. For example, if attempting to match the original strength of a composite, the resulting repair is often heavier and stiffer. Further repair options are heavily influenced by the constituent materials, fiber orientations, core material, laminate thickness, number of lamina, and designed strain level. Key factors for implementing a successful repair include surface preparation, adhesive choice, repair materials, and processing conditions. The major requirements and considerations for typical repairs are summarized in Table 2.

> The interface between the fiber and matrix is crucial for stress transfer.

Surface Preparation

Moisture in the materials (parent composite and repair) and air (humidity) can lead to a degradation of properties, especially when subject to high heat cure cycles. In sandwich structures, the skin and core can rupture due to high steam pressure from the presence of moisture during the cure process [12, 13]. Most adhesive formulations require a low relative humidity (>40%) repair environment. Moisture absorbed by adhesives (typically during application) can result in porous bondlines during high-temperature cure cycles [12, 13].

The ability of the adhesive to maintain contact with the solid parent structure—termed wettability—is largely dependent on surface preparation. Typical surface preparations include blasting, sanding, and chemical treatments. Additionally, laser surface preparation is a promising newer technique that can remove virtually all surface contaminates [14]. The type of laser is crucial, as the bulk material properties can be inadvertently affected. An integrated laser for both damage removal and surface

Table 2: Requirements and Considerations for Repair of Composites [6]

Repair requirement or consideration	Important factors
Static strength and stability	Full versus partial strength restoration
Repair durability	Fatigue loading Corrosion Environmental degradation
Stiffness requirements	Deflection limitations Flutter and other aeroelasticity effects
Aerodynamic smoothness	Manufacturing techniques Performance degradation
Weight and balance	Size of the repair Mass balance effect
Operational temperature	Low and high temperature requirements Temperature effects
Environmental effects	Types of exposure Effects of epoxy resins
Related on-board aircraft systems	Fuel system sealing Lightning protection Mechanical system operation
Costs and scheduling	Downtime Facilities, equipment, and materials Personnel skill levels Materials handling
Low observable characteristics	Radar cross section Laser cross section

preparation could provide a great benefit for bonded composite repairs, most notably the reduction of human variability [5].

Adhesive Choice

Adhesive choice is also a crucial element for successful composite repair. The repair patch must have a strong and durable bond to the parent composite throughout the remaining lifetime. The adhesive choice will depend on the repair patch and parent composite materials, operating environment, geometry, accessibility (ability to remove the part), and manufacturing facility.

Typically, high-temperature adhesives are brittle and stiff at low temperatures, and low-temperature adhesives are too weak or degrade at high temperatures. Adhesives capable of withstanding a high-temperature environment generally require higher cure temperatures. High-temperature curing, requires caution, as it is possible to create even more damage through overheating of the undamaged parent materials. This curing also poses a higher risk of damage, such as a ruptured core or delamination, due to pressure, which occurs as any absorbed moisture is converted into steam. Typical characteristics of common composite repair adhesives are provided in Table 3.

Adhesive Fillet

With many composite repairs, adhesive joints result in peel stress (moment) concentrations at the end of the overlapping repair patch. When subjected to high peel stresses, the composite will likely fail in the transverse direction, as there is little to no load-carrying between lamina. Both the stress concentration and the transverse stress distribution in the composite can be significantly reduced by filleting the adhesive joint. The maximum transverse stress location in an adhesively bonded metal doubler, with and without an adhesive fillet, for a thermal and tensile load is illustrated in Figure 2. The ability of an adhesive to be used in a fillet is a major consideration for structural composite component repair. For such applications, high-viscosity adhesives are a highly desirable characteristic. And once cured, the exposed fillets

Table 3: Typical Characteristics of Adhesive Types [13]

Type	Form	Cure Temperature, °C (°F)	Maximum Use Temperature, °C (°F)	Advantages	Disadvantages
Epoxy	Two-part paste	Room or accelerated at 93–178 (200–350)	Generally below 82 (180)	Ease of storage at room temperature; ease of mixing and use; long shelf life; gap filling when filled	Not generally as strong or environmentally resistant as typical heat-cured epoxies
	One-part film	121 (250) 149 (300) 178 (350)	To 82 (180) 149–177 (300–350)	Covers large areas; bondline thickness control; wide variety of formulas; higher-temperature curing materials; better environmental properties	Store at 18 °C (0 °F); short shelf life; high-temperature cure; brittle and low peel strength
Acrylic	Two-part liquid or pastes	Room to 100 (212)	105 (221)	Fast setting; easy to mix and use; good moisture resistance; tolerant of surface contamination	Strong, objectionable odor, limited pot life
Polyurethane	One- or two-parts	Room to heat cure	...	Good peel; good for cryogenic use	Moisture sensitive before and after cure
Silicone	One- or two-part pastes	Room to 260 (500)	To 260 (500)	High peel and impact resistance; easy to use; good heat and moisture resistance	High cost; low strength
Hot melt	One-part	Melt at 190–232 (375–450)	49–171 (120–340)	Rapid application; fast setting; low cost; indefinite shelf life; nontoxic ; no mixing	Poor heat resistance; special equipment required; poor creep resistance; low strength; high melt temperature
Bismaleimide (BMI)	One-part paste or film	>178 (350) and 246 (475) postcure	177–232 (350–450)	Structural bonds with bismaleimide composites; higher temperature than epoxies; no volatiles; good shelf life	Brittle and low peel
Polyimide	Thermoplastic liquids; one- and two-part pastes	260 (500) and postcure	204–206 (400–500)	High-temperature resistance; structural strength	High cost; low peel strength; high cure and postcure temperatures; volatiles for some forms
Phenolic-based	One-part films	163–177 (325–350)	To 177 (350)	High-temperature use	Low peel strength

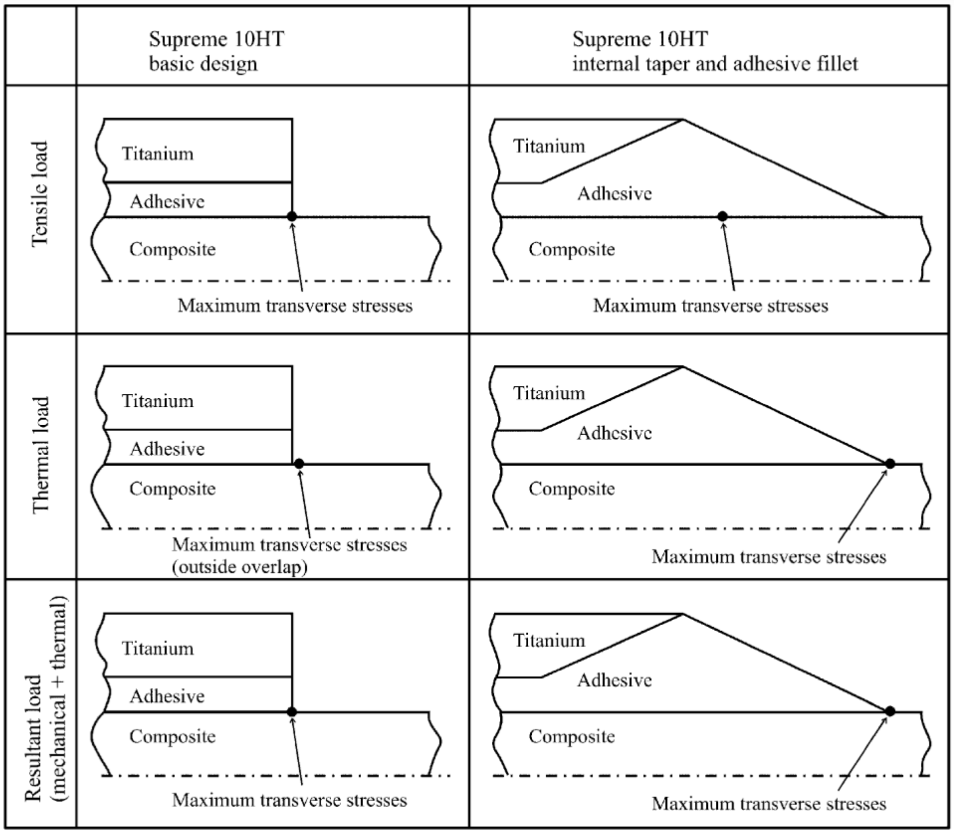

Figure 2: Maximum Transverse Stress Locations in the Composite for a Tensile Load and a Thermal Load [15].

and bondlines of a repair are typically protected with the use of a sealer.

Thermoset Adhesives

The most common adhesives for composite repairs are thermosets, and the specific choice of adhesive depends largely on the constituent material. The cross-linking of a thermoset, and therefore the quality of the bond, are largely dependent on cure process settings. The rate and degree of cross-linking can be tailored through the combined use of accelerators and temperature.

With similar properties to constituent composite materials, epoxy is the most common family of adhesives. Epoxy adhesives can be altered with a variety of additives, such as viscosity modifiers, flexibilizers, and tougheners. Further, epoxy adhesives are supplied as a film and one- or two-part curing liquid (or pastes). One-part epoxies require an elevated temperature for curing (250–350 °F) whereas two-part epoxies are capable of curing and cross-linking at room temperature due to the chemistry of a curing agent [13].

Adhesives for Thermoplastic Composites

A major advantage of thermoplastic composite repair is the composites' higher processing temperatures. Thermoset and amorphous thermoplastic adhesives generally require lower cure temperatures than semi-crystalline thermoplastics, mitigating concerns for temperature-induced damage of the parent material. The ability of thermoplastic materials to be melted and reshaped, in conjunction with their mechanical and thermal properties, makes their use appealing for future repair technologies.

Because thermoplastic materials have a lower surface energy than thermosets, they are more difficult to wet for an adhesive bond [2]. Accordingly, the surface treatment requires methods to alter the chemistry and surface geometry (roughing) for adequate adhesive bonding [16].

Surface treatments for thermosets are often inadequate for thermoplastics, requiring the repair of thermoplastics to adopt less-conventional surface preparation techniques. Examples of such include plasma etching, flame treatment, laser treatment, and corona discharge treatment. Plasma treatment provides surface etching on an atomic level via inert gases. Flame etching oxidizes the surface by passing a gas flame over the surface. Corona treatment is performed through electrical discharge of one or more high-voltage electrodes through the thermoplastic [2].

Adhesive-Bonded Repairs

Adhesive-bonded repairs, such as the scarf repair, are generally considered the best alternative in terms of strength, stiffness, and weight trade-offs [6, 8]. Thin, lightly loaded laminates and sandwich structures are generally limited to adhesive-bonded repairs. This limitation arises from stress concentrations induced by holes for mechanical fasteners. Accordingly, adhesive joints must be designed to sustain loading shear, such as the illustrated shear stress distribution of the various bonded joint configurations in Figure 3. Generally, adhesive bonds for composite materials are incapable of withstanding peel loading, tension, and cleavage [13].

The doubler repair is the most basic adhesive-bonded repair. The doubler repair patch is applied to one or both sides of the parent composite and is

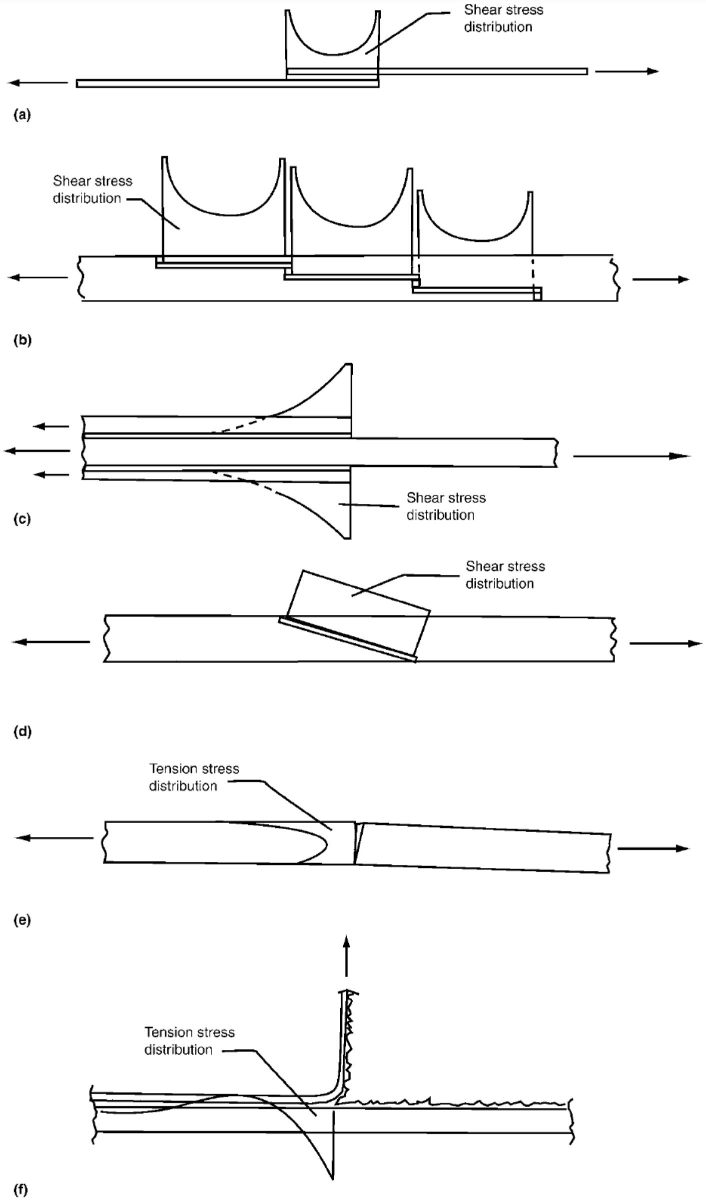

Figure 3: Various Bonded Joint Configurations. (a), (b), and (c) Shear, (d) Scarf, (e) Tension, (f) Peel [13].

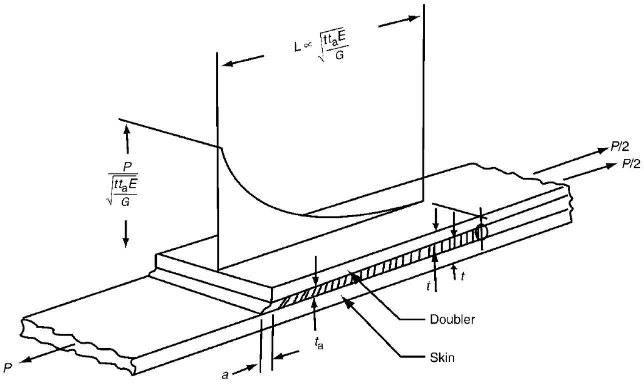

Figure 4: Adhesive Shear Stress for a Skin-Doubler Specimen. E, Tensile Modulus of Adherends; G, Shear Modulus of Adhesives [13].

typically referred to as a single or double lap. The doubler patch overlay must be long enough to distribute elastic forces through the adhesive [6]. The adhesive shear stress for a skin-doubler specimen is illustrated in Figure 4. For these types of sandwich structures, the damaged core is removed, a replacement core is fixed in the void, core splice adhesive bonds the replacement core to undamaged core, film adhesive bonds the core to ply (transverse direction), and a doubler patch is bonded over the replacement core and parent lamina. When implementing a doubler repair, the use of a vacuum to apply pressure for an adhesive cure is not recommended as it can result in voids and increased porosity, leading to a poor bondline [13].

The two primary aerodynamic composite structure repair methods are referred to as stepped and scarf. In a stepped repair, each ply is cut down individually, leaving a stepped pattern of decreasing area as depth increases. Care is required when removing the individual plies to avoid damaging fibers in undamaged areas from grinding and sanding. Surface preparation is also crucial for adhesive bonding. Ply patches are oriented in the parent composite's ply fiber orientation. It is generally preferred to use precured patches of the same material. However, precured patches are not always suitable (e.g., as with a complex surface), requiring precautions to avoid overheating.

The primary drawback to the stepped repair is matching the repair patch to the parent ply's void. Mismatches result in sharp edges with stress risers. Additionally, stiff edges resulting from patch plies and/or adhesive can lead to peel mode failures and damage to the underlying part.

Stress discontinuations in the stepped repair can be mitigated with a scarf repair (also referred to as a tapered repair). With a scarf repair, the damaged area is removed at a constant cutting angle, called the scarf angle. Low-peel stress can be achieved by using an extremely small scarf angle. This angle is typically limited to approximately 2° to 3°, resulting in a negligible peel stress compared with the shear stress [6, 17].

Bolted Repairs

The bolted doubler repair is commonly used for repairs requiring strength. Plates, typically steel or titanium, are bolted on both sides of the damaged area as illustrated in Figure 5. While simplistic in its implementation, there are advantages and disadvantages to the bolted doubler repair method. The bolted doubler repair method requires less training as drilling and fastening require little specialized expertise; however, knowledge of the materials is crucial, and proper drilling, sealing and corrosion prevention are common areas of concern. For example, both heat and vibration from drilling can cause undesirable effects to the undamaged composite. Further, bolted repairs are generally not feasible for thin laminates, aerodynamic applications, weight-balanced components, and applications with low-observability (signature) requirements [8].

As with bolted designs for metal, bolted designs for composites should aim for low bearing stresses. Accordingly, when designing the optimal bolt pattern, the designer must know the underlying fiber layup pattern. A typical bolted repair requires at least 12.5% of the fibers in the 0°, ±45°, and 90° direction (a maximum of 37.5%) [1]. Fasteners should be selected to prevent corrosion; for carbon/epoxy composites, they are typically made of titanium or a nickel-copper alloy [11]. The patch should be sealed to the parent composite, followed by inserting and sealing the fasteners in the wet condition [6].

> Bolted designs for composites should aim for low bearing stresses.

Thermoplastic Composite Repairs

Similar to thermoset composites, thermoplastics can be repaired using adhesives and mechanical fasteners. The ability for thermoplastics to be melted and reformed allows for fusion bonding and thermo-reforming. A fusion bond is generated through high heat and pressure, and thermo-reforming involves the removal of the part for re-processing on the original mold [2]. Both repair techniques are suitable for repairing cracks and delaminations in thermoplastics.

Welding thermoplastics with a heated tool (co-consolidation) is limited by the ability to control the melt, as the viscosity of a thermoplastic is a function of temperature. Elaborate tooling and fixtures are required for parts that cannot be removed and returned to their original mold. Resistance heating is another method for welding carbon composites that can be performed using an appropriate power supply. The natural electrical resistance of carbon fibers can generate a sufficient amount of heat, when subjected to a voltage, to facilitate a weld. In fact, the U.S. Air Force concluded resistance heating can be employed as a viable repair method for on-aircraft, in-field repairs using a heater ply of APC-2 unidirectional prepreg tape with polyetherimide (PEI) film, as illustrated in Figure 6. The amorphous thermoplastic PEI is preferred over PEEK because of its lower

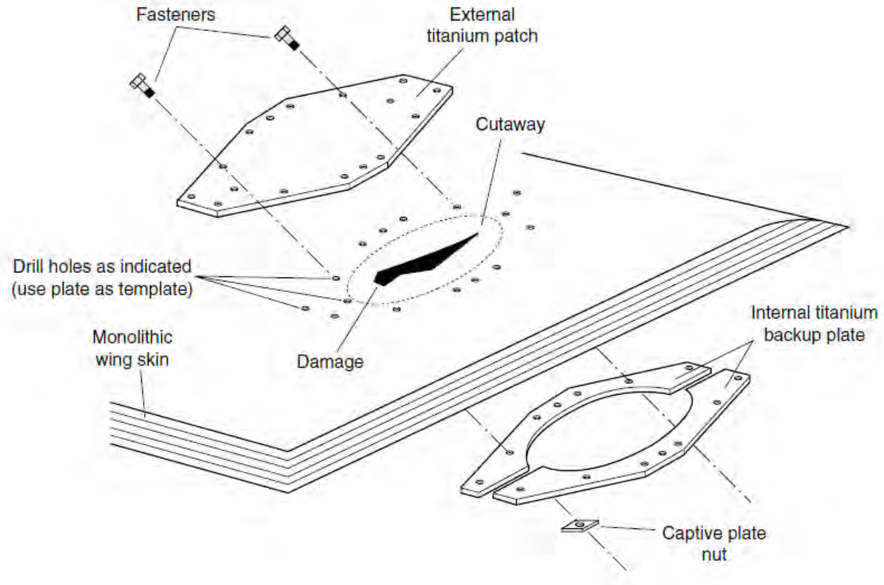

Figure 5: Bolted Doubler Patch Repair on a Thick Skin Composite [8].

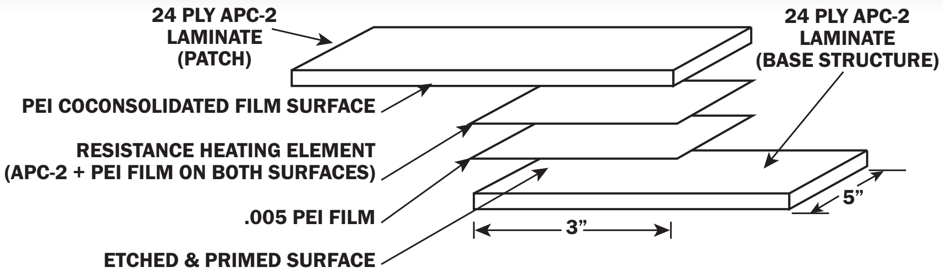

Figure 6: Configuration for Amorphous Thermoplasic Bonding via Resistance Welding [18].

processing temperatures, as the high-temperature curing of PEEK film during the repair process damages the parent composite [18].

Similar welding repair methods include induction and ultrasonic welding. As with resistance welding, induction welding also leverages the composite material properties to generate heat. The conductive and ferromagenetic materials in the composite facilitate the weld by absorbing electromagnetic energy to generate heat. With ultrasonic welding, frictional heat generated from high-frequency ultrasonic acoustic vibrations facilitates the weld. Ultrasonic repair welds are limited by the beam size. Large repairs require multiple passes of the beam and yield variable results [18].

Repair Verification

Composite repair verification training is becoming increasingly important as the number of skilled repair technicians is not meeting the demands of increased composites use. Verification of repair quality is also growing increasingly expensive and more difficult to perform with the growing complexity of composite components. As with many structural repairs, it is seemingly impossible to know the strength of a repair without breaking it. Therefore, it is crucial to make companion test coupons for every adhesive repair. The long-term durability of a bonded repair requires periodic inspection throughout the remainder of the component's lifetime. ■

BIOGRAPHY

MADELINE MCAULEY currently works as an Associate Engineer with the SURVICE Engineering Company. She has participated in numerous research initiatives studying new materials and predicting processing requirements. She has also taught plastics properties and processing courses at Western Michigan University. Ms. McAuley was also the lead designer and mechanical advisor for the Sunseeker Solar Car race team, a lightweight composite monocoque track car with proven design integrity. She holds a B.S. in engineering design, an M.S. in manufacturing engineering, and an M.S. in industrial engineering from Western Michigan University.

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DTIC SEARCH TERMS:

Composite Material Repair

RESULTS: 72,600

- SBIR Reports (1,900+)
- SBIR (1,900+)
- Composite Materials (1,750+)
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- Medicine & Medical Research (1,300+)
- Logistics, Military Facilities & Supplies (1,200+)
- Symposia (1,100+)

***See page 3 for explanation ▸**

Lockheed Martin

Figure 1: A Convoy of Autonomously Travelling Army Trucks in a 2014 AMAS Demonstration.

NAVIGATING THE FUTURE BATTLEFIELD WITH AUTONOMOUS GROUND VEHICLES

By Joe Zinecker

The ongoing development and use of autonomous/unmanned ground vehicles (UGVs) continue to offer much promise when it comes to addressing the inherent, significant personnel risks that come with putting "boots on the ground" in today's combat zones. Despite the complex and varied nature of today's missions and threats, UGVs are an increasingly versatile, capable, and appropriate solution for military planners, researchers, and developers.

Recently, Lockheed Martin and several Government and industry partners (including the U.S. Army Tank Automotive Research, Development and Engineering Center [TARDEC]) achieved several important milestones in the development and demonstration of autonomous ground vehicles. On the autonomous appliqué side, developers successfully demonstrated driver-assisted and semi-autonomous convoys of military logistics trucks operating at speeds up to 45 mph and with convoys as long as seven vehicles. Likewise, in the area of off-road missions, a fully autonomous reconnaissance and logistics mission was demonstrated using an unmanned aerial vehicle (UAV)/UGV pair. These accomplishments, along with numerous others, continue to prove the maturity and near-term applicability of these types of autonomous solutions.

Two examples of major UGV systems currently being developed and tested by Lockheed Martin are the Autonomous Mobility Appliqué System (AMAS) and the Squad Mission Support System (SMSS). The following sections provide a brief overview of these programs.

AUTONOMOUS MOBILITY APPLIQUÉ: THE AUTONOMOUS MOBILITY APPLIQUÉ SYSTEM (AMAS) AND ITS DERIVATIVES

The Mission

For some applications and missions, it is cost effective and reasonable to employ an "autonomy appliqué" on an otherwise conventional manned vehicle, such as a truck. Military convoys are a prime candidate for application of an autonomy appliqué because (1) even limited autonomy will reduce accidents caused by driver fatigue, inattention, and some road conditions; (2) autonomy can free up the driver/crew to obtain greater situational awareness and security, enhancing their survivability; and (3) autonomy may permit the Army to reassign some drivers to other roles, supporting net force count reduction and cost savings. But even with automation

of the basic driving function, there is good reason, at least for the near term, for maintaining the "mannability" of these vehicles to drive them in congested areas, such as ports, and to enable many functions that robotics are not currently employed to do.

The Program

The AMAS program is jointly funded by several Department of Defense (DoD) agencies and Lockheed Martin and is aimed at solving the autonomous convoy problem. AMAS physically consists of two main elements: a Drive-By-Wire/Active Safety Kit and an Autonomy Kit. The Autonomy Kit is composed entirely of components and software that would be common to any logistics convoy vehicle, including sensors, computers, and the controlling software. The Drive-By-Wire/Active Safety Kit includes some vehicle-independent components but also all of the vehicle-specific parts necessary to interface to specific vehicle steering, throttle, transmission, and brakes.

Under the AMAS program, developers initially addressed driver-warning and driver-assist functions, such as collision, rollover, and blind-spot warning. Additionally, the program has focused on stability control, lane-keeping, and the ability to execute convoy operations in a semi-autonomous leader/follower mode, including related functions, such as remote control, teleoperation, and waypoint navigation.

> With no human nearby and the vehicle possibly far from recovery or repair capabilities, the UGV must possess extraordinary mobility, power, robustness, and reliability.

Recent Progress

The AMAS completed design, fabrication, and installation of Autonomy and Active Safety/Drive By Wire Kits early in 2014 and entered into a series of Technology Demonstrations, Safety Tests, and Operational Demonstrations, which were completed in August 2014. Those tests demonstrated the abilities of the Driver Warning/Driver Assist functions to deal with real-world convoy problems, such as traffic and weather. Performance of the system was excellent.

In addition, under an adjunct to the AMAS program, Capability Advancement Demonstrations of a fully autonomous convoy operation featuring an autonomous leader and followers were conducted. As shown in Figures 1 and 2, the capability was demonstrated in simulated on-road and urban environments with simple obstacles, such as pedestrians; oncoming, passing, and crossing traffic; unplanned route interruptions demanding autonomous real-time route replanning; go-to-point navigation; traffic circles; and stop sign intersections.

Future Plans

The aforementioned demonstrations have convinced potential users that the area of ground robotics has reached sufficient maturity that it can be considered for manufacturing development and fielding in the short to medium term (i.e., within 5 years). There are a number of programs that could possibly deploy elements of AMAS

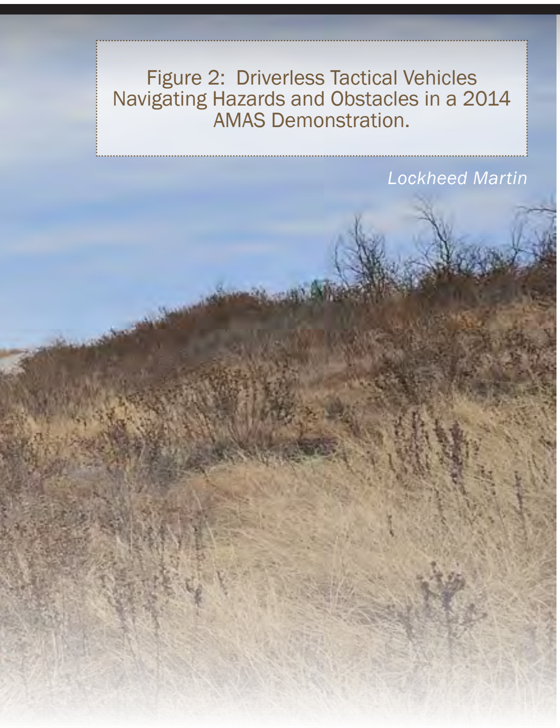

Figure 2: Driverless Tactical Vehicles Navigating Hazards and Obstacles in a 2014 AMAS Demonstration.

Lockheed Martin

onto heavy logistics trucks in the near future. At present, the AMAS program is now entering a year of maturation in which software will be added to address additional functionality requested by the users or deemed desirable to address performance gaps.

AUTONOMY-OPTIMIZED GROUND VEHICLES: THE SQUAD MISSION SUPPORT SYSTEM (SMSS) AND ITS DERIVATIVES

The Mission

For some applications and missions, rather than add an autonomy appliqué to an existing vehicle, there is good reason to use a "mobility platform" that is optimized as a robotic vehicle. The reality is that so long as an unmanned vehicle design also has the requirement to be human-drivable, that vehicle design is forever burdened with concessions to the human form (such as seats and steering wheel and space for the human) that reduce its available payload for "mission equipment."

In selecting or designing a mobility platform for an off-road autonomous UGV application or for a family of off-road autonomous UGVs, the design must address a central issue: with no human nearby and the vehicle possibly far from recovery or repair capabilities, the UGV must possess extraordinary mobility, power, robustness, and reliability. To obtain those qualities, one must usually trade away the space and weight that would otherwise be reserved for the human. If that trade isn't made, the design is stuck with double the burden.

Additionally, the UGV must be highly mobile and able to move in soft soils, mud, and water because there is no human to direct the vehicle from one subtly difficult path to a slightly less unpleasant path. And if the vehicle gets stuck, there may be no humans around to free it. The vehicle must also be powerful enough to forge through difficult environments that might slow or stop a human and to get the payload through to its objective. Should a potential mobility platform not have adequate performance, it could be lost and become a source of supply for the enemy. The mobility platform must also be robust and reliable because there may be no human to repair it if it becomes damaged or disabled. And because off-road driving algorithms are still developing, a UGV is more likely to become hung up on a stump, rock, or other obstacle than a human-driven vehicle.

The Program

With these thoughts in mind, an independent research and development (IR&D) program was executed to develop a UGV mobility platform optimized as a robot, while also seeking high versatility, which is a requirement for any new platform. In addition, because the objective was to develop a mobility platform to support "small unit" military operations (platoons and squads), or their civilian counterparts (fire department or police units), developers quickly vectored toward a payload requirement of approximately 1 ton. Combining all those requirements quickly led to the design of the SMSS platform. The SMSS is a six-wheeled, skid-steered platform with a 45-HP diesel engine powering a hydraulic drive system. The platform uses the same basic Autonomy Kit that is used on AMAS. Over the last 7 years of development, the Autonomy Kits of the SMSS and AMAS (and its predecessor, the Convoy Active Safety Technology [CAST] project) have leveraged the progress of each other, with each one leaping ahead of the other for its own needs on an almost annual basis. At this time, the software and hardware bases for the Autonomy Kits on AMAS and SMSS have been completely aligned, and they are now running software from the same library.

SMSS has been used in a number of demonstrations and experiments over the last few years, culminating in a deployment to Afghanistan in 2012. While the SMSS was not used in a fully autonomous mode in that deployment, it was used as a highly mobile and powerful logistics transport, essentially a radio-controlled pickup truck. And the results were obvious. Soldiers reported that every pound of sandbags or concertina wire carried by SMSS during that deployment would have otherwise been carried by hand, potentially resulting in numerous injuries to personnel.

Recent Progress

Most recently, a fully autonomous reconnaissance, surveillance, and target acquisition demonstration was conducted using SMSS, a K-MAX unmanned helicopter, and a Gyrocam optical sensor in Fort Benning, GA. The K-MAX rotorcraft was selected for this application because, in 2011, it became the first unmanned aircraft system to deliver cargo in theater for the U.S. Marine Corps. As troops were frequent targets of improvised explosive devices (IEDs) and insurgent attacks, the K-MAX helped to reduce the number of truck resupply convoys and their troop escorts, thereby reducing the risk to combat personnel.

During the demonstration, K-MAX delivered SMSS by sling load to conduct an autonomous resupply mission scenario for soldiers defending a village. At mission completion, SMSS proceeded to an observation point, where the system raised its Gyrocam sensor and began scanning the area for enemy forces. In an actual mission, upon observation of enemy forces, the remote operator would notify the commander on the ground, who would assess the threat and determine the appropriate method of neutralizing that threat.

Future Plans

The U.S. Army is now planning a series of experiments for Early Entry and related missions in which robotics could play a decisive role, and developers anticipate that SMSS may become a part of that exercise. This exercise, as well as other experiments and demonstrations planned through 2016, will be used to inform requirements and the programmatic path forward for an Engineering & Manufacturing Development (EMD) program to start in the next 3 to 5 years. That EMD program will be aimed at filling a number of roles for small unit operations. ■

BIOGRAPHY

JOE ZINECKER is the Director for Combat Maneuver Systems for Lockheed Martin Missiles & Fire Control. He is responsible for business development and program execution of UGV activities and several specialty ground vehicle businesses. In particular, he oversees SMSS UGV development and all of its derivatives, as well as the AMAS program and its spin-offs. Mr. Zinecker is also responsible for development and marketing of the Common Vehicle Next Generation (CVNG) and is the Managing Director of HMT Vehicles Ltd of the United Kingdom. He holds B.S. and M.S. degrees in electrical engineering from the University of Houston.

NEW RELEASE ALERT

BlueMax6 Version 2.0

BlueMax6 is a pseudo-6-DOF point-mass aircraft flight dynamics model that uses installed propulsion data, trimmed aerodynamic data, flight control laws/limiters, and structural limit data. The model is used to construct realistic air-vehicle Time and Space Position Information (TSPI) data for input into other models, analysis tools, and environments to conduct aircraft susceptibility, survivability, and vulnerability analysis. It also is used as a standalone tool for determining aircraft mission performance, aero-performance, and energy maneuverability.

Version 2.0 updates to BlueMax6 include the following:

- Aircraft data files have been converted to source code (.cpp) files and compiled into libraries (.dll), eliminating the need for a data parser.
- Two libraries are included, one for “Released Aircraft” and one for “User Defined Aircraft.”
- A template for a user-defined aircraft source code file (.cpp) is included with the release.
- The Scenario Input File (.scn) is now loaded at initialization and stored in the waypoints array, which are flown sequentially (Mission File in Real-Time mode).
- The Maneuver Limits options have been updated to include Auto Pilot Limits, Sustained Limits, and Maximum Limits options.
- The GUI has been improved, simplifying the scenario file construction.
- A Multi-Player Execution mode has been added to support Engagement Analysis between multiple players.
- A Maneuver page has been added to construct maneuvers in the Multi-Player mode.
- and more.

Contact DSIAC for more information or a copy of the latest version of BlueMax6.

DTIC SEARCH TERMS:
Autonomous Ground Vehicle

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- Military Operations, Strategy Tactics (2,800+)
- Cybernetics (2,649+)
- FBIS Collection (2,200+)
- Theses (2,200+)
- SBIR (2,100+)
- Algorithms (2,014+)
- Computer Programming & Software (1,900+)
- Symposia (1,900+)

***See page 3 for explanation ▸**

CONFERENCES AND SYMPOSIA

JANUARY 2015

AIAA SciTech
5–9 January 2015
Gaylord Palms Resort & Convention Center
Kissimmee, FL
http://www.aiaa-scitech.org/default.aspx ▸

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http://www.ndia.org/meetings/5880/Pages/default.aspx ▸

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Omni Hotel
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http://www.ieee.org/conferences_events/conferences/conferencedetails/index.html?Conf_ID=33207 ▸

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10–11 February 2015
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MARCH 2015

30th Annual National Test & Evaluation Conference
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31st Annual National Logistics Forum
16–18 March 2015
Ronald Reagan Building and International Trade Center
Washington, DC
http://www.ndia.org/meetings/5730/Pages/default.aspx ▸

Lightweight Tactical Vehicle Summit
16–18 March 2015
Detroit, MI
http://www.lighttacticalvehiclesummit.com/ ▸

16th Annual Science and Engineering Technology Conference
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The Waterford at Springfield
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Admiral Kidd Conference Center
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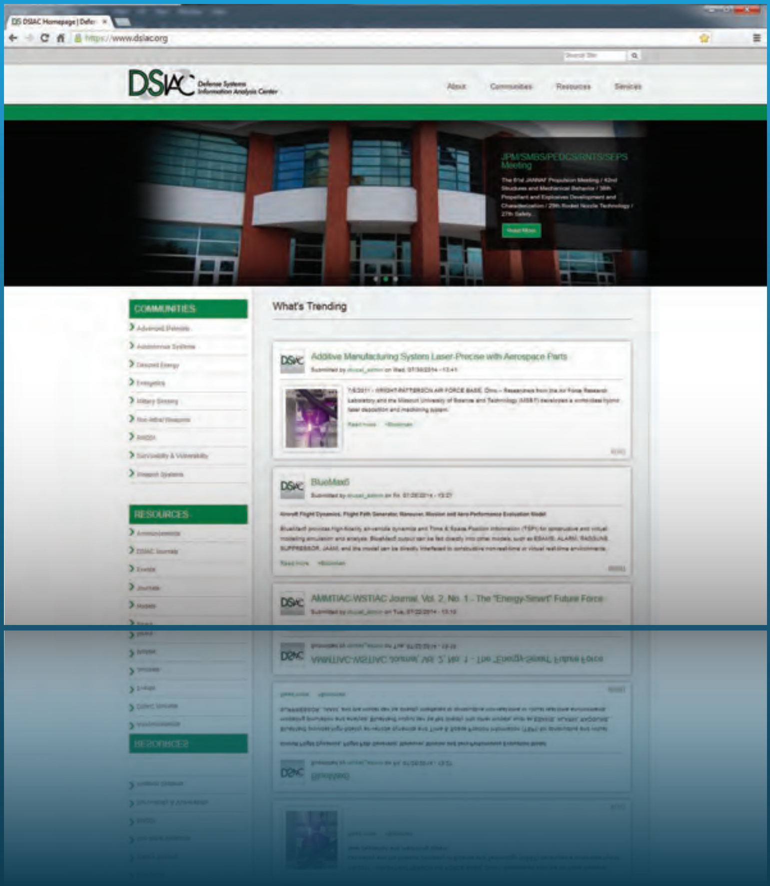
- Participating in key DoD conferences and forums to engage and network with the S&T community.
- Performing customer-funded Core Analysis Tasks (CATs) under pre-competed IDIQ Delivery Orders.



DSIAC SCOPE AREAS INCLUDE:

- Advanced Materials
- Autonomous Systems
- Directed Energy
- Energetics
- Military Sensing
- Non-Lethal Weapons
- Reliability, Maintainability, Quality, Supportability, and Interoperability (RMQSI)
- Survivability and Vulnerability
- Weapon Systems