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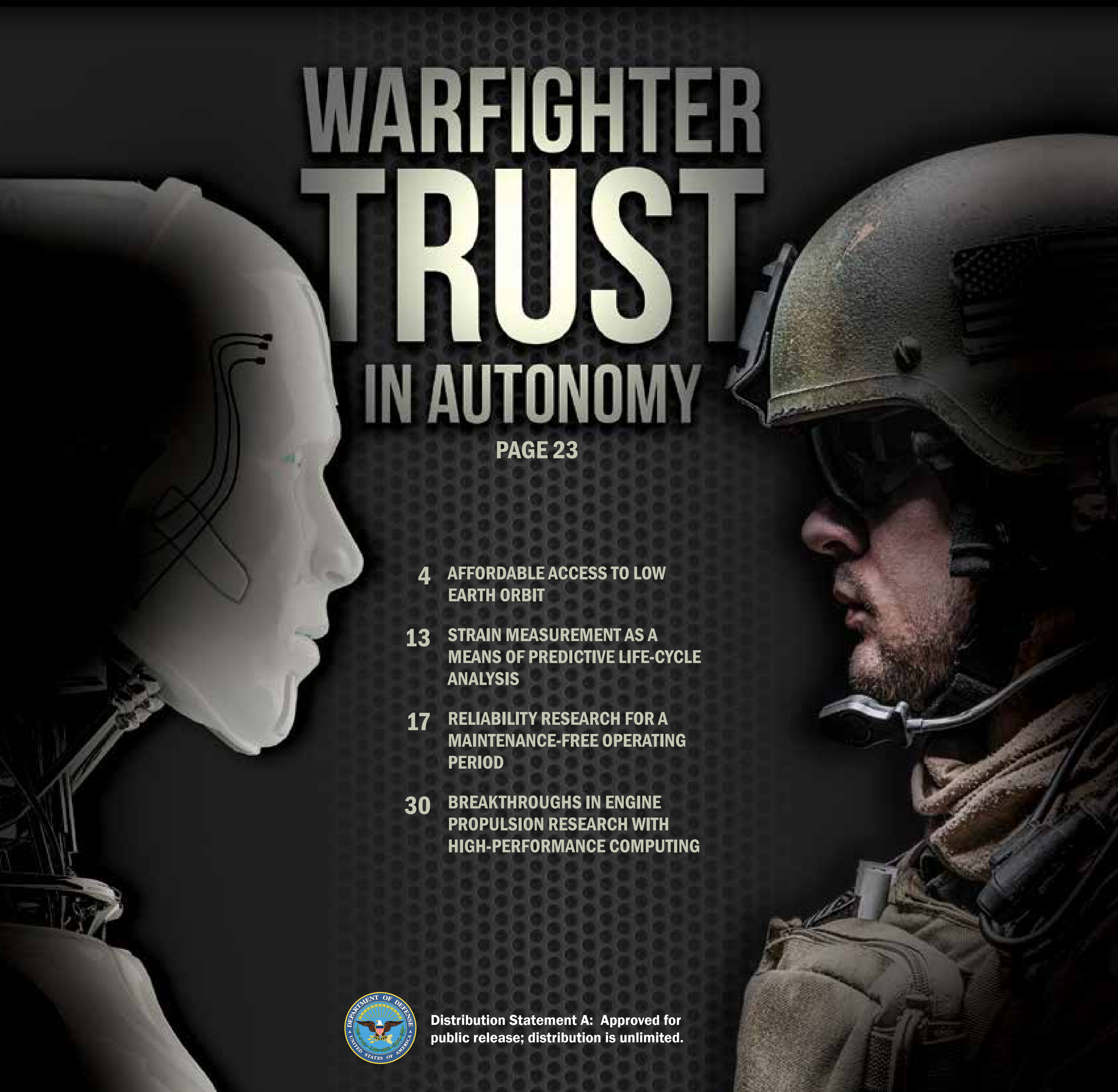

WARFIGHTER TRUST IN AUTONOMY

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MESSAGE FROM THE EDITOR

By Brian Benesch

"Wow, I didn't even know research was being done on that subject!"—one of the goals of the *DSIAC Journal* is to cause the reader to have reactions such as this one when reading these pages and discovering some of the new ideas being studied within the realm of defense systems. Scientific and engineering work on defense system topics is so diverse and widespread in the United States and beyond that the community faces a formidable challenge in staying abreast of the latest findings. The *DSIAC Journal* exists to help combat this challenge, providing a forum to help researchers, engineers, and technical managers share their work with the larger defense systems community.

As a reminder, there are nine expressed focus areas that DSIAC specializes in: Advanced Materials; Autonomous Systems; Directed Energy; Energetics; Military Sensing; Non-Lethal Weapons; Reliability, Maintainability, Quality, Supportability, and Interoperability; Survivability and Vulnerability; and Weapon Systems. Each quarter, emerging trends in these areas are published in the *DSIAC Journal*.

Through publication and propagation of cutting-edge defense systems research, the journal helps to, among other things, mitigate redundant research being performed. Whether the work is performed directly by the Department of Defense (DoD) or supporting organizations in academia or industry, sharing the findings and lessons learned promotes knowledge reuse, ultimately saving the defense systems community time and money and enhancing overall science and technology.

The five articles in this issue well represent findings from the diverse defense systems community. Three come from DoD organizations, one is from academia, and one is jointly produced by DSIAC and industry.

This issue's feature article comes from Jonathan Gillis on the topic of "Warfighter Trust in Autonomy." Using his experience serving as a Marine and working for the Marine Corps Warfighting Laboratory, Mr. Gillis describes obstacles and then proposes remedies toward integrating autonomous systems into combat units. The goal of this information is to aid autonomous system designers and DoD decision-makers as the inevitable rise of autonomous systems continues.

In our article "Affordable Access to Low Earth Orbit," DSIAC's Albert DeFusco and RocketStar CEO Christopher Craddock highlight some tremendous benefits (as well as high costs) of some low earth orbit applications and developments. In particular, research on the latest vehicle and engine technologies is described. The developments in these areas are expected to break through the financial barrier and provide unprecedented affordable access to space.

Our "Strain Measurement as a Means of Predictive Life-Cycle Analysis" article comes from Texas Research Institute/Austin, an academic member of the DSIAC team. In this article, researchers Michael Mazurek, Russell Austin, and Kristen Donnell highlight evolving strain-sensing technology in concert with the advancement of high-strength, low-weight materials (such as those used in aircraft structures) and their benefit for military sensing application as a predictive DoD life-cycle analysis tool.

In addition, our article on "Reliability Research for a Maintenance-Free Operating Period" (MFOP), written by Army Research Laboratory (ARL) scientists Todd Henry, Terrence Johnson, Jeff Gair, and Robert Haynes, discusses how accurately identifying a vehicle's MFOP offers significant cost savings to the DoD but also requires proper monitoring and dedicated design. This article describes ARL's research in damage monitoring and topology optimization to make way for the MFOP of defense vehicles.

Additional ARL research is presented in Luis Bravo's article on "Breakthroughs in Engine Propulsion Research with High-Performance Computing." Fully predictive modeling of liquid-fueled direct injection engines, which are used in many DoD vehicles, has long been impossible due to the incredible complexity of the physics involved. However, DoD enhancements in high-performance computing have enabled the execution of never-before-seen computer simulations that are proving to be highly accurate. These breakthroughs will allow the DoD to better understand the physics and close existing technical knowledge gaps.

In closing, let me invite you to share your work through the *DSIAC Journal*. Although many of your peers may be aware of your efforts, there are surely many more who are not. Please contact me at brian.benesch@dsiac.org to get your findings and lessons learned shared for the betterment of the defense systems community, and perhaps your work might be the reason the next reader says "Wow!" ■

(Source: NASA)

AFFORDABLE ACCESS TO LOW EARTH ORBIT

By Albert DeFusco and Christopher Craddock

A NEW VISION

The last decade has seen a resurgence of NASA's bold visions, from returning humans to the moon after a 50-year hiatus to colonizing Mars. President George W. Bush addressed NASA and the nation on 14 January 2004 to present this vision as the Renewed Spirit of Discovery [1, 2, 3]:

> *Inspired by all that has come before, and guided by clear objectives, today we set a new course for America's space program. We will give NASA a new focus and vision for future exploration. We will build new ships to carry man forward into the universe, to gain a new foothold on the moon, and to prepare for new journeys to worlds beyond our own.*

In his address, President Bush established three goals to accomplish the new objectives outlined for NASA: (1) completing the International Space Station (ISS) by 2010, (2) developing and testing a new spacecraft (the Crew Exploration Vehicle) for initially ferrying astronauts to the ISS and ultimately carrying humans beyond Earth orbit to other worlds, and (3) return to the moon by 2020 as a launching point for missions beyond. A key challenge to achieving these objectives that the president mentioned in his address was the expense of lifting heavy cargo into Earth orbit, limiting our ability to fund a multitude of desirable missions. As he pointed out, "Lifting heavy spacecraft and fuel out of the Earth's gravity is expensive."

LEAVING LOW EARTH ORBIT TO COMMERCIAL VENTURES

The president's vision for NASA would be accompanied by a number of other decisions and technology solutions needed to make them viable. NASA would eventually abandon exploring opportunities in Low Earth Orbit (LEO), where the ISS is located (see Figure 1), while encouraging future exploitation by other entities, such as educational, private, nonprofit, and commercial organizations [4]. For example, promoting competition for developing small satellites, such as CubeSat [5], has advanced satellite technologies for low-cost use of space. Currently, small satellites for commercialization of space are relatively inexpensive to fabricate (<$10,000). However, the cost to lift them to LEO, even in bundles, remains comparatively high per kilogram mass (see Table 1). Furthermore, commercial launches of small payloads have not expanded greatly over the past decade due to cost, scheduling uncertainties, risk of failure, and undesirable orbit placement [4, 6].

Robert Heinlein, a noted science-fiction writer, made a profound and illustrative comment regarding space travel [7]. "Once you get to Earth orbit," he said, "you're halfway to anywhere in the solar system."

His meaning reflects the need for expending an enormous amount of energy to reach that point, while going anywhere else beyond requires a negligible amount. This comment is also a reflection of the cost of space travel, where launch costs can consume a large portion of the mission costs. (For more information on space propulsion, see our article entitled "Space Travel Aided by Plasma Thrusters: Past, Present, and Future" in the spring 2017 *DSIAC Journal* [8].)

Cost-effective access to space for future commercial and government use must rely heavily on reducing the price for launching cargo beyond Earth's gravity to desired orbit destinations and provide ample scheduling opportunities. An abundance of potential benefits will exist when launch costs are lowered and LEO is made more accessible. More frequent launches, more competition for commercialization, more opportunities for small businesses, more opportunities for research in low-gravity environments, and expansion of human flight beyond Earth's gravity are just a few.

LAUNCHER SIZE AND COST

Since the 1950s and the start of the space race, launch vehicles in the United States and other countries have grown immensely, not only in terms of size, but in cost. Figure 2 shows the progression in size for several launch vehicles in NASA's Launch Services Program [9]. As shown in Table 1, overall costs per launch for the Delta IV vehicle have reached as high as $400 million. NASA's retired Saturn V rocket (not shown), one of the largest to

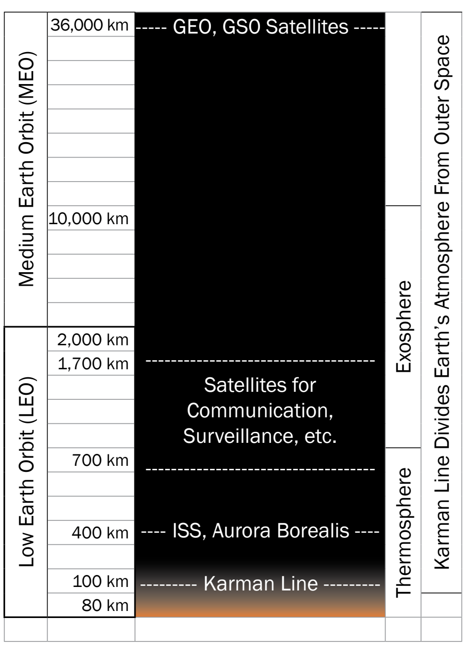


Figure 1: Earth's Near Orbits and Atmospheres (NOTE: Distances Not to Scale).

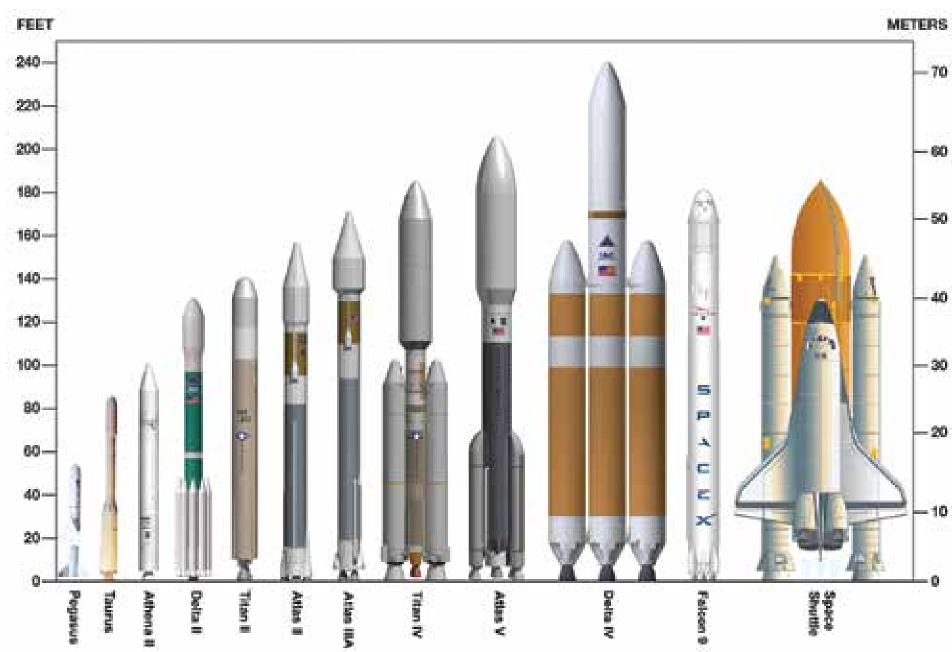


Figure 2: U.S. Launch Vehicle Comparison [9]. (NOTE: Space Shuttle Shown for Size [Height] Comparison Only).

Table 1: Current Orbital Launch Vehicles in the United States [12]

VEHICLE	OPERATOR	YEAR OF FIRST LAUNCH	MASS TO LEO (KG)	ESTIMATED PRICE PER LAUNCH ($)	ESTIMATED PRICE ($)/ KILOGRAM	REUSABLE
Antares	Orbital ATK	2013	3,500–7,000	80–85 million	12,000–23,000	No
Atlas V	ULA and LMCLS	2002	8,123–18,814	110–230 million	12,000–14,000	No
Delta IV	ULA	2002	9,420–28,790	164–400 million	14,000–17,000	No
Falcon 9	SpaceX	2010	13,150	61.2 million	4,700	First Stage Only
Minotaur-C	Orbital ATK	2017	1,278–1,458	40–50 million	31,000–34,000	No
Pegasus XL	Orbital ATK	1994	450	40 million	89,000	Launcher Aircraft Only

fly, was 111 m (363 ft) tall, weighed 2.8 million kg (6.2 million lbs) and carried around 118,000 kg (130 tons) of cargo. Costs reached about $1.2 billion per launch [10]. Its last mission launched Skylab into Earth orbit in 1973 [11].

NASA continues the trend to larger vehicles with its proposed newest member in the heavy-lift launch family, the Space Launch System (SLS) Block 2 vehicle. This vehicle is destined to take humans beyond Earth orbit. At roughly 112 m (365 ft) tall, it will weigh nearly 3 million kg (6.5 million lbs) and is expected to carry 130,000 kg (268,000 lbs) of cargo into orbit using three stages. Five-segment solid rocket boosters (SRB), more powerful than those used on the Space Shuttle, will help propel the vehicle out of Earth's low atmosphere [13, 14]. Early unofficial estimated costs per launch were $500 million to $1 billion, with only two or three launches per year to LEO with this expendable vehicle [15, 16].

NASA and commercial companies have recognized that launch costs vary considerably depending on cargo, mission, facilities, and supplier. Past

> An abundance of potential benefits will exist when launch costs are lowered and LEO is made more accessible.

experience has shown that launch costs can reach $34,000/kg of cargo [4, 17] for primarily expendable vehicles. However, more recent launches by Space Exploration Technology (SpaceX) have demonstrated launch costs less than $5,000/kg [4]. Unfortunately, these costs still prohibit some small start-up venture companies from participating in the small- to medium-sized commercial satellite market. Launch suppliers will need to provide costs in the neighborhood of $2,000/kg of cargo [18], while assuring ample availability to flight schedules and destinations (precise orbits) to cultivate a more competitive market. SpaceX currently claims entry to this level of pricing to LEO based on its Falcon Heavy rocket, which is a fully expendable vehicle [19]. The long-term goal is to bring LEO launch costs to no more than the price of a commercial airline fare.

REUSABLE VEHICLES, A KEY TO REDUCING LAUNCH COSTS

At present, several initiatives have sought to reduce launch costs based on reusable vehicles. Most noteworthy were the recent achievements by SpaceX. With support from NASA over the past several years, SpaceX has completed many successful orbital launches with its Falcon 9 rocket, including resupply missions to the ISS and the demonstration of a recoverable and reusable first-stage rocket in March 2017 [20].

Blue Origin is another company that has taken part in development and demonstration of reusable launch vehicles. Its suborbital rocket employs the company's BE-3 engine using liquid hydrogen (LIH) and liquid oxygen (LOX). Designed to travel nearly 110 km above the earth (Karman line), several successful tests have been demonstrated with their New Glenn reusable single-stage booster rocket [21] (depicted in Figure 3). At this time, Blue Origin has the ability to launch small 50-lb payloads to the Karman line, with up to 4 min of weightlessness for experimental tests. Eventually, two- and three-stage vehicles powered by Blue Origin's BE-4 engines will launch a capsule with up to six astronauts into LEO and then return the reusable first stage to Earth. The BE-4 engines will burn liquid natural gas (LNG) and LOX and have 5 times more thrust than their BE-3 counterparts. Launch costs are not publicly known at this time, but Blue Origin advertises human flights to the edge of space by 2020 as one of its near-term commercial ventures.

Figure 3 compares the design and size of these new and old launch vehicles. Table 2 describes future launch vehicles for accessing LEO as provided by the Federal Aviation Administration Annual Compendium [12]. Vehicles that employ expendable and reusable stages are indicated, along with estimated launch price/kilogram of cargo, with reusable vehicles generally providing lower costs. Both SpaceX and Blue Origin advertise reusable first stage rockets from multi-stage vehicles, with SpaceX offering launch costs below $5,000/kg. However, the United Launch Alliance (ULA) with its Vulcan vehicle set to launch in 2019 may prove to be competitive even without reusable hardware.

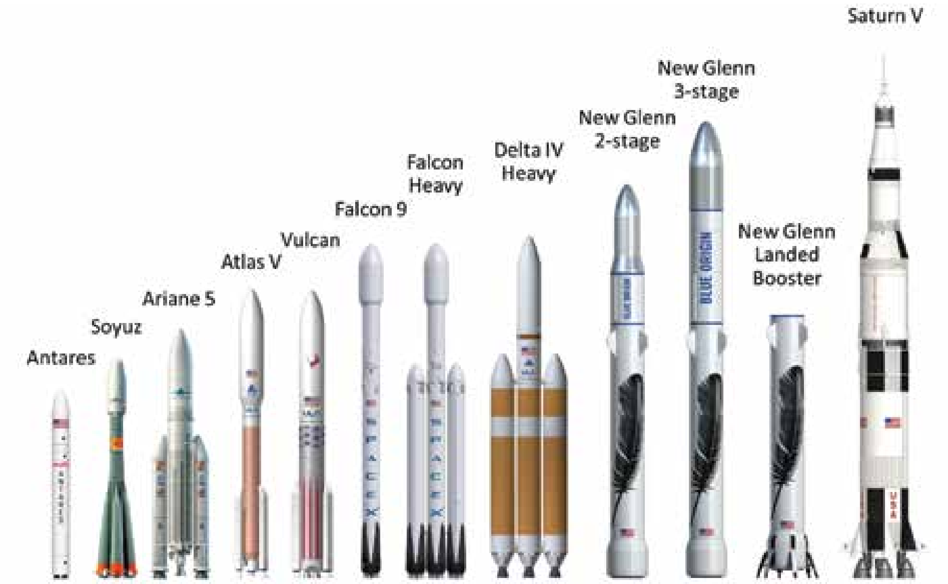


Figure 3: Size Comparison of New and Old Launch Vehicles.

Table 2: Future Orbital Launch Vehicles in the United States [12]

VEHICLE	OPERATOR	YEAR OF FIRST LAUNCH	MASS TO LEO (KG)	ESTIMATED PRICE PER LAUNCH ($)	ESTIMATED PRICE ($)/KILOGRAM	REUSABLE
Alpha	Firefly	Uncertain	400	8 million	20,000	Possibly First Stage Only
Orbital Launch Vehicle	Blue Origin	2020	Undisclosed	Undisclosed	Undisclosed	First Stage Only
CAB-3A	Cube Cab	2017	5	250,000	50,000	No
Electron	Rocket Lab	2017	Undisclosed	4.9 million	Undisclosed	No
Falcon Heavy	SpaceX	2017	53,000	270 million	5,094	First Stage Only
LauncherOne	Virgin Galactic	2017	400	10 million	25,000	No
Star Lord[a]	**RocketStar**	**2018**	**300**	**6 million**	**20,000**	**Fully Reusable SSTO**
Haas 2CA[a]	**ARCA Space Corporation**	**2018**	**100**	**1 million**	**10,000**	**Potentially Reusable SSTO**
Stratolaunch	Stratolaunch Systems	2018	3,000	Undisclosed	Undisclosed	Launcher Aircraft Only
Vector R/H	Vector Space Systems	2017	60-110	3 million	27,000–50,000	No
Vulcan	ULA	2019	9,370-18,510	85 million–260 million	9,000–14,000	No

[a] *Engine uses aerospike nozzle design rather than conventional bell designs.*

Companies such as those shown in Tables 1 and 2 typically offer secondary (piggy-back) launch services for small satellites to maintain low costs for small commercial ventures. However, these types of launches using heavy-lift vehicles limit orbit placement and scheduling opportunities because they are driven by primary customers who have specific requirements (and who supply the majority of funding). Pegasus XL launched by Orbital ATK from a reusable L-1011 airliner offers single-payload services and specific orbit placement, but at a high price of $89,000/km, as shown in Table 1. The L-1011 launcher is considered reusable hardware, replacing an expendable first-stage rocket.

The successes and future prospects described previously for Earth-based launch vehicles have certainly opened new opportunities for the commercial use of LEO, especially with the demonstration of reusable first-stage rockets. However, further cost reductions may only be afforded by using a future fleet of fully reusable vehicles that will have a life expectancy (reuse capability) rivaling today's commercial and defense aircraft, some of which have flown for more than 50 years. Keys to unlocking the development of fully reusable vehicles may lie in two areas of vehicle technology: (1) reuse of all stages from multi-stage rockets, and (2) reintroduction and development of reusable single-stage-to-orbit (SSTO) vehicles, which can eliminate the need for multiple stages. Imagine a fleet of recoverable vehicles that can be delivered in 1 to 2 decades and have a 50-year life span. Conceivably, this fleet could provide flexible and multiple launches every year during their life time and offer precise orbit placement of cargo and human travelers at the price of a commercial airline ticket.

THE AEROSPIKE ENGINE

In the 1960s, NASA described development of a vehicle using an aerospike rocket nozzle concept that could provide a fully reusable SSTO vertical-launch rocket [22, 23]. These nozzles allow for optimum operation of rockets at all altitudes, rather than relying on less efficient multiple stages that are designed to operate in specific altitude (pressure) ranges. Figure 4 compares the aerospike nozzle concept to a conventional bell nozzle. When used in linear or annular arrangements, they may also provide steering capability by throttling fuel flow through each nozzle, thereby eliminating attitude control systems. Mechanical thrust vector control (TVC) can also be accommodated on an aerospike engine array.

How Aerospike Nozzles Work

As shown in Figure 5, aerospike engines are fundamentally altitude (pressure)-compensating designs and bear a similarity in function to internal pressure-compensating pintle (controllable) nozzles. The unique aerospike design can be visualized as a self-adjusting inside-out pintle nozzle without moving parts. The surrounding atmosphere acts as the pressure-compensating boundary (atmospheric bell). Liquid or gaseous fuel is pumped through injectors at the forward end (entrance) of the nozzle, ignited, and then burned to provide thrust. Rather than constrict the exhaust gases inside a conventional bell nozzle, the aerospike nozzle directs the gases along the exterior of the "spike."

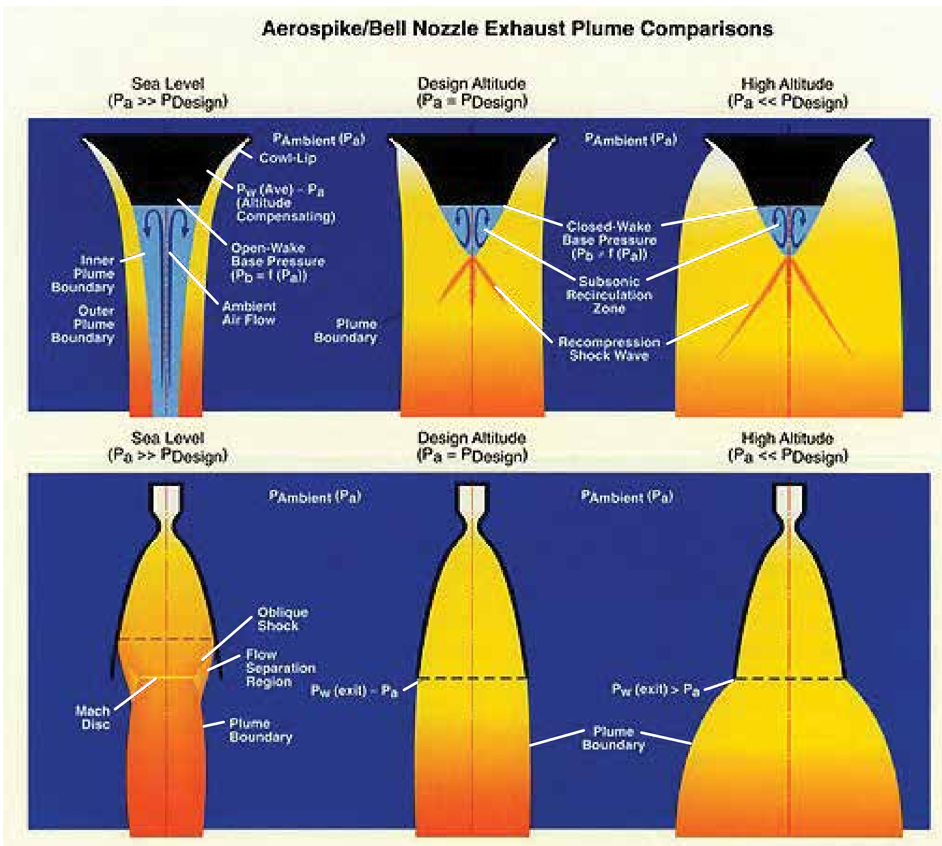


Figure 4: Aerospike Nozzle Concept Compared to a Conventional Bell Nozzle.

One of the advantages these nozzles have over conventional nozzles is that they typically use 25–30% less fuel at low altitudes, where a large fraction of the on-board rocket fuel is consumed to generate initial thrust for accelerating heavy vehicles through the lower atmosphere. Beyond having the weight and cost advantage of carrying and consuming less fuel than conventional nozzles, aerospike nozzles can also be conveniently arranged in multiple linear or annular configurations, be throttled individually for steering, and be easily adapted for mechanical TVC. Most importantly, aerospike nozzles provide an excellent opportunity for advancing fully reusable SSTO space launch vehicles by eliminating multiple expendable stages. Aerospike nozzles can also employ materials that have already proven useful and critical for conventional bell nozzles, thereby minimizing the need for costly development and demonstration of new technologies and materials. Furthermore, the use of three-dimensional (3D) (or additive) manufacturing can offer opportunities in reducing manufacturing costs and weight in aerospike nozzle geometries and ancillary components.

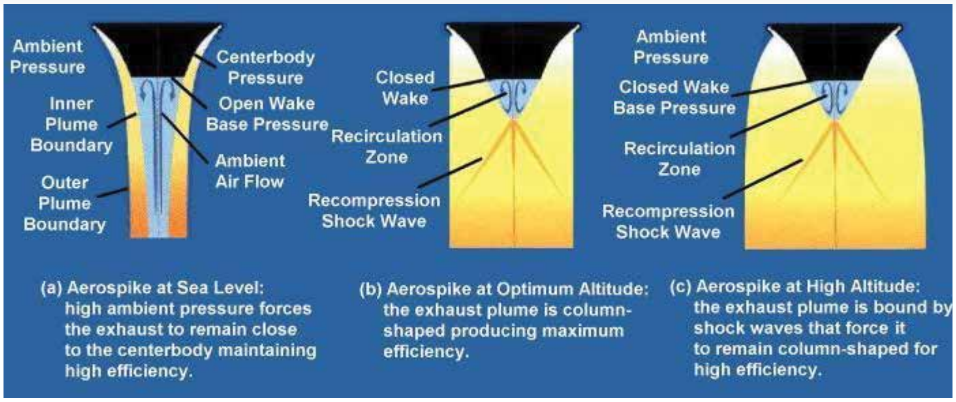


Figure 5: Operation of Aerospike Nozzles *(Source: Aerospaceweb.org).*

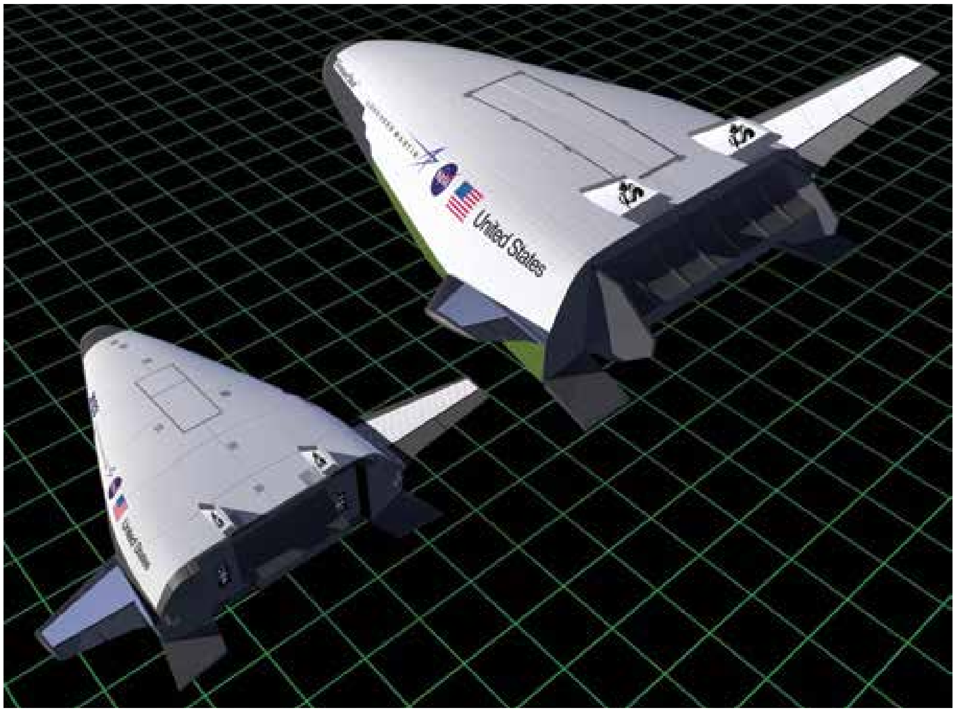


Figure 6: X-33 and RLV Concept Drawings With Multiple Linear Aerospike Engines *(Source: NASA).*

Early Aerospike Vehicle Concepts

Blending space and flight technologies, the aerospike nozzle engine was first destined for use on NASA's X-33 vehicle and Reusable Launch Vehicle (RLV) space planes, shown in Figure 6. A 20%-scaled-down version of the X-33 reusable space plane with nine linear aerospike nozzles and its ancillary hardware were first tested for aerodynamics and component integrity atop an SR-71 aircraft [24]. Many tests for evaluating safety using inert gas flowing through the craft's engines (cold flow tests) and many live-fire ground tests were conducted. However, no live solo launch or flight tests were performed due to LOX leaks in the fuel system. Because enough live-fire data were gathered from ground tests, launch and live solo flight tests were discontinued and the project was abandoned. Interestingly, the RLV space plane was projected to lower the cost of satellite launches to 1/10th that of the Space Shuttle by adapting aircraft-type landing, inspection, refueling, and reuse.

Flight Successes With Aerospike Nozzles

In 2004, approximately 40 years after its conceptualization, a solid-fueled toroidal aerospike engine was first flown jointly by NASA, the U.S. Air Force, and Blacksky Corporation [25]. Figure 7 shows Blacksky's aerospike nozzle, which allowed its rocket to exceed Mach 1.5 and achieve altitudes above 8 km (over 26,000 ft).

Patrick Lemieux from California Polytechnic State University later designed and successfully tested an aerospike engine using a hybrid rocket motor with nitrous oxide and a solid fuel. The engine was tested repeatedly several times using cooling of ablative materials to reduce erosion, thereby demonstrating reusability even in highly corrosive and thermal environments [26].

Firefly Space Systems succeeded in demonstrating a first-stage aerospike engine using LOX and RP-1 fuel in a ground test of its Alpha launcher [27]. Although never flown or fully demonstrated, the Firefly Alpha launcher planned to use 12 aerospike nozzles in a circular array.

Figure 7: Close-up Photograph of Blacksky's Aerospike Nozzle Flown in 2004 *(Source: NASA).*

THE RACE TO THE KARMAN LINE AND THEN ON TO LOW EARTH ORBIT

As the need for low-cost launch technology continues, corporations are revisiting the use of aerospike engines for launching payloads to LEO with the intent of providing fully reusable launch vehicles and low-cost access to space. RocketStar recently cosponsored a project at Stony Brook University to assess the feasibility and document the history of aerospike engines [28]. The report from this effort discusses improved performance with aerospikes compared to conventional bell nozzles and outlines previous tests with various aerospike designs (toroidal, truncated, and others).

As part of a progressive plan to demonstrate the feasibility of aerospike nozzles prior to LEO launches, RocketStar recently conducted a ground test of a nearly 2-m-long sounding rocket designed to reach an approximate 3-km altitude. The rocket also used a 3D-printed aerospike engine. This test showed promise for solid booster technology as the aerospike nozzle produced an average performance improvement of 22.4% over a traditional bell nozzle during low-power tests and static firing. The rocket ultimately reached more than 3 km and 0.88 speed of sound [29].

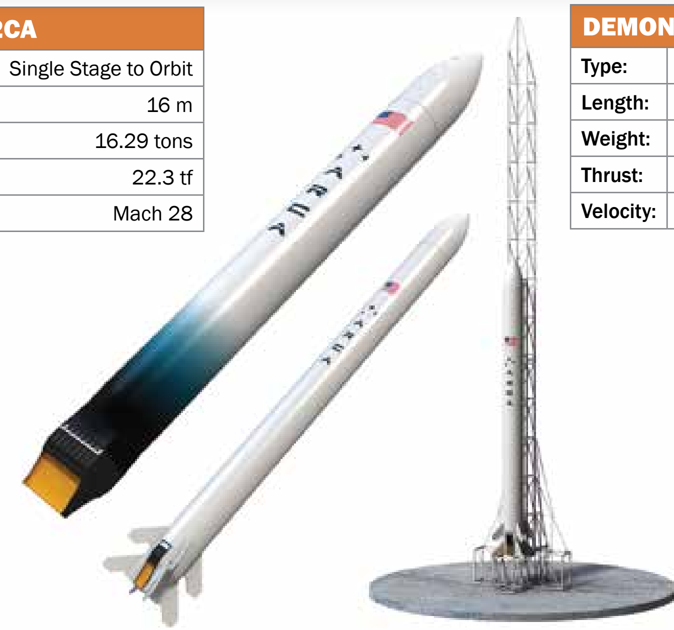
Attempting to win the race to the Karman line prior to the end of 2017, RocketStar's next step will be to launch a 7.62-m aerospike suborbital rocket to the edge of space as a prerequisite to its first LEO launch. The launch will be used to evaluate the novel toroidal nozzle geometry and carbon fiber composite fuel tank and fins.

Following the test to reach the Karman line, RocketStar is planning to launch a fully reusable aerospike vehicle to LEO as early as the first quarter of 2018. The company's orbital launcher, Star Lord (Figure 8), will also rely heavily on 3D printing technology to minimize manufacturing costs. Injectors, most of the flight motor, and some of the main fuselage parts will use additive manufacturing. Star Lord is designed to be a completely reusable SSTO rocket and will be recovered from its first launch in early 2018. Similar in size to an Orbital ATK Minotaur rocket, Star Lord will take multiple CubeSat satellites, or one large satellite, into LEO and deploy them before the rocket returns to Earth, demonstrating that an SSTO rocket can be recovered, validated as flight worthy, and then flown again. RocketStar's ultimate goal is to achieve routine low-cost small satellite launches with a fleet of reusable rockets having a life span similar to today's commercial aircraft [30].

Currently, RocketStar projects a cost of approximately $20,000/kg for small satellite launches starting in 2018 (see Table 2), along with potentially convenient schedules and destinations. Plans for achieving consumer accessible costs, with figures closer to $6,000/kg over the next few years, are in place and will rely on successful ground and flight tests as commercial vehicles mature. In addition, the company fully expects the cargo costs per kilogram to shrink to a few hundred dollars within 10 years and is embracing the concept of building a fleet of fully reusable space launch vehicles to support commercialization of LEO for many years to come.

Figure 8: RocketStar Star Lord With Truncated Aerospike Nozzle.

HAAS 2CA	
Type:	Single Stage to Orbit
Length:	16 m
Weight:	16.29 tons
Thrust:	22.3 tf
Velocity:	Mach 28



DEMONSTRATOR 3	
Type:	Suborbital
Length:	10 m
Weight:	2.24 tons
Thrust:	4.2 tf
Velocity:	Mach 6

Figure 9: ARCA Haas 2CA and Demonstrator 3 Vehicles [32].

ARCA Space Corporation has also announced the development of an SSTO vehicle, the Haas 2CA (shown in Figure 9), with flight testing expected in 2018. This vehicle will burn hydrogen peroxide and RP-1 fuel for propelling a 100-kg payload within a 24-hr notice. With a projected launch cost of approximately $1 million to LEO for small payloads [31], the price translates to about $10,000/kg of cargo. ARCA has not disclosed plans to recover the Haas 2CA SSTO vehicle following the first LEO launch.

Also as a prerequisite to a future LEO launch, a flight of the ARCA Demonstrator 3 suborbital rocket with a linear aerospike design, using only clean-burning low-flame-temperature hydrogen peroxide, is planned before the end of 2017 [32]. Competing in the race to reach the edge of space, this flight will validate ARCA's aerospike engine design and the use of a composite fiber fuel tank prior to the critical first launch of the Haas 2CA vehicle for achieving LEO.

CONCLUSIONS

The past half-century in the space industry has witnessed significant achievements in launch vehicle size and power for placing increasingly heavier payloads into LEO and beyond. However, the potential for further exploitation and commercialization of LEO has suffered primarily due to high launch costs. Currently, the space launch industry is at a turning point, where new achievements have been witnessed for reducing launch costs, presenting opportunities for low-cost use and commercialization of LEO and offering human space travel to the private sector. Over the past decade, commercial companies such as SpaceX have sought, and recently demonstrated, the feasibility of reusing rocket hardware. This first step, which takes advantage of reusing expensive first stage rockets, has introduced a new era in the space industry. This trend for reducing costs is destined to continue by demonstration of the reuse of additional stages, along with cargo and crew vehicles.

Furthermore, success in reusing rockets is awakening a renewed interest in aerospike nozzle technology that offers the potential for a completely reusable SSTO vehicle. Initially investigated by NASA for space plane concepts, aerospike nozzles offer a path to eliminate expensive multi-stage rockets by using an SSTO vehicle. Coupled with the ability to recover and reuse rocket hardware, aerospike nozzle technology also has the potential to reduce overall rocket size and weight through more efficient use of on-board fuel. With such achievements on the horizon, accessing and using LEO for commercial development and educational research is attainable at reasonable costs. Before the end of this decade (or soon after), cargo and humans may begin to travel routinely to a low-gravity environment for no more than the cost of a commercial airline fare as the status quo of space travel is altered forever. ■

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BIOGRAPHIES

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CHRISTOPHER CRADDOCK is currently founder and CEO of RocketStar, LLC, a launch service provider dedicated to launching small satellites into LEO and beyond. Previous to founding RocketStar, he founded CC Trading Company, a registered commodities broker, which he headed for 10 years; and he has more than 16 years of Wall Street experience, from selling stocks and bonds at Salomon Smith Barney to trading futures and debt obligations at private wealth firms. Mr. Craddock has a degree in Physics from SUNY Stony Brook.


(Source: U.S. Navy)

STRAIN MEASUREMENT
AS A MEANS OF PREDICTIVE LIFE-CYCLE ANALYSIS

By Michael Mazurek, Russell Austin, and Kristen Donnell

INTRODUCTION

When considering catastrophic failures in structures, one often imagines the worst-case scenario, in which a large force can cause an immediate destruction. However, events of these types are rare in nature. More often, a structure succumbs to fatigue failure long before any major destructive event can befall it. This fatigue can be an insidious threat to structures, as it is often imperceptible until the damage has occurred, resulting in a need to repair the structure and costing time and money. Thus, in the case of the aircraft industry, as more airframes see an extended life cycle, monitoring the strain and fatigue experienced by the aircraft has become increasingly important.

CURRENT METHODS OF MEASURING STRAIN

Strain Gages

Relatively inexpensive and reliable, strain gages have been used for decades to provide effective point-based measurement of strain in a material. As shown in Figure 1, the strain gage is made of a long, thin wire embedded in a thin material that is affixed, usually by adhesives, to the surface of whatever structure is being observed. When force is applied in a strain gage, it causes a geometric change in the gage, resulting in a change in the resistance of the gage as well. Applying Ohm's law allows one to solve for the current, which can be translated into strain.

One downside to strain gages is that they must be individually wired and emplaced on a structure and connected to a data acquisition system. Accordingly, these limitations make large-scale wide-area monitoring by strain gages impractical.

Fiber Bragg Grating

A newer development for wide-area monitoring is the Fiber Bragg Grating (FBG) sensor. As Yolken and Matzkanin describe in a paper for the Nondestructive Testing Information Analysis Center (NTIAC) [2]:

> *Since the advent of photo-induced Bragg gratings in optical fibers in 1978, Bragg fiber gratings have found many applications in telecommunications and sensing. Bragg gratings have emerged as elegant in-fiber sensors particularly suitable for multiplexed and distributed applications. The growing interest and rapid progress made in the area of strain sensing using Bragg grating based sensor systems indicate recognition of the fact within the sensor community that fiber Bragg grating based sensors provide*

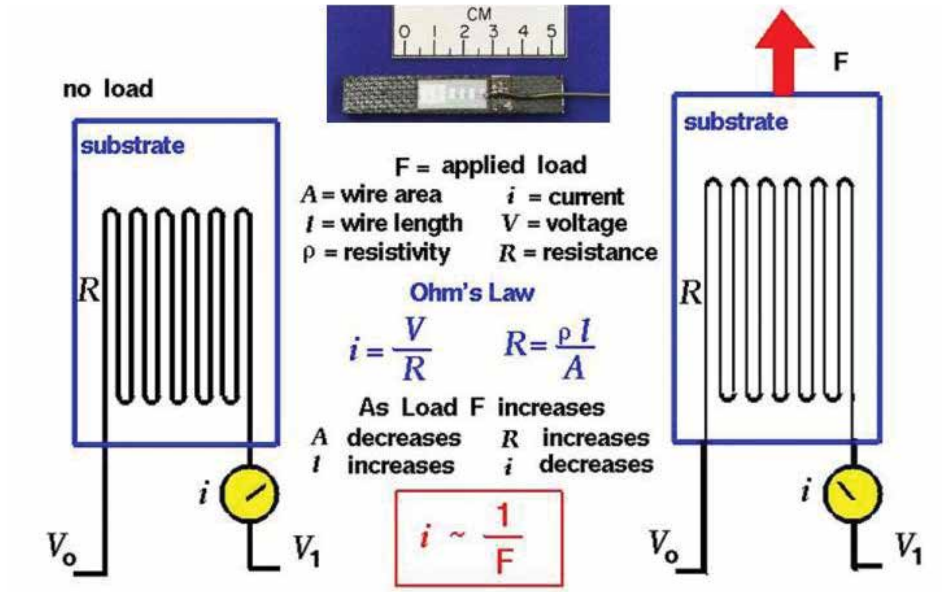

Figure 1: The Functioning of a Simple Strain Gage *(Source: NASA)* [1].

powerful sensing techniques which can be uniquely applied to a range of structural sensing applications.

FBG systems are made of fiber optic filaments that have had a series of highly reflective, frequency selective filters embedded throughout the length of the fiber. When temperature or strain is applied to a fiber section containing the grating, the grating spacing and index of refraction are modified, thus changing the Bragg wavelength [2]. Because FBGs work in the frequency domain, as opposed to the amplitude domain, the system can have large sensitivity due to small changes in the light wavelength.

Figure 2 provides a description of how FBGs measure strain due to shifts in the wavelength. The benefit of using FBGs is that any given length of fiber can have thousands of individual sensors embedded in it, which allows engineers to move beyond point-based measurement of strain as seen by strain gages and toward field-based sensing over large areas. This capability has direct implications in areas such as civil engineering, where large-scale structures are the norm. Engineers can emplace multiple fibers and create a web of sensors to track and monitor any changes seen in the strain profile. Also, due to the lightweight nature of FBGs, they can be readily applied to aircraft to provide wide-area interrogation of strain loads.

Figure 3 demonstrates how strain can be measured in aircraft structures. A foil strain gage provides point strain data, while two FBGs run down the length of the composite structure, providing wide-area interrogation profiles. Also shown is a "Smart Layer" consisting of FBGs woven within the composite panel itself. This process can provide even more detail into the internal strains experienced in flight, and it demonstrates how easily FBGs can be incorporated into aircraft structures.

NEW METHODS OF MEASURING STRAIN

Elastomeric Sensors

While strain gages and FBGs work well for traditional materials, as more less-rigid materials are introduced into engineering concepts, there is a need for strain sensors that can read higher strain loads beyond where traditional methods experience failure. One recent development is the creation of carbon-filled elastomers.

Figure 4 shows the work of Mattmann et al. on creating a strain sensor that can handle the loads seen in textiles [5]. Textiles typically can stretch well beyond the limits of metal or other rigid materials, rendering the use of traditional strain-sensing methods useless. To measure the high strain loads, Mattmann et al. filled a

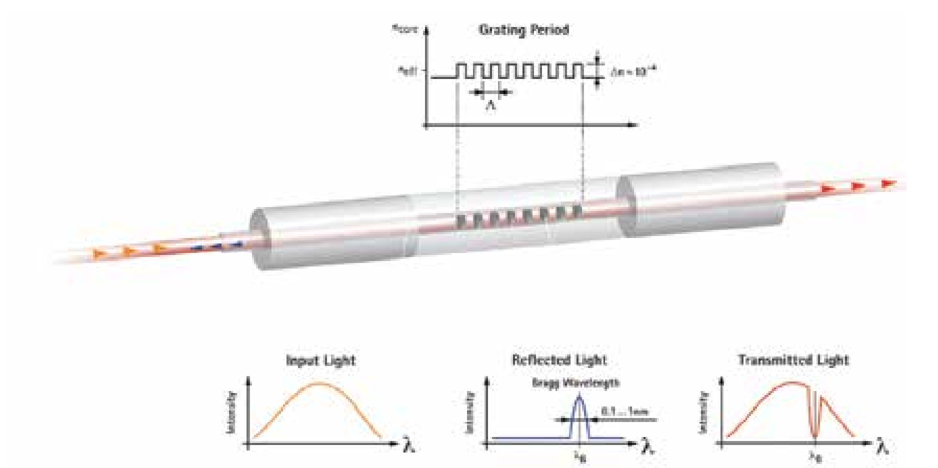

Figure 2: FBG Systems Monitor Reflected Light Off the Grating to Determine the Change in Fiber Length. As the Fiber Stretches or Contracts, the Reflected Light's Phase Angle Shifts and Can Be Correlated Into Strain Change [3].

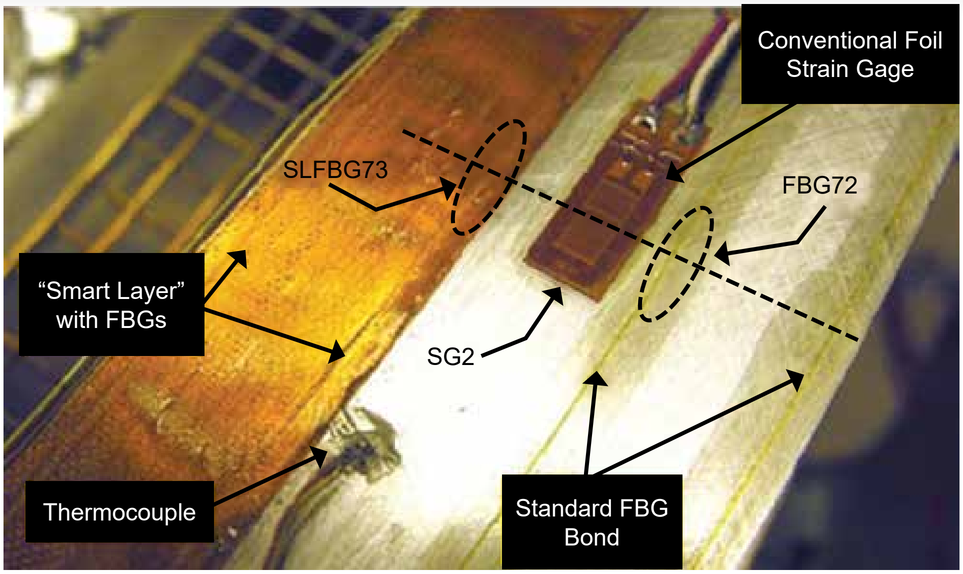

Figure 3: Three Methods for Measuring Strain in Aircraft Wings: Bonded FBG, Single-Point Foil Strain Gages, and FBG Incorporated SMART Layers With the FBG Embedded in the Composite Panel Itself [4].

conductive thermoplastic elastomer with conductive carbon black and extruded the material into a filament. The underlying principle for the filament is that, as it stretches, its electrical conductivity changes, which directly correlates to the strain seen in the system.

As Figure 5 demonstrates, in bench top testing, there is a strong correlation between the change in resistance and the experience strain. While this technology is still in its infancy and requires more testing before commercially viable sensors become available, the research shows strong promise for creating a sensor system that can measure high strain loads.

Frequency Selective Surface Sensors

Another emerging technology is the use of Frequency Selective Surface (FSS) sensors to remotely monitor strain in structures. Figure 6 shows how FSS sensors are used, with an array of elements applied to a structure surface. Once in place, the elements are illuminated using electromagnetic energy, and the reflected response is correlated to the strain profile of the underlying substrate. As the substrate shifts and moves due to strain, the elements in the array contort in response, which changes the reflected response seen by a remote interrogator.

Figure 6 shows the strain profile seen in the steel core of a column undergoing buckling. Note how the foil strain gages cover only a range of the entire loading sequence while FSS sensors show a

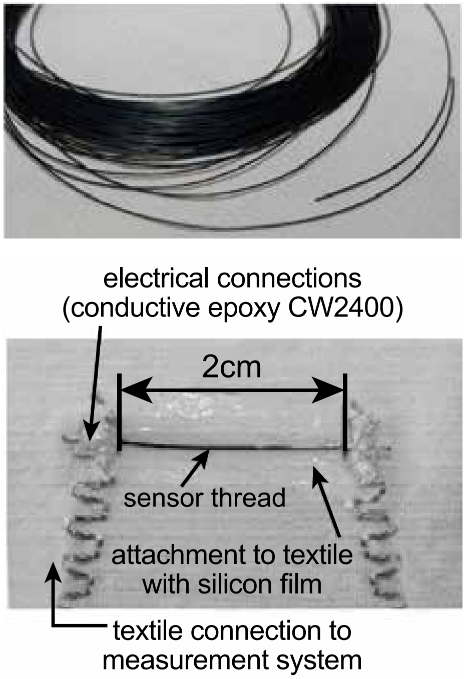

Figure 4: The Extruded Carbon-Filled Elastomer Sensor Thread (top); The Sensor Thread Attached to a Textile Layer With a Silicone Film (bottom) [5].

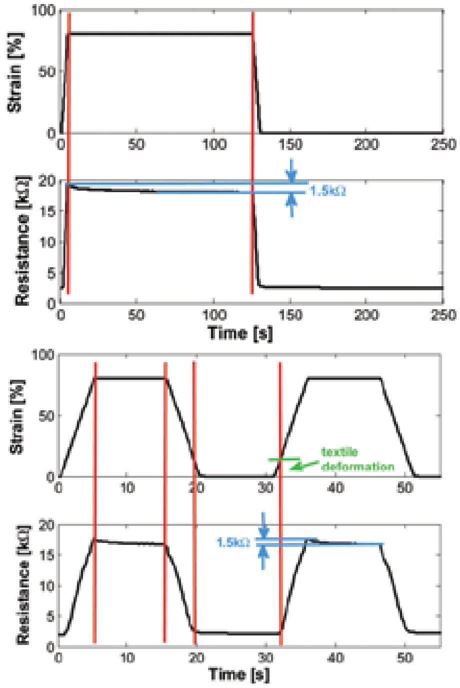

Figure 5: Strain Response for a 2-cm Sensor Thread for 2-min Strain Load (top) and 10-s Strain Load (bottom) [5].

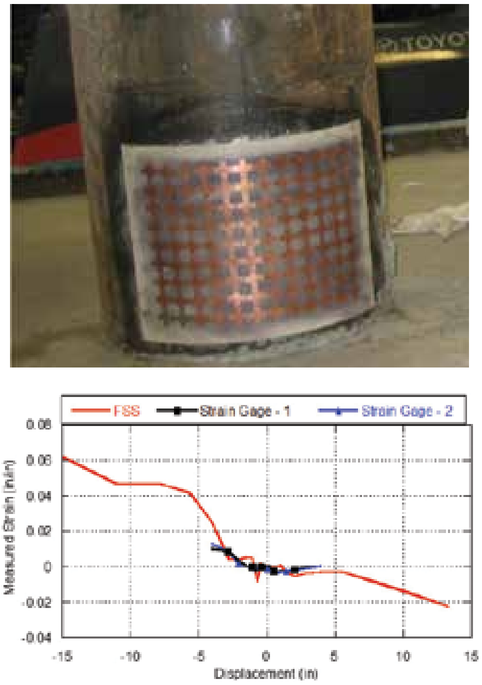

Figure 6: An Array of FSS Elements on a Steel Core (top); Strain Response of the FSS on the Steel Core Compared to Strain Gages (bottom) [6].

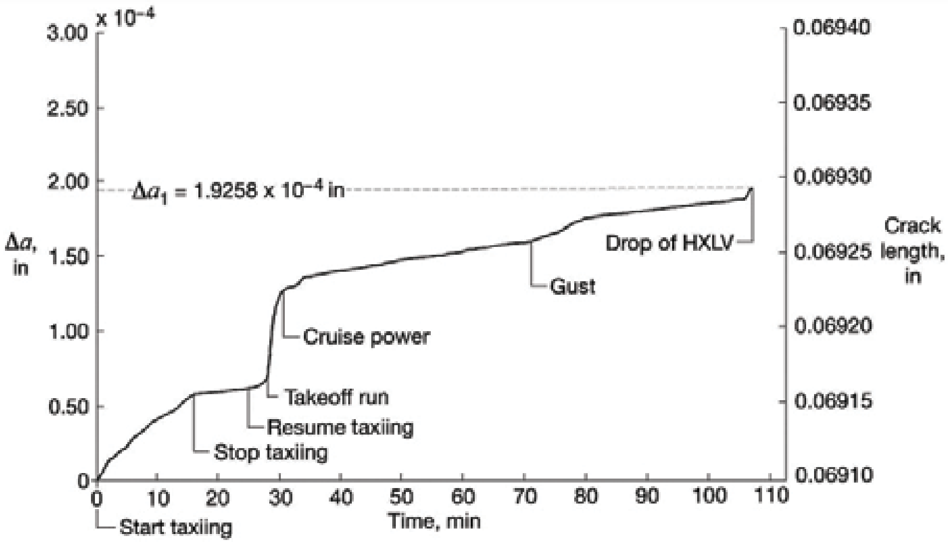

Figure 7: Crack Growth Curve of the B-52 Front Pylon Hook [4].

much broader range of data capture. This broader range allows engineers to have a much more complete view of the loads experienced by the structure. FSS sensors are relatively inexpensive to produce, and multiple arrays can be distributed across a surface to create an array of arrays to provide complete coverage of an entire structure. And given that the entire system is wireless, large numbers of arrays can be installed without worrying about wires getting in the way or tangled.

Life-Cycle Analysis

No matter which method of strain measurement one uses, the strain data can be used for predictive life analysis. For example, NASA studied the effect of fatigue loading using FBGs on a B-52 front pylon hook (as shown in Figure 7). FBGs were used because of their high spacial resolution and ability to conform to complex geometries. Strain data collected from the FBGs can be fed into models such as the Walk crack growth equation, which will determine the amount of crack growth in each flight. Based on the calculated crack growth, engineers can calculate the remaining operational life for each component of the aircraft. And with constant monitoring of the parts through the use of embedded strain monitoring systems, the crack growth and operational life equations can be constantly refined through the operational life of the part.

CONCLUSION

Strain measurement is an integral part of life-cycle analysis. Often times, minute changes in the strain profile of a component can have a large impact in the health of a part. Being able to detect, measure, and document the changes in the strain profile can help engineers and designers ensure that all components meet applicable safety standards. Additionally, as new sensor technologies continue to be developed and improved, engineers can keep adding to their set of tools for monitoring strain. ■

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BIOGRAPHY

MICHAEL MAZUREK has been a research engineer at Texas Research Institute/Austin for the past 10 years, focusing on nondestructive inspection technology and advanced materials development. In particular, he has researched multispectral imaging to detect infrastructure damage, automated defect detection, and advanced aircraft coatings. He is a member of the American Institute of Aeronautics and Astronautics and the American Helicopter Society. He also serves as the Electronic Warfare Officer for the 36th Combat Aviation Brigade of the Texas Army National Guard.

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RELIABILITY RESEARCH FOR A MAINTENANCE-FREE OPERATION PERIOD

By Todd Henry, Terrence Johnson, Jeff Gair, and Robert Haynes

INTRODUCTION

Maintenance requirements for the rotorcraft fleet of the U.S. Army are sizable. Specifically, for the fiscal year 2016 budget, 35% of Army funds were spent on operations and maintenance costs while only 19% of Army funds were spent on procurement and research and development [1].

Some components are subject to a time-based maintenance (TBM) schedule that requires damage inspection at regular usage intervals. Battle damage assessment and repair (BDAR) is not the driving factor for maintenance. Instead, fatigue of vehicle components and erosion of rotor blade and engine components drive cost.

The significant resource requirement of TBM motivates the implementation of a maintenance-free operating period (MFOP). An MFOP is attractive because (1) the logistics tail that exists to supply vehicles in-the-field with replacement parts can be removed, eliminating the need for several forward positions to be kept for maintenance purposes; (2) the prognostics that enable confidence in the MFOP will reduce costs, labor, and downtimes and increase the mission availability; and (3) parts will only be replaced when they are unable to sustain a level of performance for an additional MFOP instead of replacement when damage of an arbitrary size is found.

(Source: U.S. Navy)

Condition-based maintenance (CBM) [2–4] is a step toward the MFOP, where a measurable change correlated to some aspect of failure is targeted and tracked over time. CBM is similar to TBM in that tasks are performed at regular intervals, but action is taken only if failure onset is detected. Mechanisms of failure that are independent of the monitoring technique, however, will not be found, and the nucleation and propagation mechanisms of that damage are unidentified. For an MFOP to be viable, the structural state of critical components of the aircraft needs to be accurately monitored and precisely related to remaining useful life.

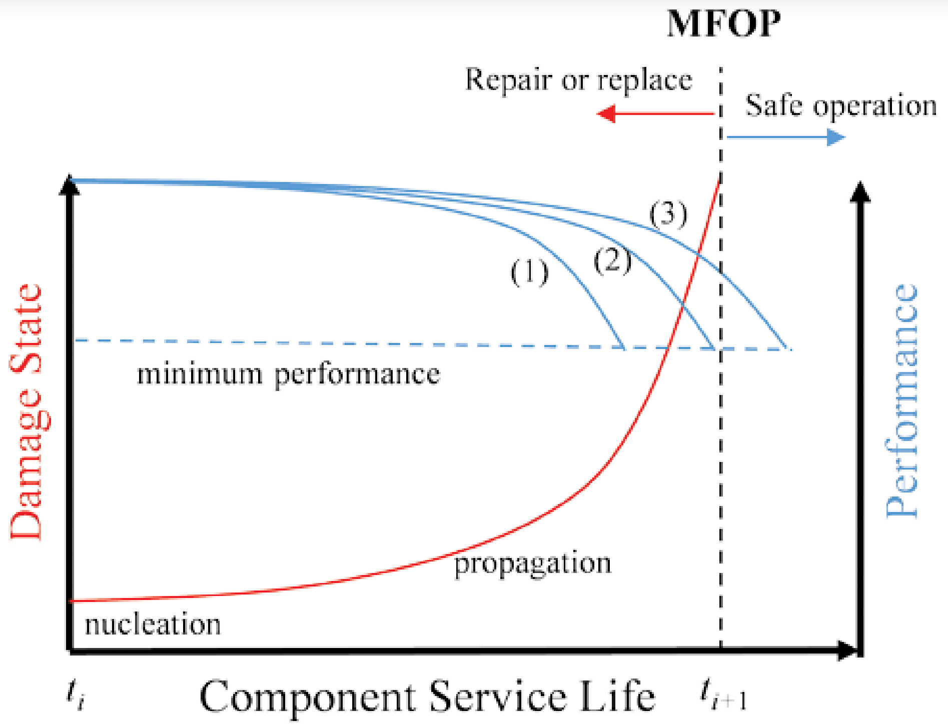

Figure 1: Damage Progression and Performance vs. Component Service Life as It Pertains to MFOP.

DAMAGE NUCLEATION, PROPAGATION, AND IDENTIFICATION

Damage nucleation occurs at submillimeter scales, often long before CBM can be detected. The nucleation event can be influenced by acoustic [5, 6] or electromagnetic [7–9] energy changes caused by grain boundary interactions, persistent slip band formation, fragmentation or rotation of grains, etc., until the damage propagates to a length scale [10–15] where it can be reliably tracked (Figure 1). At this point, the part would be replaced, although some part life remains. Once a phenomenon is identified, the nucleation-propagation behavior could be sensed by an automatic system perhaps embedded within the structure itself for reporting to a remote location. While tracking the damage state, the user can decide on adapting the vehicle operation either to maintain performance at a continual accumulation of damage or to decrease performance to sustain a longer operating life. The MFOP would then be the amount of time over which performance is maintained before a considerable amount of the component service life has been consumed and action must be taken to repair or replace the part.

Given that a detection of state is known, there are three possibilities for vehicles life compared to the MFOP:

1. Vehicle needs mission adaptation to meet MFOP (e.g. maintenance, adaptive control laws, etc.).
2. Vehicle will meet minimum performance objectives over MFOP.
3. Vehicle has margin above performance objectives over MFOP.

Several works conducted by the U.S. Army Research Laboratory (ARL) have sought to link different monitoring techniques to the remaining useful life of composites and metal structures [16–19]. Composite specimen compliance, for example, has been shown to increase during fatigue testing. The resulting decrease in the stiffness over time for the data set can be modelled (labelled slope and intercept methods) to calculate the current remaining cycles for any specimen (Figure 2). Accuracy of the method is the difference between

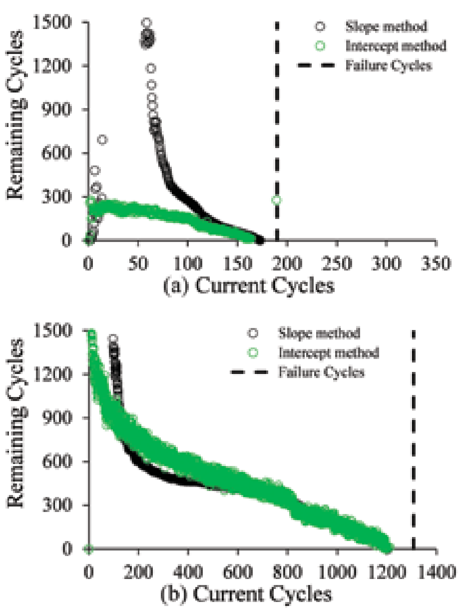

Figure 2: Remaining Useful Life Prediction vs. Current Cycle Count Number Fatigued at 90% Strength (a) and 70% Strength (b). Vertical Dashed Line Represents Experimentally Measured Failure Cycles [16].

the vertical dashed line and the x-axis intercept. This method could be applied in cases where the compliance increase behavior has already been measured for a set of specimens and the load and displacement are being measured on the specimen of interest.

Measurements of small-scale damage have also been conducted in steel alloy 1095. A specimen tapered in width was tested in tension-tension fatigue to create a distribution of stress and thus life for a single applied load.

Tests were then conducted along the length to assess (a) nano-indentation response, which measures small-scale modulus and hardness behavior (Figure 4a); (b) X-ray diffraction response, which measures residual stress variation (Figure 4b); and (c) eddy current response, which measures magnetic permeability (Figure 4c/d). The experimental results from testing show changes in material properties, which can be tracked to remaining useful cycles.

The primary obstacle to developing these technologies from small scales to present relevance for aircraft structures is either minimization of the machines that conduct these experiments in the laboratory or development of sensors that detect the changes presented here and test their applicability at larger scales. Laboratory testing is practical for identifying what changes in the material should be investigated and what technology must be developed further to create the MFOP.

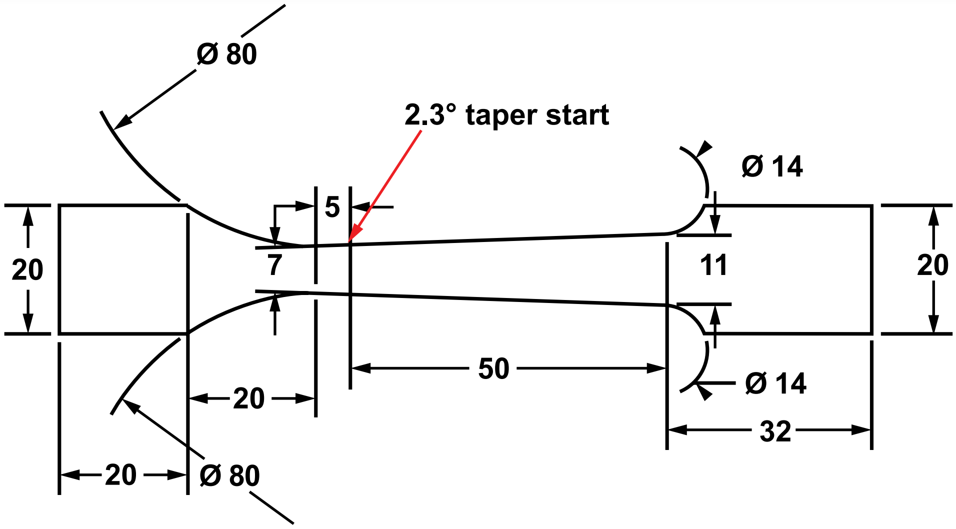

Figure 3: 1095 Steel Specimen Tapered in Width (in Millimeters) [17].

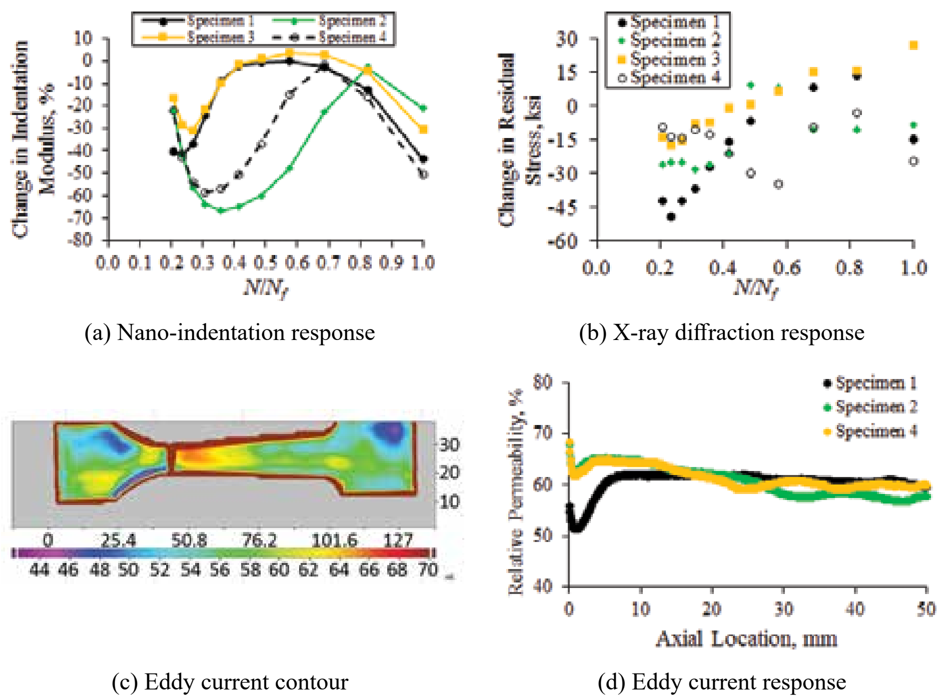

Figure 4: Technique Response as a Function of the Current Cycle (N) Over Failure Cycle Number (Nf) or Axial Location Along the Specimen [17].

TOPOLOGY OPTIMIZATION AND ADDITIVE MANUFACTURING

A structure may be designed more intelligently, adding, subtracting, or redistributing material volume for longer fatigue life by reducing stress levels. Topology optimization (TO) is an extremely powerful free-form rigorous design method developed around this ideology for designing structures [20] (Figure 5). TO can produce extremely complex yet efficient designs for prescribed objectives and constraints, which makes it ideal for use with additive manufacturing (AM). AM has the capacity to realize TO designs that are not possible by traditional manufacturing processes due to cost and tool-path constraints. Traditional TO formulations for lightweighting (i.e., without consideration of fatigue) often produce designs with stress

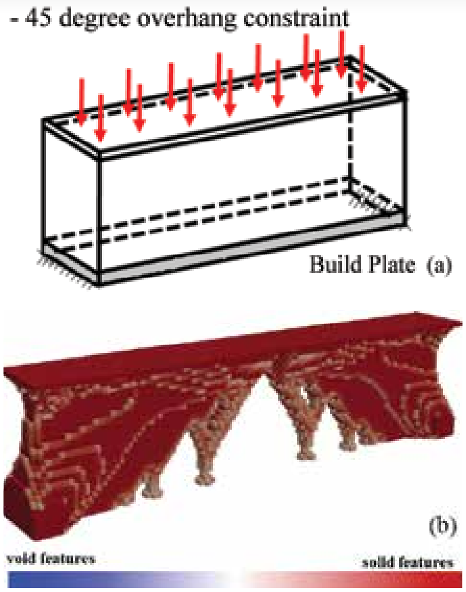

Figure 5: Topologically Optimization for Given Boundary Conditions (a) and TO Solution (b).

concentrations or singularities that cause a reduction in fatigue life. As a result, manual adjustments or additional structural optimization is needed after the TO process to fulfill fatigue requirements. Therefore, research efforts are placed in developing and experimentally validating design methodologies that consider/couple fatigue within TO design for the lightweighting of structures.

AM processes are sometimes limited by feature size, locations of unsupported material known as overhangs, trapped material in hollow structures (analogous to voids), and material warping due to residual thermal stresses during manufacturing that result during cooling. TO design methodologies need to take into account the printing methods by which AM structures are made—in particular, TO design methodologies for considering overhangs and internal voids. Overhang areas require additional AM support material for the structure as the primary material is being built up while internal voids create stress concentrations and premature structural failures.

Several works seek to eliminate overhangs to produce self-supporting structures by limiting the printing angle, with respect to the vertical [21]. The resulting structure does not require extra support material for a solution of greater machinability to the boundary condition and loading conditions of the problem. Figure 6a represents a three-dimensional TO solution for a cantilever beam. The converged solution contains an internal void, which could trap AM printing material. Research has been conducted to design for empty spaces instead of solid feature via void projection [22]. It can be seen in Figure 6b that this methodology results in a burrow from the top through the bottom of the beam, ensuring a path for material to escape. An application for this approach could be AM sandcasting where void space is filled with a sand-slurry-like material, which acts as a place holder for future castings.

Current TO design methodologies for maximizing structural stiffness do not give attention to the structure's fatigue life, which can result in worse stress-life behavior.

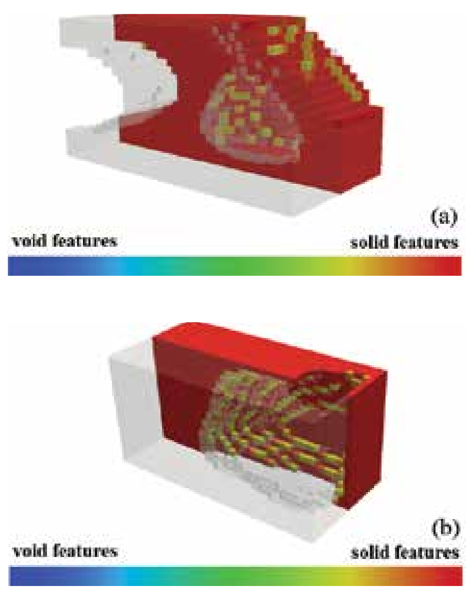

Figure 6: Cantilever Beam Topology Optimized Beam With Overhang (a) and Internal Voids Topology Optimized Beam With No Internal Voids (b).

Consider a simply supported beam in bending and the topology optimized solution in Figure 7. The objective of this optimization was a maximization of structure stiffness while keeping the structure's volume lower than 50% of its original volume. The result was a doubling of the structural von Mises stress, which results in a considerable reduction in its fatigue life. Structural failure and fatigue properties must be considered for designs that are expected to be used in service. The reduction in structural fatigue life can be mitigated by first assessing the initial structure and then modifying fatigue constraints so that minimum performance is maintained while mass or volume is reduced.

In addition to maintaining fatigue life, it is believed that design solutions could also be used to improve fatigue life through use of multifunctional and self-sensing materials. TO designs considering fatigue life can be summarized as follows: (1) keep mass constant and change fatigue properties, or (2) keep fatigue properties constant and change mass [23]. Both objectives are of interest to the Army.

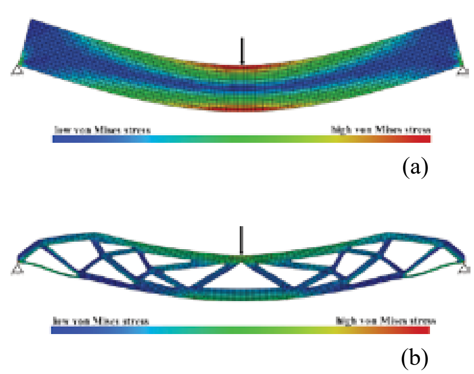

Figure 7: Simply Supported Beam in Bending Beam Without Topology Optimization (a) and Topology Optimized Beam (b).

HIERARCHICAL AND MULTIFUNCTIONAL COMPOSITES

In addition to identifying and tracking damage progression, a structure may be designed with elements of toughening to resist specific failure mechanisms. Work at ARL has also designed nanotube-coated composite fibers to increase the bridging from one composite lamina to another. Such a structure resists delamination crack growth by creating a traction through-the-thickness across the interface. Wicks et al. achieved conformal coatings of radially aligned carbon nanotubes (CNTs) on the surface of alumina fibers, which exhibited enhanced interlaminar shear reinforcement [24]. Additional material systems of interest include ceramic fiber composites with a similar architecture with the goal of developing durable and damage-tolerant structural composites for mobile systems. Conformal coating of the ceramic fibers in CNTs gives rise to electrical conductivity via fluctuation-induced tunneling. Composites made from these materials thus have the potential for a wide range of applications.

For example, when accumulating damage, composites have been shown to increase in resistivity [25], thus indicating that damage-sensing applications for such materials are within reach. The conductive tunneling also gives rise to heat generation with greater efficiency than traditional resistive heaters, resulting in composites that can be used for heating with minimal current [26]. If a suitable structural thermoplastic matrix material can be found, the heat generated by these low currents could be used to melt, and thereby heal, accumulated matrix damage. Novel copolymer blends can also provide multifunctionality through manipulation of hard- and soft-blocks for tunable elastic and dynamic behaviors for polyurethane and poly(urethane-urea). The integration of these technologies may one day lead to mobile systems with real-time material state awareness, with the ability to self-sense and self-heal damage prior to catastrophic failure. This ability would not only improve the operational effectiveness of the vehicle but also reduce maintenance cost and risk of failure.

> Current TO design methodologies for maximizing structural stiffness do not give attention to the structure's fatigue life, which can result in worse stress-life behavior.

CONCLUSIONS

The MFOP would save Department of Defense and Army resources that are currently dedicated to logistical sustainment of fleet vehicles. It would eliminate maintenance downtimes during the MFOP and increase Army readiness. However, there exist many challenges in developing fatigue damage nucleation-propagation understanding and techniques that are able to track the damage from the smallest possible scales and inform material state accurately. The decision-maker for the fleet should be given surety that performance can be maintained for the MFOP before action must be taken. The primary obstacle for transition from nano- or micrometer-scale testing to millimeter-scale measurement is developing measurement technologies from the laboratory to the field in the form of a compact and energy-efficient sensor.

TO research can be used to more intelligently design structures to have longer fatigue lives or be stronger given constant mass. Manipulation of AM with multifunctional, self-sensing, and hierarchical materials may increase the design space for longer part life given a specific mission as well. Careful consideration must be given to limitations of the technique in general, though with respect to overhangs and internal voids. Material development to design superior structures that are self-aware of their damage state, maintaining a minimum performance threshold, is a large step forward for the Army. ■

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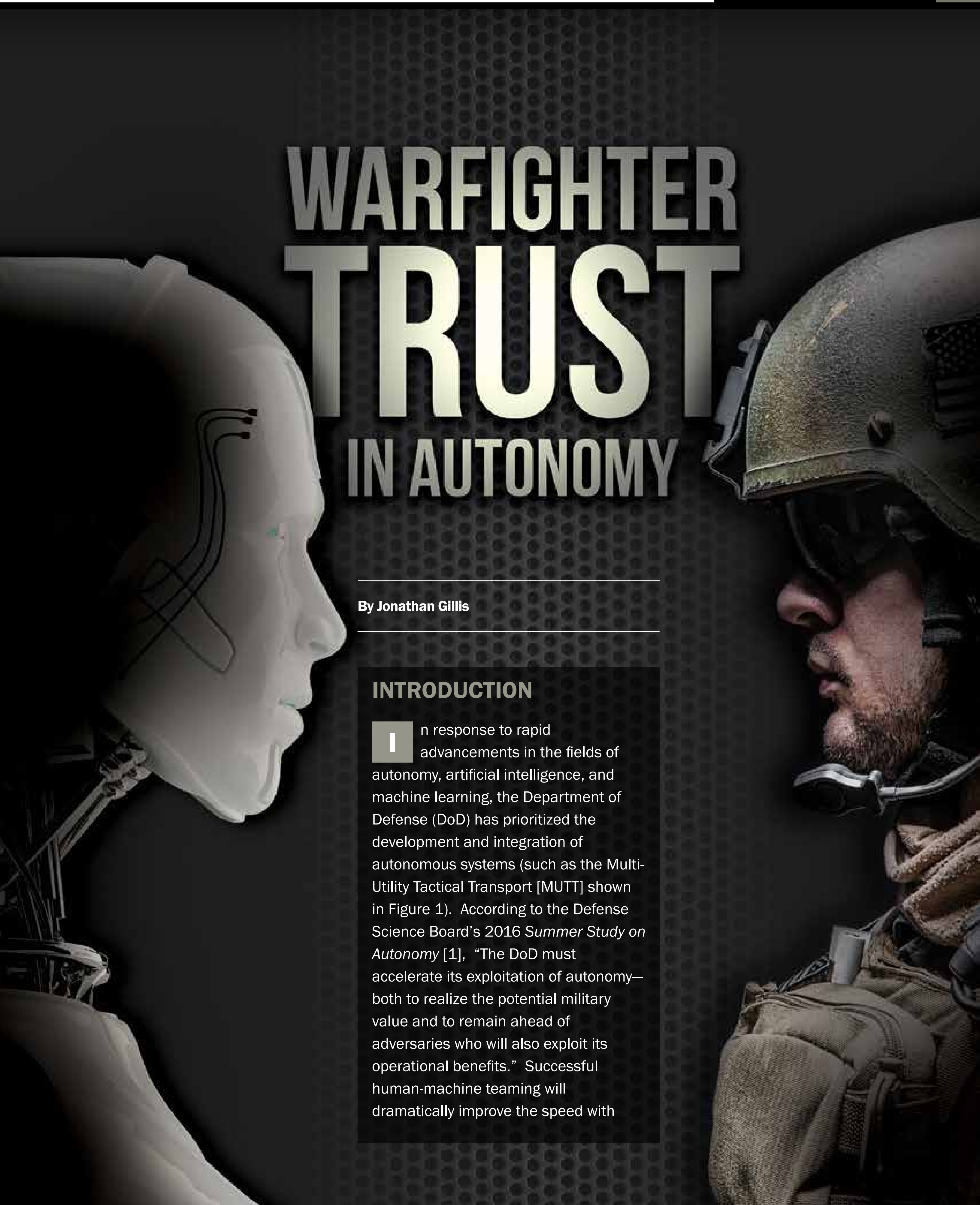

WARFIGHTER TRUST IN AUTONOMY

By Jonathan Gillis

INTRODUCTION

In response to rapid advancements in the fields of autonomy, artificial intelligence, and machine learning, the Department of Defense (DoD) has prioritized the development and integration of autonomous systems (such as the Multi-Utility Tactical Transport [MUTT] shown in Figure 1). According to the Defense Science Board's 2016 *Summer Study on Autonomy* [1], "The DoD must accelerate its exploitation of autonomy—both to realize the potential military value and to remain ahead of adversaries who will also exploit its operational benefits." Successful human-machine teaming will dramatically improve the speed with

Figure 1: MUTT *(Source: Cpl. Levi Shultz, U.S. Marine Corps).*

Figure 2: Big Dog *(DARPA Photo).*

which the military collects, analyzes, and responds to data. This capability is critical to maintaining the tactical edge against increasingly tech-enabled adversaries. However, to fully realize autonomy's battlefield potential, the military must first cultivate trust in autonomous systems down to the lowest tactical level.

THE WARY WARFIGHTER

The vast majority of military applications for autonomy are likely to be non-lethal. Fields such as intelligence, operational planning, logistics, and transportation anticipate highly capable non-lethal systems within the next decade. The private sector has already pioneered many of these applications, most notably with self-driving cars (such as Google's Waymo [see https://waymo.com/) and autonomous warehouse robotics (such as Amazon's Kiva [see www.amazonrobotics.com). As those technologies become increasingly commercially available, military members are likely to invest more trust in autonomous systems with comparable applications inside the DoD.

When it comes to frontline combat, however, there is no commercial equivalent; the battlefield is fluid, dynamic, and dangerous. As a result, Warfighter demands become exceedingly complex, especially since the potential costs of failure are unacceptable. The prospect of lethal autonomy adds even greater complexity to the problem. And without comparable applications for autonomy in the commercial sector, Warfighters will have no prior experience with similar systems. Developers will be forced to build trust almost from scratch.

For these reasons, the majority of infantry personnel—who rarely interact with computers in an operational setting—continue to believe that autonomy on the battlefield is more science fiction than fact. The state of current developmental ground technologies has made Warfighters even more circumspect. Loud and cumbersome robots supported by teams of engineers have led Warfighters to distrust/dislike many developing technologies (such as the Big Dog robot shown in Figure 2, which the Marines felt was too noisy for use in combat) as well as question whether there will ever be a tactical role for autonomy.

When one talks with enlisted personnel about their aversion to autonomy on the battlefield, four main reasons for this resistance emerge:

1. Warfighters often have little understanding of autonomy and its enabling technologies.
2. Warfighters are concerned about their ability to communicate and collaborate with autonomous systems.
3. Warfighters are concerned about increases to their logistical burden.
4. Warfighters are concerned about operational safety.

Accordingly, building trust in autonomous systems, whether or not they are weaponized, is likely to be especially challenging at the tactical level. To ensure that future autonomous systems meet user needs—and that these systems are actually employed—the DoD must recognize and address low-level Warfighter concerns. In particular, developers must understand small-unit trust relationships, tailor systems to fit into that social environment, educate Warfighters on "the technology, and maintain collaborative relationships with end users going forward.

DEFINING AUTONOMY

It is important to define *autonomy*, especially as distinguished from *automation*. The Defense Science Board defines automation as "[a system] governed by prescriptive rules that permit no deviations [1]." Autonomy, on the other hand, is defined as a system with "the capability to independently compose and select among various courses of action to accomplish goals based on its knowledge and understanding of the world, itself, and the situation."

The key distinction here is the ability of a machine to think or reason on its own. The vast majority of Warfighters are accustomed to working with automation—that is, they are used to machines executing narrowly defined tasks. For example, the Mortar Fire Control System (MFCS) (such as the one shown in Figure 3) is an automated system that receives targeting data from its user and adjusts a mortar tube for enhanced accuracy [2]. The targeting data are generated by human forward observers; the MFCS simply calculates the charge and trajectory required to hit that target. Automated systems such as the MFCS still require a level of Warfighter trust; but because users are responsible for all inputs, the system's scope is relatively narrow, and the outputs are defined, users generally trust the system once it is initially proven to work.

By contrast, a Perdix unmanned aerial vehicle (UAV) (shown in Figure 4) is an autonomous system that interacts in a swarm with dozens of other independent UAVs. Rather than following strict rules, such as a pre-programmed flight pattern, Perdix UAVs share sensor data and come to collaborative navigation decisions [3].

Figure 3: MFCS *(Picatinny Arsenal Photo).*

The ability for the swarm to both collect information and make decisions means that a single human can manage hundreds of a UAVs with relative ease. Of course, it also raises concerns among potential users that the swarm may "decide" to do something counter to the human controller's intent. Users may not always understand the mechanisms behind the decision-making process, which makes them wary to trust the machine's judgement. And without a "human element" built into the decision cycle, there is also a fear that machines will make inappropriate decisions with potentially lethal consequences.

Figure 4: Perdix UAV *(DoD Photo).*

These hurdles are not insurmountable, but they do suggest that Warfighters may require much more communication and assurance from autonomous systems than they require from automated systems. Recognizing what information to share and how best to share it is important. Cohesive small units often develop intuitive communication networks; individuals learn to anticipate one another's needs and push information as appropriate. Fitting an autonomous system into this mix will thus first require developers to understand the social dynamics within a team.

TRUST IN SMALL UNITS

Small-unit cohesion has long been considered the backbone of military success. Warfighters going back centuries have been made to live, eat, and work together in small teams to build close personal ties and improve resiliency and communication on the battlefield. Cohesion is directly correlated with lethality. As French military theorist Charles Ardant du Picq observed, "Four brave men who do not know each other will not dare to attack a lion. Four less brave, but knowing each other well, sure of their reliability and consequently of mutual aid, will attack resolutely [4]."

The development of unit cohesion is dependent on more than just friendship. In fact, small military teams are united first and foremost by *task* cohesion, which is "a shared commitment among members to achieving a goal that requires the collective efforts of the group." It is during the struggle to accomplish those tasks that Warfighters then develop *social* cohesion, or the enjoyment of each other's company. Mutually shared hardships, such as combat or field exercises, give birth to "altruism and generosity that transcend ordinary individual selfish interests." These displays of selflessness validate and enhance existing relationships, making the development and maintenance of unit cohesion a constantly iterative process [5].

Unit cohesion is a reflection of interpersonal trust. Trust between military team members depends on one another's *proficiency, predictability*, and *genuine concern*. Proficiency gives Warfighters confidence that their leaders, peers, and subordinates can and will contribute meaningfully toward unit goals. Predictability allows team members to anticipate one another's actions and synchronize efforts. Genuine concern gives Warfighters the assurance that the team cares for their well-being and will come to their assistance when required.

Only when these three characteristics converge do Warfighters feel comfortable trusting each other in an operational setting. As trust researcher F. J. Manning has noted, "soldiers can and do distinguish between likability and military dependability, choosing different colleagues with whom to perform a risky mission and to go on leave [5]."

> The majority of infantry personnel—who rarely interact with computers in an operational setting—continue to believe that autonomy on the battlefield is more science fiction than fact.

When arriving at a new unit, Warfighters are afforded a certain level of confidence simply because they share a common identity with the rest of the team. Identity-based trust makes it easier for small units to integrate new members quickly by allowing them to assume a common set of skills and experiences [6]. Training then builds task cohesion and gives Warfighters the opportunity to win personal trust by demonstrating their individual proficiency, predictability, and genuine concern. When Warfighters interact consistently and prove themselves trustworthy both personally and professionally, social cohesion then tightens the knot. While not strongly correlated with combat performance, social cohesion is associated with job satisfaction, morale, well-being, and psychological coping.

Strong task and social cohesion give Warfighters much more patience for mistakes, but the trust can still be broken. The key to maintaining trust after failure is forgiveness, which is often dependent on a cohesive narrative explaining the failure. For example, if a Marine fails to get into position to provide suppressing fire during an attack, the team may question whether the Marine is proficient or reliable enough to be trusted in the future. However, if the Marine can explain that he/she was fixed in position by fire, or even that he/she had tripped and injured himself/herself, team members can empathize with the experience and forgive the mistake. Only if the Marine consistently makes similar mistakes, or fails to show remorse, does a team's patience begin to wane.

In summary, military teams are united by shared tasks, solidified by personal interaction, and kept together by the willingness to forgive. The process for building trust in autonomous systems will not look the same, but there are elements of overlap. Once developers are aware of a team's human interactions, they can better discern how autonomy will fit into that picture.

BUILDING TRUST

Autonomous systems cannot and should not be expected to win trust in the same way as humans. Warfighters, at least in the short term, will not invest identity-based trust into an autonomous system because they have no ability to relate on common hardships, frustrations, and experiences. Additionally, autonomous systems cannot empathize, so they are unable to demonstrate genuine concern in any believable or meaningful way.

Finally, autonomous systems will not be integrated into a unit's social network because they are unable to provide the companionship that correlates with improved quality of life.

Autonomous systems cannot contribute to social cohesion, but they can build task cohesion, which is statistically more important to combat effectiveness. Human-machine teaming requires users and autonomous systems to align goals and synchronize actions. As with humans, autonomous systems will build trust by performing well in training. For autonomy, that means demonstrating proficiency and predictability as least as well as, though ideally much greater than, a high-performing human.

Proficiency for an autonomous system is the ability to execute assigned tasks in a way that enhances small-unit combat power. This means that, in addition to succeeding on specific tasks (such as identifying targets), autonomous systems also need to be able to move and function on the battlefield without imposing cognitive or physical burdens on the team. It is not enough for autonomous systems to simply recognize meta-objectives (such as "seize a building"); they must also infer micro-objectives (such as "provide suppressing fire," "take cover," and "remain quiet").

A system must also be predictable enough for humans to anticipate its behavior. Human members of highly functional teams intuitively provide each other with information and resources based on their ability to understand the situation and predict one another's responses. This action allows them to synchronize without extensive communication. Autonomous systems must likewise provide the same level of consistency. These systems will also need to anticipate human actions and communicate their intentions without overwhelming end users.

> Autonomous systems need to know when and how to push information to other individuals or to the squad as a whole without overwhelming them.

If autonomous systems can demonstrate the ability to reliably execute specified and implied tasks without becoming burdensome, they can win an initial amount of human trust. However, that initial trust can be destroyed in an instant if the system fails. Maintaining trust in autonomy is different than simply winning it in the first place. That accomplishment requires systems to provide enough value to feel worth "forgiving" and to communicate the reason for failure in a way that can be understood by the end user. It also requires end users to be familiar enough with the technology to recognize how certain components work, why they might fail, and how the unit might be able to help avoid failure in the future.

WARFIGHTER ENGAGEMENT

Maintaining trust requires developers to build autonomous systems that are adaptable to specific user requirements. Because most Warfighters at the tactical level have no experience working with autonomy, it will initially be difficult for them to give useful and accurate feedback on aspects such as user interfaces and communication methods. Engineers and Warfighters will thus need to maintain collaborative relationships to identify and act on opportunities for improvement as the technology evolves.

As previously mentioned, Warfighters need systems that can execute assigned tasks and share information in appropriate ways without becoming logistical burdens or safety hazards. There are no strict definitions of those requirements. Rather, the requirements are dependent on how Warfighters prefer to share information and how they calculate the tradeoffs between an autonomous system's logistical requirements, safety hazards, and tactical value.

Engaging with the end user is vital to designing a system that strikes the optimal balance between value and cost. When discussing autonomy with potential end users, it is helpful to focus on four main areas: (1) user understanding of the technology, (2) communication with the system, (3) logistical requirements, and (4) operational safety.

User Understanding of the Technology

Most Warfighters at the tactical level are unfamiliar with the inner workings of military technology. For these users, systems are often delivered with little technical explanation and are thus treated as black boxes. While this situation may be acceptable for automated systems, it will inhibit a Warfighter's ability to trust an autonomous system's reasoning and decision-making. It is thus important when engaging with end users to ask them how much they understand.

If an autonomous system relies on computer vision and machine learning, Warfighters need to understand both of those concepts, at least at a basic level. If a system relies on global positioning system (GPS) technology, Marines need to know the expected margin of error.

Explaining the technology can go far in developing trust because it helps Warfighters to calibrate their expectations to the actual abilities of the system. Additionally, once they understand the capability set, Warfighters will begin recommending applications, giving developers valuable insight into how Warfighters think about the technology and where it might be most useful in their current operations.

Communication With the System

Complex operational environments impose a tremendous cognitive workload on infantry personnel. Individuals may be scanning for enemy indicators, adjusting their position in a formation, navigating unfamiliar terrain, and identifying key terrain for cover and concealment, all at the same time. Warfighters in high-trust teams develop an intuitive understanding of how much information their peers require and how best to deliver it. Likewise, autonomous systems need to know when and how to push information to other individuals or to the squad as a whole without overwhelming them.

Not surprisingly, there is no single communication solution. Autonomous systems should allow teams to shape the way they communicate across a range of possible scenarios. Squad leaders may be receptive to lots of information on one mission and overwhelmed by the same amount on the next. Warfighters may require more information from a new system than one that has been in use for several weeks. And some squads may prefer audible communication while others prefer text communication.

The key is to communicate information as simply as possible. Messages should be short and explicit, with the opportunity for users to engage further if more information is needed. Additionally, Warfighters should be able to customize aspects such as fonts types, font sizes, voices, volumes, and accents, which are standard settings on their cell phones.

> Ironically, autonomy integration is, in large part, a human problem; and it will thus require human users to be at the center of the development process.

In communicating information about its state, an autonomous system also needs to be able to self-diagnose, recommend solutions, and, when possible, self-correct. Human actors on the battlefield do this frequently; Marines are trained to respond to injuries by alerting teammates, recommending a course of action, and applying self-aid. Autonomous systems that are capable of the same actions will remove much of the maintenance and tracking burden from human team members.

Logistical Requirements

Small units are stretched thin by the amount of equipment they are required to manage. Warfighters are resistant to any additional weight or responsibility that does not contribute significantly to combat power. Thus, batteries, fuel, radios, remote controllers, and other components are important considerations when it comes to introducing autonomous systems to ground combat units. Depending on a system's perceived value, and the mission set for which it is meant, Warfighters may opt to leave the system at home rather than incur the added weight. Additionally, systems that are too heavy or difficult to move by hand may go unused (or underused) if Warfighters are concerned that they will fail in the field.

Developers need to be cognizant of how a system's support requirements impact small-unit logistics. If Warfighters are hesitant about the logistical burden, it is a signal that developers either need to prove the system is invaluable or attempt to slim down the support requirements. Systems that require extensive logistical support can serve to reduce trust in autonomy if Warfighters believe that the burden will negatively impact combat power. Warfighters should be consulted on the weight and size of systems, their components, and their fuel requirements. If the logistical requirements are too great for the end user, the technology should be tabled until better solutions are available.

Operational Safety

Warfighters will accept a certain amount of risk if the payoff creates an asymmetric advantage on the battlefield. Once they understand the technology, how to communicate with it, and what its logistics train entails, they will make an informal assessment on whether or not it is worth the reward. Developers need to understand these assessments. If Warfighters do not believe a system is worth employing, they will be even more unlikely to forgive that system when it fails.

The threshold for safety increases dramatically if an autonomous system is weaponized. Many Warfighters have a strong aversion to incorporating autonomous weapons into their operations, especially on the ground. To win trust and build confidence in autonomy, developers should focus on autonomous surveillance, reporting, and load-bearing systems with lower risk factors first, and then integrate weapons after Warfighters have become familiar with the technology. Additionally, developers should be careful of designs that could roll over, crush, or otherwise injure Warfighters in an operational setting. Any safety incidents early in the integration process could become a serious hindrance to further integration.

CONCLUSION

Robotics and autonomous systems will inevitably have a place on the future battlefield. Winning trust in those systems now is a matter of educating Warfighters on the technology and working closely with them to ensure that their initial experiences are intuitive, safe, and fruitful. Ironically, autonomy integration is, in large part, a human problem; and it will thus require human users to be at the center of the development process. By paying specific attention to user needs, developers can ensure that systems provide indisputable value and that users trust the systems and the development teams behind them. ■

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BIOGRAPHY

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BREAKTHROUGHS IN ENGINE PROPULSION RESEARCH WITH HIGH-PERFORMANCE COMPUTING

By Luis Bravo, Dokyun Kim, and Matthias Ihme

INTRODUCTION

From the automotive diesel engine to on-board naval power generators to the aircraft jet engines, liquid atomization of hydrocarbon fuels is at the core of the energy generation and propulsion systems powering the vast majority of the Department of Defense (DoD) land-, air-, and sea-based platforms. As a result, in the foreseeable future, maintaining a critical technical superiority of the armed forces is virtually impossible without revolutionary advances in the design of combustion systems.

Combat aviation and terrestrial vehicles such as the Gray Eagle MQ-1C (shown in Figure 1) and the Joint Light Tactical Vehicle (JLTV) are powered by diesel engines running primarily on military JP-8 or F-24 fuels. Breakthroughs in engine technologies and fuel conversion efficiencies require a basic understanding of complex multiphase flow and combustion-relevant phenomena, including primary fuel/air mixture formation, particle-gas dynamics, and *supercritical states*. In liquid-fueled direct injection engines, the jet primary and secondary breakup processes have a significant influence on the fuel/air mixture formation and drop-size spatial distribution. A full understanding of the behavior is of significant interest for the design and operation of fuel injection nozzles and advanced combustors concepts. This understanding is also relevant in a broader scientific context for applications such as turbomachinery, material coating, additive manufacturing, fire suppression, etc.

(Source: U.S. Air Force)

Historically, the development of combustion systems proceeded through an empirical "trial-and-error" approach, without an in-depth understanding of all aspect of the underlying physics. One of the most common approaches is to avoid a detailed description of primary breakup in favor of a semi-empirical model describing the sudden appearance of large droplets with specific momentum that then break up into finer droplets and vaporize. Such models rely on experimental data to set adjustable model parameters. This type of approach, while costly, still allows conventional engine designs to reach a remarkable level [1]. Fully predictive modeling is thus not possible at this time with these approaches.

However, with the recent advances in supercomputing power and numerical algorithms, first-principle simulations of the atomization processes are emerging today as a viable research tool to investigate fuel/air mixture formation in ever-more-extreme conditions and regimes that are far less understood and more difficult to diagnose experimentally [2–5]. Hence, high-fidelity numerical simulations can be used to probe the spray breakup dynamics and understand the behavior of an atomizing spray during stable operations and, more importantly, in off-design regimes (see Figure 2). Such insights often cannot be obtained through modern experimentation, and they are invaluable for guiding the development of stable, reliable systems, providing major savings in time and cost.

At the U.S. Army Research Laboratory (ARL), a multiyear research effort, in collaboration with industry (Cascade Technologies) and academia (Stanford University), is underway to support the development of Army propulsion systems. Inaugurated in FY15, the 5-year Frontier project is supported by the DoD High-Performance Computing Modernization Program (HPCMP) and the 6.1 base Vehicle Technology Directorate (VTD) program. The focus is on conducting research to address critical knowledge gaps in propulsion sciences, including combustion and complex multiphase flows. The project addresses issues relating to the nonreacting behavior of atomizing sprays, including the role of perturbation-driven instabilities on breakup and droplet formation, complex evaporation, and complex particle surface interactions. The major goal of this effort is the creation of a suite of breakthrough computational tools with the ability to predict the microscale flow physics of atomizing flows and moving interfaces using fundamental principles. The DoD will then be able to apply these models to the performance of any chemical-propulsion device that uses spray combustion, with the vetted models being particularly helpful in reducing the experimental steps necessary.

Figure 1: Rendered Army Gray Eagle MQ-1C Powered by a Turbocharged 160-hp Diesel Engine *(Source: DoD).*

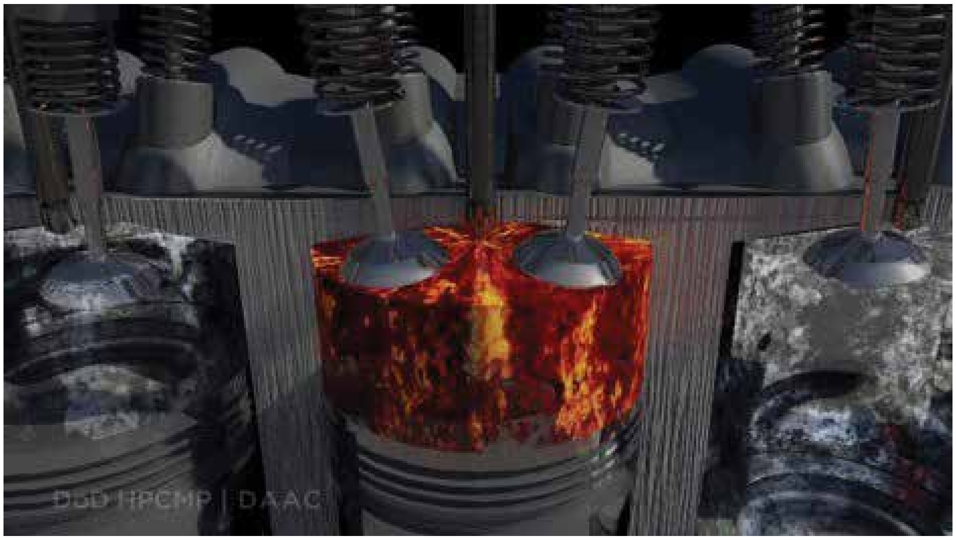

Figure 2: Conceptual Rendering of the In-Cylinder Atomization Process in a Diesel-Powered Army Gray Eagle UAV Engine *(Source: DoD).*

PHYSICAL DESCRIPTION OF PRIMARY ATOMIZATION

Liquid sprays involve a multiscale, turbulent physical process that presents several technical challenges. There is a liquid core (continuous) region that is disintegrated into fine sprays (dispersed phased) due to instabilities and aerodynamic interaction. Once the liquid core becomes unstable, it will favor the creation of ligaments that in turn will first create parent primary droplets, followed by secondary child droplets. Droplets are reduced in size due to evaporation, and combustion occurs while reduced droplets travel downstream of the injector nozzle. The resulting drop-size distribution or drop-velocities should be controlled to achieve the desired mass and heat transfer rates in most practical applications. Further, injector effects and needle wobble conditions are also important characteristics that have not been fully explored and strongly affect spray breakup.

Figure 3 shows the spray formation process. Points 1 and 2 in the figure show the ligament structure in the dense region, point 3 shows the onset of surface instabilities, and point 4 shows a characteristic outer ligament and droplet length-scales for this injector. Improved knowledge of primary breakup will lead to better predictions of spray characteristics, such as initial droplet size distribution, spray angle, and jet structure, thus enabling improvements in engine performance and control.

The characterization of spray behavior is better understood through the use of several nondimensionless parameters, as listed in Table 1. These parameters can be used to classify the spray into regimes that can, in turn, be used to predict its behavior.

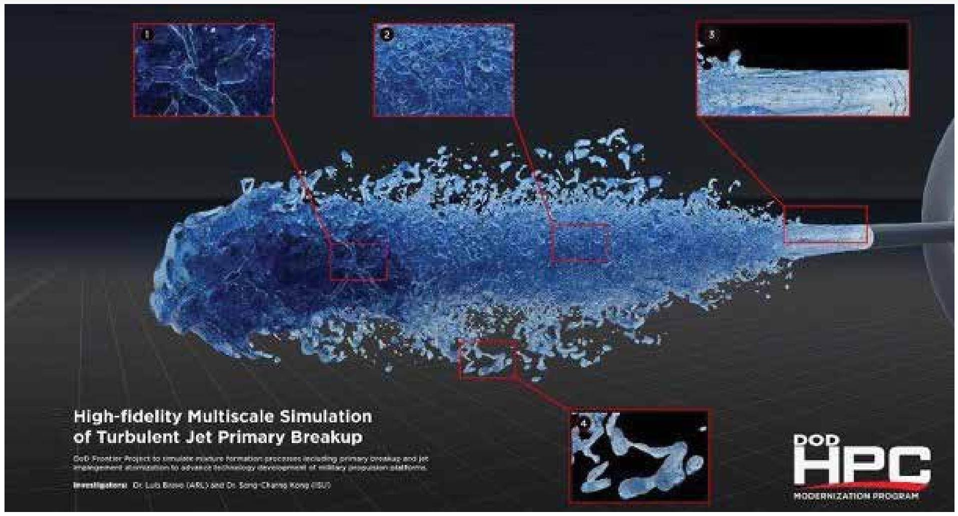

Figure 3: High-Resolution Visualization Using Ray Tracing of Spray Primary Breakup Phenomena From Diesel Injector *(Source: DoD).*

Table 1: Nondimensionless Parameters for Spray Classification

Liquid Reynolds Number:	$Re_l = \frac{\rho_l u_l d_l}{\mu_l}$.	(1)
Liquid Weber Number:	$We_l = \frac{\rho_l u_l^2 d_l}{\sigma}$	(2)
Aerodynamic (Gas) Weber Number:	$We_g = \frac{\rho_g u_{rel}^2 d_l}{\sigma}$	(3)
Ohnesorge Number:	$Oh = \frac{\sqrt{We_l}}{Re_l} = \frac{\mu_l}{\sqrt{\rho_l \sigma d_l}}$	(4)
Cavitation Parameter:	$K = \frac{2(p_l - p_g)}{\rho_l v^2}$	(5)

In primary breakup, the behavior of liquid sheets (or jets) can be classified into different atomization modes, depending on operating conditions. Figure 4 depicts the droplet breakup behavior with increasing Weber number conditions [6]. Earlier investigation of single fluid pressure atomization divided the breakup regimes of a circular liquid jet into three areas, depending on the liquid Reynolds number and the Ohnesorge number [7]. The regimes, which are illustrated in Figure 5, are further described as follows.

1. At low-Reynolds number, the jet disintegrates due to surface tension effects into fairly identical droplet sizes (Rayleigh regime, symmetric, or varicose instability).
2. At intermediate-Reynolds number, drop formation is influenced by aerodynamics forces (nonaxisymmetric Rayleigh breakup). These forces cause symmetric (first wind-induced mode) and asymmetric (second wind-induced mode, asymmetric, or sinusoidal instability) wave growth of gas liquid interface that finally leads to jet disintegrations. This regime is known as the aerodynamic regime.
3. At higher-Reynolds number, the jet disintegrates almost spontaneously at the nozzle exit. This regime is called the atomization regime.

Further, atomization can also be characterized by a jet breakup length where the fuel remains as a continuous

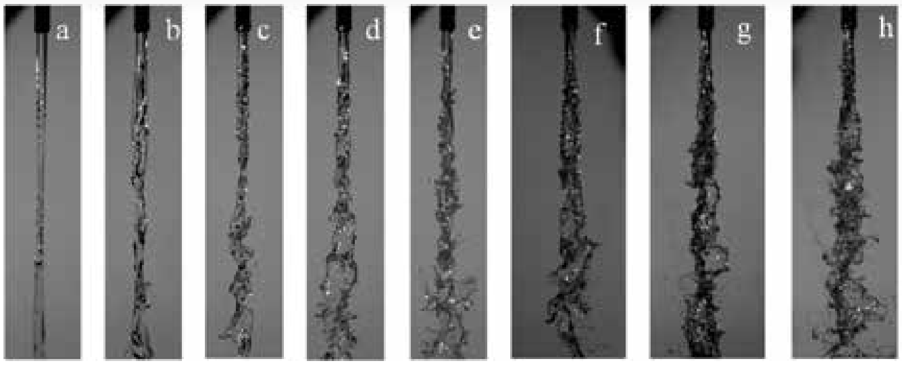

Figure 4: Turbulent Jet Breakup at (a) 6 gpm, (b) 7 gpm, (c) 7.5 gpm, (d) 8 gpm, (e) 8.5 gpm, (f) 9 gpm, (g) 9.5 gpm, and (h) 10 gpm. Corresponding We_g Ranges From 45.47 to 126.31 [6].

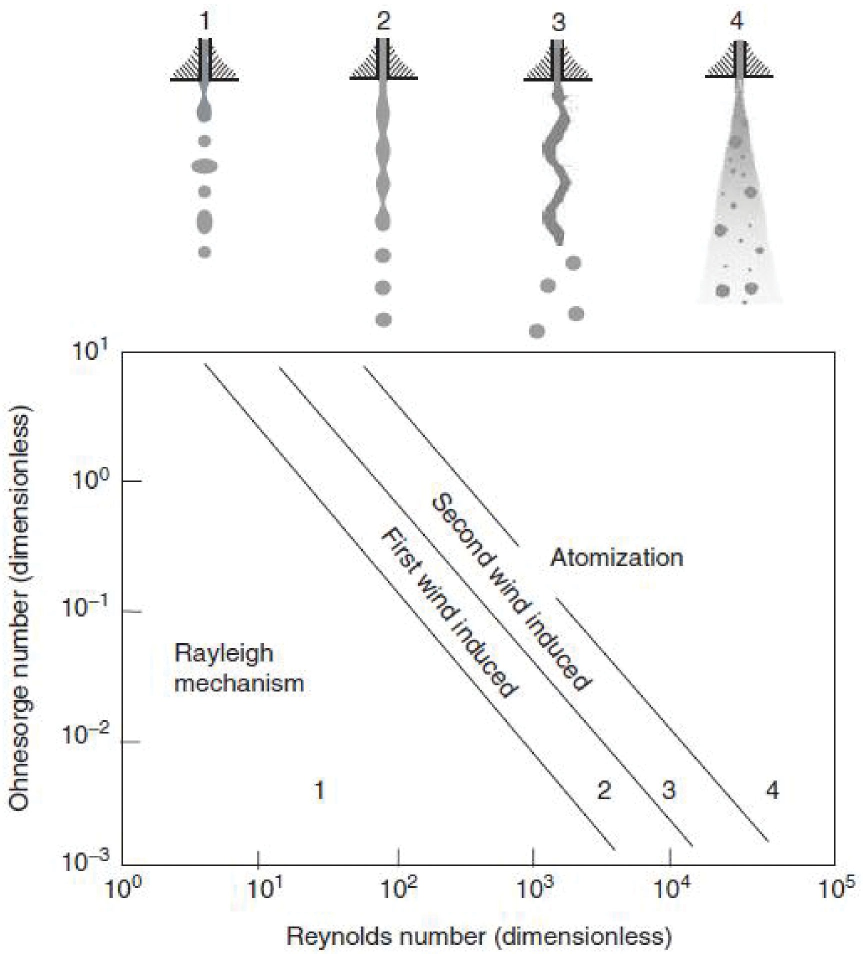

Figure 5: Primary Fragmentation Modes of a Liquid Jet in Pressurized Atomization [7].

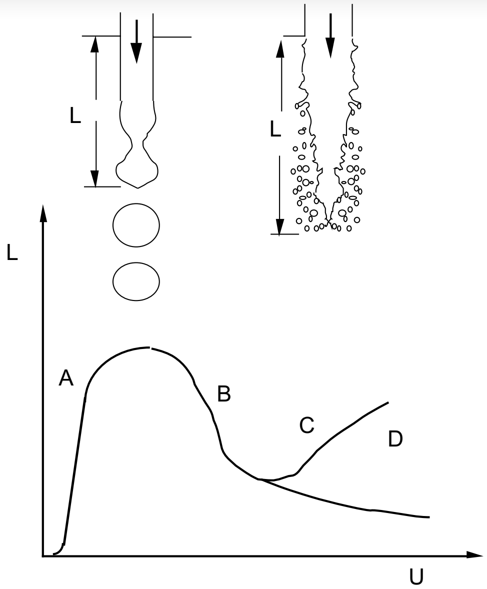

Figure 6: Liquid Jet Length (L) vs. Jet Exit Velocity (U) [8].

medium. It is the distance from the nozzle exit to the breakup point, the general behavior of the breakup length, and its dependence on the jet velocity, as shown in Figure 6.

The initial part of the curve is described as the dripping region of the jet. The laminar flow region is located up to point A, where symmetric Rayleigh instabilities prevail. The upper point B indicates the transition from varicose to sinusoidal breakup mode. The breakup length decreases in the transition region B to C. When the fluid at the nozzle exit is already in a turbulent flow stage, and aerodynamic interaction between the liquid jet and the gas dominates the breakup, the jet breakup length increases with increasing velocity (from point C to D). The behavior of the liquid jet breakup length at jet velocities beyond point D is not uniquely defined yet, but, in general, tends to decrease [9].

RESEARCH MILESTONES

High-Speed Primary Atomization Simulations

The methodology for simulating spray primary breakup is based on the solution of the Navier Stokes Equations (NSE) coupled to a geometric unsplit interface-capturing method for immiscible fluids. The Volume of Fluid (VOF) method ensures discrete conservation of the volume fraction (F) by using nonoverlapping flux polyhedra for donor volumes. The approach also uses piecewise linear interface calculation (PLIC) representation to resolve the sharp liquid/vapor interface. For consistency (and stability), mass and momentum are convected using the geometric VOF method [2–4]. Further, the code is designed for the computations of unstructured mesh-based methods on massively parallel-distributed architectures.

The fuel is delivered into the combustion chamber from a complex injector geometry that accounts for the mini-sac region (0.2 mm^3), needle valve position, and a converging nozzle with a 90-µm orifice. To ensure a high-fidelity model, the diesel injector was characterized via X-ray with a minimum resolution of 5 µm and integrated into the simulation environment. The fuel pressure is specified at 150 bar for a single-component n-dodecane fuel at a peak Reynolds, Weber, and Ohnesorge number of 9,204; 94,737; and 0.03, respectively, which sets the spray near the atomization regime. The physical properties were based on a fuel temperature at 298 K as an approximation to the water-cooled injector jacket temperature in the laboratory.

For reference, the fuel properties for n-dodecane employed are density ρ = 686 kg/m^3, viscosity µ = 0.475 mPa.s, and surface tension σ = 18.6 mN/m. To specify diesel-type conditions, the chamber gas density is set to ρ = 22.8 kg/m^3, by using 100% filled gaseous nitrogen at 303 K and a back-pressure at 20 bar. The simulation initializes with a liquid-filled injector and prescribes a rate-of-injection profile with bulk inflow velocities based from reference measurements. A turbulent inflow generation condition is employed to help capture the transition to internal flow turbulence dynamics. The simulations provide detailed diagnostics in the optically dense region within $0 < x/d < 30$ jet diameters.

In Figure 7, the mixture formation process of n-dodecane spray is presented to examine the effects of start of injection on the spray structure and emerging liquid topological structures. The detailed images show the evolution the transient spray injected into the quiescent chamber environment undergoing atomization. The jet is issued from the complex diesel injector with an experimentally prescribed mass flow rate. The issued spray is influenced by the rapid internal flow transients, and externally by the aerodynamic interactions through various fragmentation regimes. The formation of azimuthal surface instabilities is indicated by the Rayleigh-type behavior at the spray tip. The instability growth-rate continues then forming crowns and ligaments that turn into the surrounding drops. Figure 7 shows various ligament structures at the periphery of the spray that grow, convect downstream, and break up into primary droplets.

The numerical research has also revealed that the instability of the liquid jet is highly sensitive to velocity profiles and turbulence levels at the nozzle exit when the liquid jet transitions to turbulence. The sinuous breakup modes in the transitional flow were numerically confirmed, as observed in the experiment (Figure 8).

Further, an important 2016 research milestone involved the quantification via Direct Numerical Simulation (DNS) of the spray formation process using two jet-propellant fuels provided by the Federal Aviation Administration (FAA) National Jet Fuel Combustion Program. The model captured for the first time the complex liquid structures, including helical waves, ligaments, surface holes that lead to droplet generation, and turbulence interactions in an engine environment. The DNS study was validated against X-ray radiography measurements of spray density fields for two fuels, including an average properties jet-propellant (A2) and a high-viscosity alternative jet fuel (C3). The

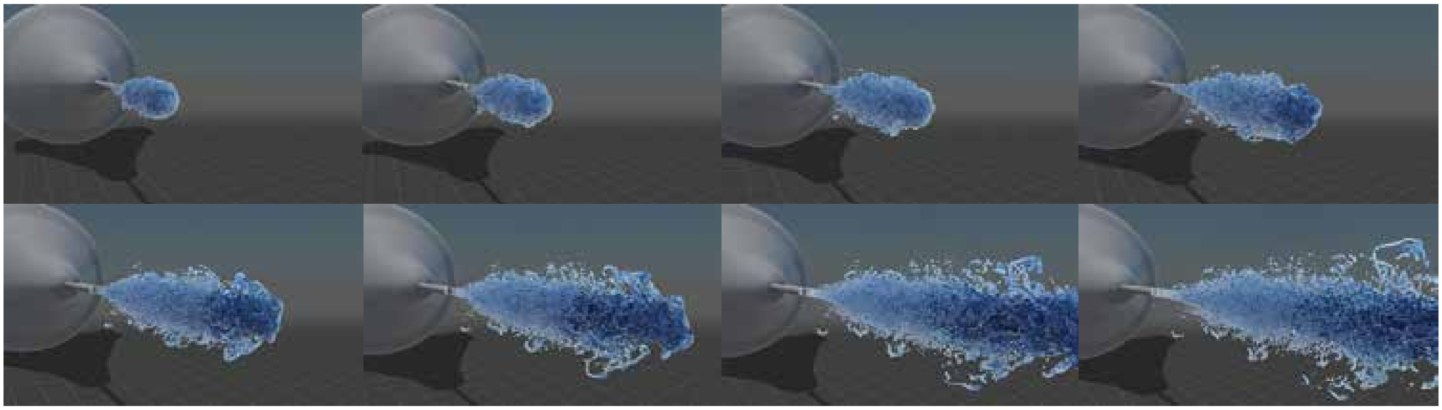

Figure 7: Transient Development of n-Dodecane Jet (150 bar) Showing Start-of-Injection Effects and Highlighting Ligament Formation and Breakup Process. Images From 0.11 to 0.18 ms at 0.01-ms Time Interval.

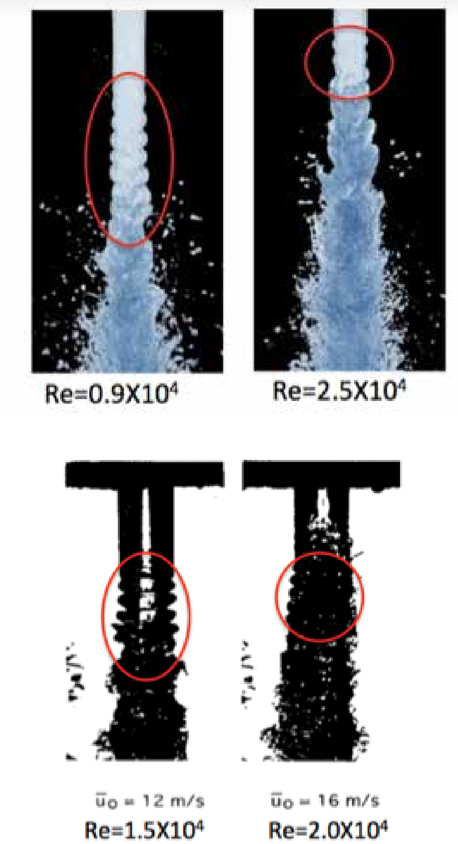

Figure 8: Sinous Mode Instabilities Confirmed Between Simulations (top) and Experiments (bottom) [10].

high-viscosity C3 fuel showed improved atomization quality and faster penetration speeds by 5%. In addition, as shown in Figures 9 and 10, the penetration speeds and transverse fuel mass distributions are in good agreement with the experimental measurements from Argonne National Laboratory using X-ray radiography [11].

The computational expense of resolving all the critical length scales at large Weber numbers is prohibitively high, so the number of detailed numerical simulations conducted at realistic conditions has been limited. Note, a liquid jet moving at 100 m/s relative velocity with respect to the quiescent gas can generate droplets with diameters as small as a few micrometers. Predictions employing interface-capturing methods and discrete approaches are crucial for research purposes but have a high computational demand. To model the range of spatial scales present, spanning more than six orders of magnitude, requires computer codes that can exploit massively parallel architectures, as well as millions of CPU hours to describe the physics.

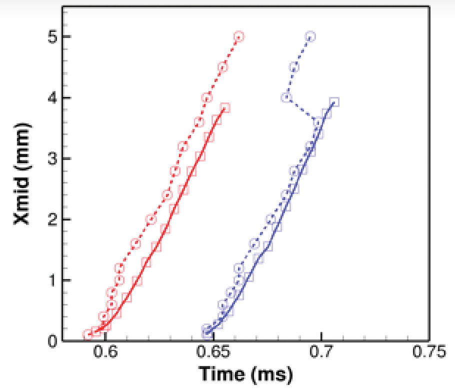

Figure 9: Liquid Jet Penetration for CAT A2 (Red) and C3 (Blue) Fuels With Experimental Measurements (Dotted Line).

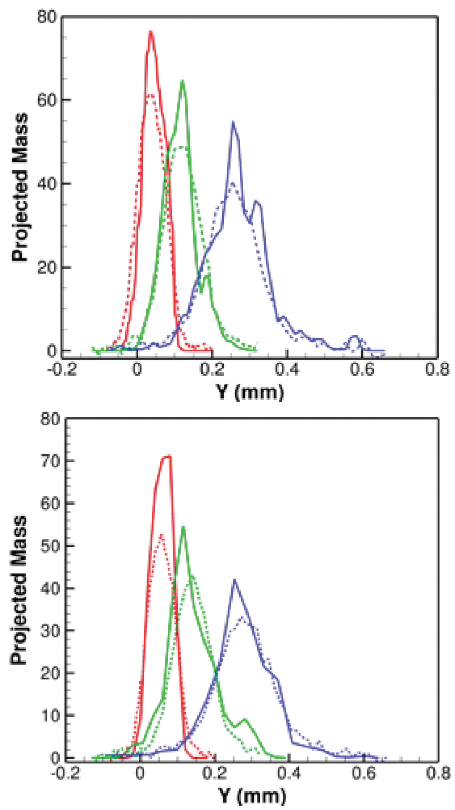

Figure 10: Transverse Liquid Mass Density Distributions (micro-gram/mm^2) on the Projected Plane for Three Different Axial Positions From the Nozzle (red=0.44 mm, green=1.0 mm, blue=2.0 mm) With the Experimental Measurements (Dotted Line): CAT A2 (top); CAT C3 (bottom).

Figure 11 shows the current scalability of ARL's code (originally developed by Cascade Technologies) and its performance on ARL's Excalibur High-Performance Computing (HPC) system. The code is able to compute at 76% efficiency even at 1,500 control-volumes/core and was tested at a maximum of 48,000 cores.

Droplet Impingement Simulations

In simulating the physics of an impinging jet, a methodology based on smoothed particle hydrodynamics (SPH) is employed. In SPH, a field function (e.g., fluid property) is described by the integral representation method, which is reformulated based on the use of computational particles. The drop, surrounding gas, and the solid wall are discretized into free-moving and/or fixed particles. As a result, it becomes straightforward to track drop deformation and the interface of the liquid and gas. The governing equations to describe the fluid motion are discretized into the particle space, instead of the grid space that is used in conventional computational fluid dynamics. As a result, SPH has the advantage of reproducing drop deformation and incorporating the drop properties and wall conditions easily [12].

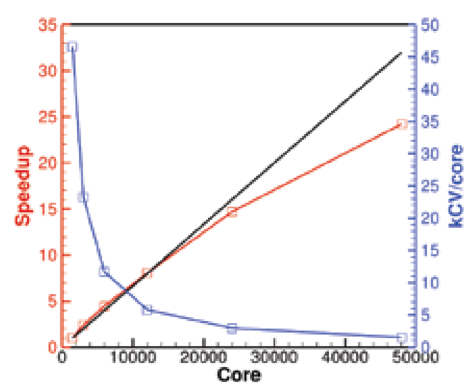

Figure 11: Scalability Study of Multiphase Weakly Compressible Code With a Performance of 76% Efficiency With 1,500 Control-Volumes/Core; Maximum Test at 48,000 Cores.

The numerical simulation of an impinging jet is accomplished by accurately predicting the details of drop-wall interactions. In a diesel engine, the size of a typical fuel drop can be from 50 to 100 μm during wall impingement, with a velocity of approximately 50 to 100 m/s. It is anticipated that a drop will be discretized by a few thousand SPH particles. The size of a numerical SPH particle can be 2.5 to 5 μm in diameter, which is the resolution of the computational domain inside and surrounding the drop. At such a small scale, the liquid-gas interface can be resolved in detail. Moreover, the surrounding gas phase can also be resolved with high levels of detail, similar to those employed in typical DNS for flow simulation.

Figure 12 shows a sequence of predicted images during a drop impacting a liquid film. A series of diesel drops impacts the wet piston surface at a 45° angle. The initial drop diameter is 100 μm with a velocity of 50 m/s. The "red" liquid is the liquid originally contained in the drop; the "blue" liquid is the liquid originally in the wall film. We can see that the inner part of the crown is composed of the liquid from the drop. The leading drop impinges on the piston surface and creates a liquid film at a 45° angle. The subsequent drops impact the film, causing the film to spread and generate liquid ligaments and secondary droplets. These ligaments can further form droplets as time progresses. In a combustion engine, the gas flow will alter the trajectory of fuel drops, ligaments, and secondary droplets. The high-temperature gas and wall in the combustion chamber will also cause the liquid drops and wall films to vaporize and create combustible mixtures. These phenomena require further investigation by coupling the present numerical method with advanced physical models.

Supercritical Sprays

As propulsion engine designs continue to push toward extreme conditions, the need for high-fidelity computer models that can describe transcritical to supercritical sprays is clearly needed. The nature of flows in a diesel injection process has motivated several recent studies to use the diffused interface method for the modeling of the injection sequence. In contrast to a sharp interface method, such as a volume-of-fluid method, where interfaces are explicitly tracked or resolved, the diffused interface method artificially diffuses the interfaces. This approach is particularly attractive for transcritical flows where interfaces are not present. However, it remains an open research question whether interfacial flows or droplets exist under conditions relevant to real applications [13].

Associated with the transcritical conditions are large thermodynamic gradients as the fluid undergoes mixing and possibly phase transitions. Accurately simulating these real-fluid environments remains a challenge. Here, a result from a diffused interface method is presented for the modeling of the fuel injection process under conditions relevant to high-pressure diesel engines. Compressible multi-species conservation equations are solved in conjunction with the Peng-Robinson state equation and real-fluid transport properties [14, 15].

In this study, a case denoted "Spray A" is considered, representing a benchmark target of the Engine Combustion Network. The single-hole diesel injection is operated with pure n-dodecane at a rail pressure of 1,500 bar. Liquid n-dodecane fuel is injected at 363 K through a nozzle with a diameter of 0.09 mm into a 900 K ambient environment at a pressure of 60 bar. The nonreacting case is considered, with the ambient gas consisting of pure nitrogen. At these conditions, the liquid n-dodecane undergoes a transcritical injection, where the liquid fuel is heated and mixes with the ambient gaseous environment. Fuel mass flux and temperature are prescribed at the injector nozzle using the time-dependent rate of injection modeled using the virtual injection rate generator

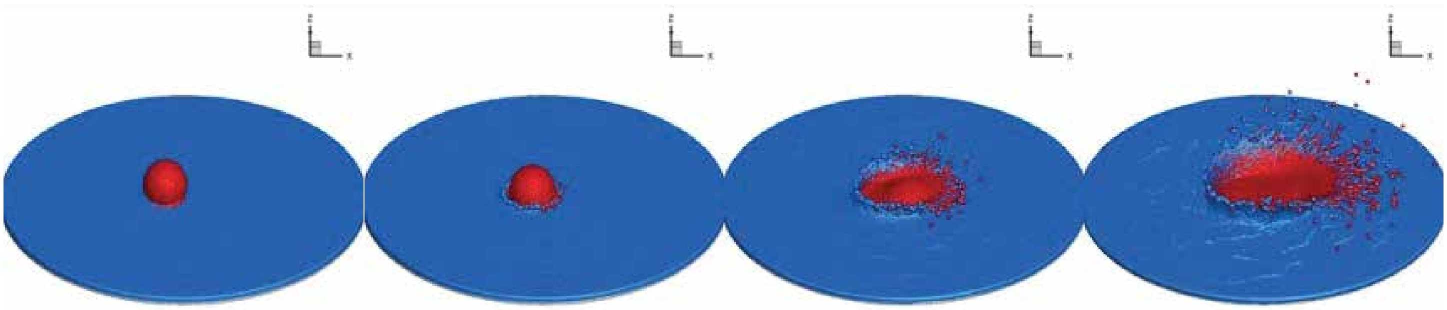

Figure 12: Typical Fuel Drop (Red) Impinging on Liquid Film (Blue) at a 45° Angle and Resulting in Crown Formation, Including Fuel Drops, Ligaments, and Secondary Droplets.

[16], recommended with default input parameters for the Spray A case (i.e., 1500-bar injection pressure, 60-bar back-pressure, 0.0894-mm outlet diameter, 0.90 discharge coefficient, 713.13-kg/m^3 fuel density, and 1.50-ms injection time).

The liquid and vapor penetration lengths are extracted from the simulation results using a threshold value of 0.6 and 0.01, respectively, for the fuel mass fraction. The results up to 1 ms after injection are shown in Figure 13. The experimental vapor penetration length determined from Schlieren imaging and liquid penetration length from Mie scattering [17] are also shown for comparison. It can be seen that, for the vapor penetration, an excellent agreement with measurements is obtained.

The flow structures and mixing behaviors of the injection process further downstream are compared to the measurements of mixture fraction by Rayleigh scattering. Multiple injections in the experiments provide ensemble-averaged statistics. In the simulation, the statistics of the steady period of injection are obtained by temporally averaging between 0.6 ms and 1.2 ms after the injection. Figure 14 shows a comparison of the radial mixture fraction distribution at two different axial locations (x = 25, and 35 mm). As can be seen, there is a good agreement in the mean values of the mixture fraction at all three locations, while the simulation predicts slightly higher rms values compared to the experimental data. These results, along with the excellent agreement of the vapor penetration length as presented, show that the current numerical method is capable of predicting that the turbulent mixing process between fuel and the surrounding environment downstream of the injector after the dense liquid fuel is fully disintegrated.

Observed differences in the flow-field behavior near the injector require further investigations both numerically and experimentally.

FUTURE PERSPECTIVE AND NEEDS

In light of the previously described advancements being made in the Frontier project at ARL's VTD, engine spray models have the opportunity to further enhance the capability to address existing technical knowledge gaps. Specific areas in which the models are expected and recommended to improve include the following:

1. The ability to accurately describe the entire spray process, including the primary breakup dense, dilute region, and droplet-film region.
2. The ability to describe the subgrid-scale models for multiphase flows and develop reduced models for the droplet formation process.
3. The ability to couple molecular dynamics and continuum methods to improve the fidelity of equations of states for complex fluids and thermodynamics.
4. The ability to capture the effects of injector nozzle turbulence and its mutual interaction with cavitation phenomena from first principles.
5. The ability to describe the effects of an electrical field or charge, which is important for engineering-level electrostatic spray applications.
6. The development of on-the-fly reduced-order models (low-dimensional manifolds) that can serve as surrogate models and be used for transition and concept design purposes.
7. The ability to develop Uncertainty Quantification methods and tools for ensemble visualization to address wide variability in model physical properties. ■

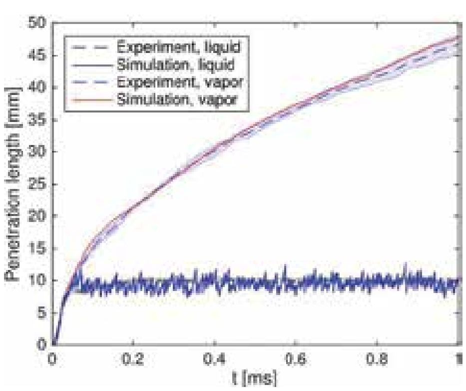

Figure 13: Liquid and Vapor Penetration Lengths Predicted in Comparison With Experimental Data [15].

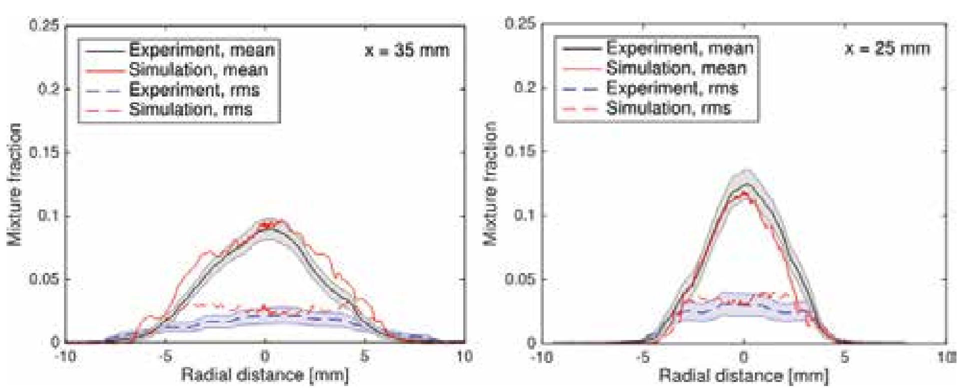

Figure 14: Radial Profiles of Mean and rms Values of Mixture Fraction at Two Different Axial Locations in Comparison With the Experimental Data Measured by Rayleigh Scattering [15].

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BIOGRAPHY

LUIS BRAVO is a mechanical engineer at ARL's VTD, leading several DoD efforts in partnership with academia, industry, and cross-service agencies that span basic/applied research in propulsion and computational sciences. Dr. Bravo is a senior member of the American Institute of Aeronautics and Astronautics and is also the Chair of Modeling & Simulation of the Propulsion System Alliance, fostering collaborations between government agencies in propulsion sciences. Dr. Bravo also serves as a subject-matter expert for the Army Research Office and the Office of Naval Research, as well as external programs, including the NASA Transformational Tools and Technologies and the National Jet Fuel Combustion Program. In addition, he is the lead of the DoD HPCMP Frontier project, developing revolutionary concepts in multi-physics sprays for propulsion systems. Dr. Bravo holds a B.S., M.S., and Ph.D. in mechanical engineering from the City University of New York (CUNY) City College, the CUNY Graduate Center, and the University of Maryland, respectively.

DOKYUN KIM leads the research team on multiphase flows at Cascade Technologies, where he works to develop efficient high-fidelity tools for liquid-fuel injection in combustion devices. Previously, he worked at Stanford University's Center for Turbulence Research. He developed, with Dr. Frank Ham, the novel unsplit geometric volume-of-fluid method, which enables exact mass conservation on unstructured grids for the first time. He has also served as the principal investigator for several DoD and Department of Energy (DoE)-funded projects on turbulent multiphase flows. Dr. Kim holds a Ph.D. from Stanford University, where he was involved in numerical simulations of liquid atomization in combustion devices.

MATTHIAS IHME is currently an Associate Professor at the Center for Turbulence Research in Stanford University's Department of Mechanical Engineering. His research interests include the computational modeling of reacting and high-pressure flows, the development of high-order numerical methods, and the investigation of advanced combustion concepts. Previously, he served on the faculty of the University of Michigan's Aerospace Engineering Department. He is a recipient of the National Science Foundation's Faculty Early Career Development (CAREER) Award, the Office of Naval Research's Young Investigator Award, the Air Force Office of Scientific Research's Young Investigator Award, and the NASA Early Career Faculty Award. Dr. Ihme holds B.S. and Ph.D. degrees in mechanical engineering, as well as an M.S. in computational engineering.

CONFERENCES AND SYMPOSIA

NOVEMBER 2017

54th Annual AOC International Symposium and Convention
28–30 November 2017
Marriott Marquis and Walter E. Washington Convention Center
Washington, DC
https://www.crows.org/conventions/2017.html

DECEMBER 2017

Defense Manufacturing Conference (DMC) 2017
4–7 December 2017
Tampa Convention Center
Tampa, FL
http://www.dmcmeeting.com/index.html ▸

Hacking the Human Element
1–3 December 2017
SOFWERX
Tampa, FL
https://www.sofwerx.org/hackingthehumanelement/ ▸

Winter Simulation Conference
3–6 December 2017
Red Rock Casino Resort & Spa
Las Vegas, NV
http://meetings2.informs.org/wordpress/wsc2017/ ▸

JANUARY 2018

Army Autonomous Systems Symposium & Exposition
1–2 January 2018
Detroit Marriott at the Renaissance Center Detroit, MI
https://www.ausa.org/autonomous ▸

AIAA SciTech Forum
8–12 January 2018
Gaylord Palms
Kissimmee, FL
http://scitech.aiaa.org/ ▸

ITEA Engineering Workshop and DEPS Directed Energy T&E Conference
16–18 January 2018
Sheraton Uptown
Albuquerque, NM
https://protected.networkshosting.com/depsor/DEPSpages/DETEconf18.html ▸

2018 High Temple Workshop
29 January to 1 February 2018
Renaissance Palm Springs Hotel
Palm Springs, CA
https://hightemple.udri.udayton.edu/ ▸

For more events, visit:
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