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## U.S. MILITARY EYEING FUTURISTIC

# HOVERBIKE TECHNOLOGY

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*Tethered Test Flight of Malloy Aeronautics P1 Hoverbike Prototype (Computer-Generated Background).*

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# MESSAGE FROM THE EDITOR

**ERIC FIORE**

Oscar Wilde once opined that "life imitates art far more than art imitates life." And if one needed further convincing, he need look no further than the "technical" art of Leonardo Da Vinci. How many of Da Vinci's fanciful designs, which probably seemed preposterous at the time, are part of our everyday life today? And in this age of rapid innovation, the notion that something can come into fruition in the real world that was inspired by creative speculative work only decades earlier is becoming a much more common occurrence. In this issue of the *DSIAC Journal*, we discuss several such technologies that are at the forefront of the latest technological renaissance.

From "Avatar" to "Star Wars," the concept of a terrestrial craft that can simply hover above the ground is commonly written into virtually every fictional action scene. However, as authors Mark Butkiewicz and Chris Malloy discuss in our feature article on a new futuristic hoverbike, such technology is no longer relegated to science fiction. And since this technology can be used with either an operator or autonomously, it holds great promise as a new mode of transportation. The convergence of the new disruptive technologies that make the hoverbike possible will likely one day usher in a revolution in transportation that will be as disruptive to the transportation industry as mobile phones have been to communication.

In Greg Robinson's article on digital technologies and rapid prototyping, he discusses how the current digital revolution, which is affecting almost every aspect of our lives, is also changing how we manufacture everyday items. Many of the changes, such as our latest mobile phones and the emergence of driverless cars, are popular examples. However, other changes that are much less visible are just as important and are having a profound impact on product development. In particular is the emergence and popularity of digital three-dimensional (3-D) technologies, such as computer-generated solid models and additive manufacturing (3-D printing) techniques, which have greatly expedited the preparation of prototypes. While subtractive manufacturing techniques, such as computer numerical control (CNC) milling and laser cutting, have made prototype generation faster and less expensive, advances in these technologies are not receiving as much recent attention as additive manufacturing. But improvements in both of these technology areas are providing the ability to produce multiple iterations of cost-effective prototypes, which in turn has facilitated the development of exquisitely optimized manufacturing designs. And the solid models that results from these designs are the beginnings of a "digital thread" that will provide an entire product's life cycle from conception to design, manufacturing, and sustainment in a model-based engineering process that is increasingly being adopted by many DoD and related organizations.

Advances in materials are not only being developed to invent new technologies; they are also being developed to help restore people as well. Jake Montez presents an account of a future wounded warrior as he discusses the emerging new technologies that are becoming available to save lives and restore human operability. Additionally, a companion article traces the fictional path of a future warrior's combat injury and treatment, including how additional advances in medical technology will be used to repair recoverable injuries and replace limbs that are not recoverable.

While advanced materials continue to demonstrate improved performance with reduced weight, dismounted Warfighters are considerably less effective when saddled with 190-lb loads and excessive power requirements for their equipment. Capt. Anthony Ripley's article on load lightening discusses how the Army is addressing current material and power limitations with a novel Soldier as a System (SaaS) concept. This systems engineering approach ensures that several critical requirements be considered, such as the maximum weight an individual through a company (as a system) can carry, as well as individual- to aggregate-unit-level power requirements.

Finally, the article by Patrick Filbert on penetrating the ever-increasing defensive perimeters of our adversaries, also known as the anti-access/area denial (A2/AD) environment, discusses research and development efforts to plan, integrate, and synchronize the effects that can be delivered by unmanned aerial swarms. The article further discusses how recent and future test events will be used to refine the concept of employment, which is critical for the development of requirements and Joint force integration capability. This new technology is critical for shaping fourth- and fifth-generation strike platforms. ■

# ADVANCES IN COMBAT CASUALTY CARE

## FOR THE WOUNDED WARRIOR

By Jake Montez

With recent advances in medical technology and combat casualty care, today's wounded warrior (such as the one discussed in the companion article, "An Account of a Future Wounded Warrior," on page 5) is being supported with state-of-the-art treatment materials and techniques never before seen. As a result, critical injuries can be repaired more rapidly; nonrecoverable limbs can be replaced more effectively; and lives can be saved more often. In this article, we examine some of the major technologies that are expected to help make these improved outcomes possible.

## MEDICAL MATERIALS AND WOUND CARE

Simply put, the battlefield is an extremely dangerous place. Many sharp edges moving at high velocity and expansive projectiles moving at even higher velocities represent a tremendous danger to the Warfighter. Likewise, concussive waves and effects from exploded ordnance can significantly minimize or negate the protection afforded by the use of body armor. Traditionally, a Warfighter coming in contact with these combat threats has meant that, at best, medical teams were likely going to have their hands full and, at worst, there was a strong possibility of losing valued combat personnel.

Fortunately, solutions are becoming available to counteract these injury scenarios to the Warfighter, both in the near term and future. In the areas of both internal and external hemorrhaging, several unique materials and techniques are emerging to help sustain a Warfighter against his/her wounds. As discussed in the sections that follow, these include expansive medical foams, doped primary care (DPC) wound dressings, and hydrogel scaffolds.

### *Expansive Medical Foams*

Consider the age-old elementary school science project: the volcano. When certain measures of vinegar and baking soda are combined, the material expands for a brief period of time as gas and bubbles. Via a similar principle, foam is simply that reaction with a suspender added so as to retain structure. Similarly, consider the behavior of a two-part epoxy system, which is typically used in adhesion processes. Two separate materials, when combined, produce a new material that solidifies. When combining the properties of foam generation, two-part epoxy systems, and biomedical application, the result is expansive medical foam (as shown in Figure 1). These foams are intended to be hemostatic in nature, meaning that their purpose is to stop the bleeding as quickly as possible. Their component structures must therefore be

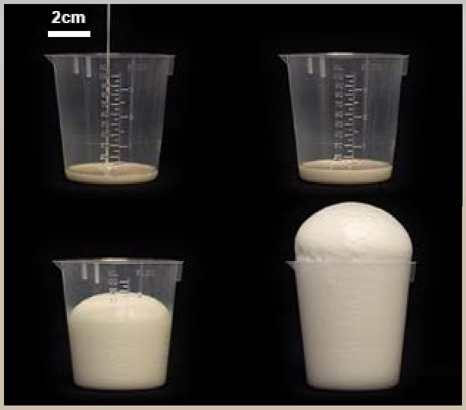

Figure 1: Example Foam Volume Expansion.

biocompatible and reduce the lethality of a severe internal bleed.

Through a Defense Advanced Research Projects Agency (DARPA) grant, the Massachusetts-based company Arsenal Medical has developed and tested an internal hemostatic foam compound based on polyol and isocyanate (common materials in electrospinning processes). The foam is injected percutaneously as a two-part mixture to create, within the abdominal cavity, a self-expanding hemostatic polyurethane foam for far-forward hemorrhage control.

In massive noncompressive bleeding testing, the results of this applied foam increased the 3-hr survival percentage nearly tenfold. Likewise, the mean survival time was increased from less than 1 hr with high variability to more than 3 hr with a smaller variability. This result means that sustained internal bleeding could be kept at bay for more than 3 hr before a surgical team is able to repair the lacerations causing the bleed. Accordingly, expansive foam is a solution that could have life-or-death implications on the battlefield.

While larger companies such as Johnson-Johnson and 3M have also begun to explore the possibility of hemostatic foams, practically no competition exists on a research basis for the work that Arsenal has successfully demonstrated. Accordingly, the company recently debuted a spinoff company, 480 Biomedical, to focus exclusively on the development of hydrogel scaffolds for the treatment of occluding diseases in the femoral artery.

### *DPC Dressings and Hydrogel Scaffolds*

DPC wound dressings are essentially specialized fiber dressings embedded at the nano-scale with chemicals to assist with assorted mechanisms of drug delivery. Applying such a bandage to a surface wound on a Warfighter can have multiple effects: it can draw out bacteria from a wound, act as a hemostatic agent (with no pressure required) (as illustrated in Figure 2), and deliver critical drugs transdermally without the presence of a wound. These unique effects and mechanisms are generated from fibers that are electrospun.

Electrospinning a fiber is the mechanism by which a polymer-laden fluid can be electrically excited into depositing itself in an extremely thin stream down to a ground plate. Upon reaching the plate, the fiber's solvent will have evaporated,

Figure 2: DPC Bandage Clotting Blood Through Ionic Interaction.

## AN ACCOUNT OF A FUTURE WOUNDED WARRIOR

**By Jake Montez**

To understand the techno-zeitgeist of combat casualty care, consider the fictional story of a soldier named Bob. On orders to patrol a nearby hot zone, Bob's platoon mounts up in a convoy of patrol vehicles and departs the base. As the convoy patrols the hostile neighborhood, Bob is jolted by a sudden chest-crushing blast of air and heat. With ringing ears and burning lungs, Bob begins to understand the gravity of his situation: he is seriously injured, and his life is in great danger. His vehicle was just struck by a roadside bomb, and shrapnel from the blast has left him in terrible condition. Many possibilities exist at this point in Bob's story, and they are all related to his future health.

The immediate prognosis suggests that Bob will require multiple amputations due to severe burns and tissue damage. He is also hemorrhaging in multiple locations and has a high risk of infection. Bob is quickly evacuated from the front line and is transported to the nearest field surgical office. En route, field medics assess that Bob has suffered third-degree burns across his left arm and massive tissue damage on his right leg. Preliminary visual observations also indicate the presence of shrapnel in the chest cavity and multiple lacerations on the face, arms, and legs. Internal organ damage is also diagnosed because of the location and severity of the chest injuries. Bob's life is now in the hands of field medics armed with new tools at the cutting edge of life preservation.

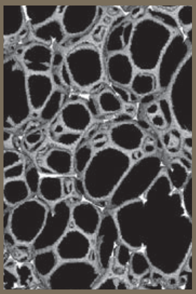

Figure 1: X-Ray Tomography Image of Open Cell Polyurethane Foam.

Bob is bleeding out, and the field medics know that chest cavity hemorrhaging is the greatest threat to his life at this moment [1]. An incision beneath his solar plexus is made, and inserted in that interstice is a cutting-edge technology that can be applied in the field: expansive medical foam. As illustrated in Figure 1, this biocompatible foam expands as two polymeric components mix together, much like a two-part epoxy. The foam expands around all of the organic tissue crevices and seals all lacerations shut in less than 10 s. In less than a minute, the greatest threat to Bob's life has been mitigated, and he is no longer suffering from internal hemorrhaging in the chest cavity. The same technology is applied to his heavily damaged leg to stop arterial bleeding by simply applying the foam at the site of injury.

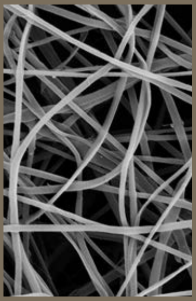

Figure 2: Scanning Electron Micrograph of Electrospun Chitosan Fibers.

Now that the majority of hemorrhages have been addressed, the medics can move along to addressing his superficial wounds. Due to the presence of foreign material in these wounds, they are first rinsed with saline. The medics notice, as a consequence of Bob's trauma, that his blood is not sufficiently clotting and he is continuing to lose blood through the multiple surface lacerations [2]. Because he is bleeding from multiple locations, simple compression treatment is not feasible. However, another new technology, pictured in Figure 2, is available: doped primary bandages. These bandages and what is left is a woven fabric imbued with chemical structures within the fibers at the nano-scale. The surface-to-volume ratio on such fibers is absolutely unmatched anywhere in metallurgical or other material pursuits, allowing for highly unique effects on human tissue interaction.

As illustrated in Figure 3, a basic electrospin system consists of an electrical power supply, a needle syringe, a ground plate, and a pump of some kind. A high voltage potential (on the order of several kilovolts) is applied to the needle syringe, and the plate below the syringe is grounded in a preconceived manner. As solution is pumped into the syringe, the voltage potential separating the air gap between the syringe tip and ground causes a droplet to gradually lose its surface tension. As a result of this loss, an extremely thin stream of solution will begin to flow from this droplet, called a Taylor Cone, down to the base plate. The manner in which this solution meets the ground contacts can be controlled by a computer, with several grounds being connected into the circuit at different locations at different times. This will control the weave of the electrospun fiber.

The contents of solution that are deposited onto the ground plate are myriad in variety; however, developing new solutions also brings with it some characterization problems. Finding the correct voltage and Taylor Cone geometry requires extensive in-lab testing, usually on a trial-and-error basis. Research has led to several well-observed solutions and solvents that behave predictably in the high-voltage potential environment and that are thus prime candidates for DPC wound dressings

Most promising on this front are chitosan-doped fibers. Chitosan is a peculiar element in that is derived from an unlikely source: crustaceans. When shrimp/crab shells are mixed with sodium hydroxide (in excess with water as a solvent), the resulting product is chitosan. Two of the most useful properties of chitosan are its ability to act as a hemostatic agent and as an antibacterial compound. Chemically, what also makes chitosan attractive as a delivery agent is that, after interaction with the sodium hydroxide, its polymeric structure becomes protonated. This quality delivers the advantage of water solubility and strong binding

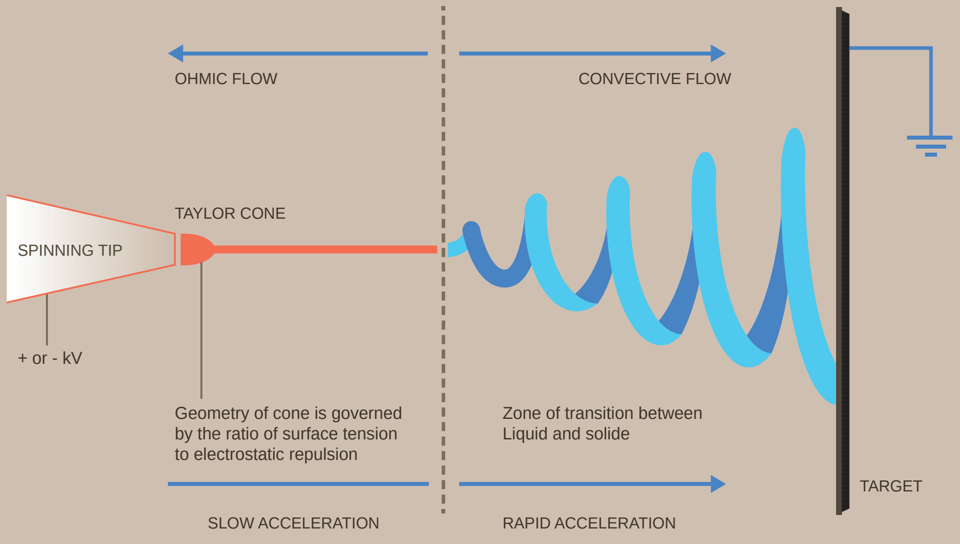

Figure 3: Electrospin Process.

to negatively charge surfaces (e.g., mucosal membranes). Thus, chitosan simultaneously functions as a highly efficient hemostatic agent, antibacterial, and drug delivery system [1].

That said, chitosan-doped fibers on their own are not quite enough to provide an advanced wound care package. Difficulties arise in scaling up the thickness of electrospun chitosan-doped fibers due to the electrospin process itself. At approximately 200 μm (in the vertical direction) from the ground plate, fiber flow becomes unpredictable and no longer adheres to itself. It is believed through observation that this negative side effect is caused by the distance from the ground plate. To counteract this effect, a hydrogel (scaffolding agent) can be used to separate layers and continue the thickness growth process.

This extensional growth process begins to cross over into the territory of tissue engineering, as the scaffolding principles with hydrogels are the same [1]. However, in lieu of printing cellular material, the doped fibers of the electrospin process are captured within the hydrogel scaffolding (as shown in Figures 4 and 5). This technique's yield can then be applied as a wound dressing. Now there exists DPC wound dressing capable of stopping traumatic blood flow, disinfection, and drug delivery simultaneously.

Unfortunately, electrospinning is not yet performed outside of research labs. While basic electrospin equipment is not inherently expensive, the parameters to generate predictable fiber behavior at an industrial level have not been realized. Research groups are currently investing in methods and equipment to scale up electrospun fiber packages using such items as a barrel mandrel to create a wave in the solvent (multiple Taylor Cones for drawing), parallel needle assemblies with multiple ground plates on the same platform, and hybridized hydrogel-chitosan fiber scaffolding techniques borrowed from tissue engineering.

Much of the research efforts developed in the electrospun fiber regime are typically conducted by universities or military labs. Consequently, it can be interpreted that DPC dressings are not yet ready to be integrated into the military supply chain on a large scale. The 3M company produces a hybrid electrospun fabric tradenamed Tegaderm, along with a line of other wound care products made from various materials, such as acrylic, alginate, hydrocolloid, hydrogel, and silver colloids.

## PORTABLE STERILIZATION

When discussing sterilization of medical devices, there are two parameters that are of utmost importance: decimal

Figure 4 (top): Electrospun Hydrogel/Tissue Scaffold.
Figure 5 (bottom): Tissue Engineered Heart Valve.

simultaneously draw out bacteria present in the wound and deposit chemicals that cause the wound to clot much more quickly than compression bandages alone [3]. Bob is now sustained until he reaches a forward operating hospital.

Meanwhile, at the forward operating hospital, the surgical staff is informed of Bob's current condition: stable but with a number of lacerations, severe burns, and a possible amputation scenario. The staff consults its bioprinting lab for stored bone and tissue grafts (an example of which is pictured in Figure 3) that were generated at an earlier time in Bob's service. When Bob arrives, the triage staff immediately begins work on him. The medical foam and doped bandages have done their job; both internal and external bleeding was contained, and hemostasis has been achieved. Unfortunately, after further examination the medical staff determine his arm and leg are too severely damaged and need to be amputated. To make matters worse, it has been a busy day for the triage staff, and surgical tools they require for the procedure have been contaminated. Fortunately, a field sterilization kit is available to provide a solution to the sterilization problem. Within minutes, the surgical tools have been sterilized without the necessity for an autoclave. The emergency surgery goes well, and Bob is implanted with bioprinted grafts to provide a robust limb terminus with a

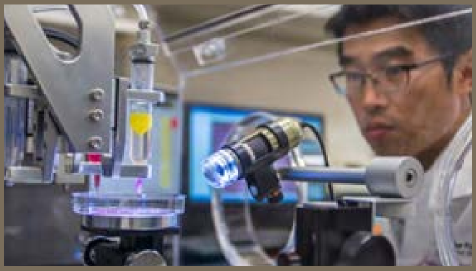

Figure 3: Dr. Y. J. Seol Constructs Muscle Tissue for Reconstructive Surgery [4].

rounded bone structure that should not require additional surgeries to correct bone malformations later. Other second-degree and third-degree burns are grafted with synthetic materials fabricated in the Bio-Lab [5]. And the healing process has begun. Bob is flown to the Walter Reed National Military Medical Center in the United States for recovery, prosthetic fitting, and physical therapy.

Bob wakes up in a place he doesn't recognize. He is two limbs short of his last recollection, and everything is a blur. He has no idea how he got where he is and remembers only his ears ringing and the heat in his lungs. He looks over his body and sees strange patterns of raised skin. In some places, he finds raised checkerboard-like ridges; in others, he finds zigzags. Otherwise, it appears superficially that all is well. Nothing feels tender, only strange—lighter. A physician appears and informs him of all that has transpired and how well he has recovered considering the extent of his injuries. The physician continues by reassuring him that advanced prosthetics, in conjunction with an aggressive physical theory regiment, will have him using a "new" hand, such as the arm/hand pictured in Figure 4, and walking again in no time.

Bob is eventually fitted with a computer-controlled ankle, which allows multi-degree-of-freedom operation and enables him to run and perform callisthenic exercises with great dexterity. His

Figure 4: DEKA Advanced Prosthetic Arm.

reduction time (D-value) and the sterility assurance level (SAL). The former is an indication of the degree of sterilization expressed by multiples of the D-value, denoting the time needed to reduce the initial number of microorganisms to 1/10th of their original values. It is a common marker in microbiology for indicating effectiveness of an antibacterial method. The SAL value represents the probability of a single unit being nonsterile after it has been subjected to some sterilization process. Typically, the SAL value is represented as $10^{-X}$, where X is some integer magnitude to express the probability. The value is verbalized as "log-reduction of" X, implying that the method has been successful at reducing the nonsterilization probability to one Xth of its original value.

With that in mind, we can begin to quantify the methods of sterilization, the most common of which apply the following modalities: heat, chemical, radiation, filtration, pressure, and sonication. As there is interest in the portable aspect of sterilization, a few of these methods may be disregarded. Heat, pressure, and radiation require a significant amount of power and safety equipment to ensure safe operation around humans. Thus, their size is the limiting factor; they are too large for portability. Filtration would be functional for gas sterilization, but medical equipment features are solid in nature. This thus leaves sonication and chemical treatment as the most viable pathways toward a portable sterilization solution.

## *Sonication Sterilization*

Sonication, or ultrasonic cleaning, uses cavitation bubbles induced by high-frequency pressure waves to agitate a liquid. This agitation process produces, via an ultrasonic transducer, compression waves that "tear" the liquid apart, leaving behind cavitation bubbles at the microscopic level. These cavitation bubbles collapse in the wake of the compression wave with tremendous energy; average temperatures and pressures around these bubbles are on the order of 8,500 °F and 20,000 psi, respectively [2]. Unfortunately, the bubbles are so small, they have only the ability to clean and remove surface contaminants. Likewise, the higher the frequency of oscillation, the smaller the cavitation bubble diameters will be. This fact is key to establishing a regime by which ultrasonic waves can be used to sterilize surgical tools. Materials that reduce surface tension, also known as surfactants, greatly enhance the effectiveness of the cavitation phenomena at work in the system [3]. Typically, the apparatus used to ultrasonically clean an object consists of a vessel filled with a surfactant agent along with the objects to be sterilized. A transducer is either lowered into or attached onto the vessel to agitate the fluid medium.

Unfortunately, due to the high SAL values imposed for sterilization, sonication at atmospheric pressure alone is not enough to destroy all biological agents present on an object. However, it has been shown that increasing the pressure from 1 to 2 atm destroyed 90% of bacterial agents present on the work piece. This result represents 1 D-value factor. To meet sterilization standards, 5 more D-value factors must be reached. Thus, it is a step in the right direction. A research team at the Georgia Institute of Technology claims that by circulating the fluid at 2 atm of pressure, it can achieve total sterilization in 10 minutes. If this claim is confirmed, these results would mean it would take 70% less time to sterilize than the current leading low-temperature sterilization method: peracetic acid washing.

### *Chemical Treatment Sterilization*

Chemicals can likewise be used for sterilization. Chemical means are typically chosen if materials have heat sensitivity, such as biologics or electronics. In these instances, either liquid or gas may be used, with each having its own trade-offs. While using chemicals does avoid the problem of heat in the sterilization process, special care must be taken toward workplace safety, as these chemicals are often toxic, are incompatible with some materials, and can catalyze in air (auto combustion).

There are two primary chemicals in use on an industrial level that have varying degrees of success in terms of viability from a portable perspective. These two chemicals, which are discussed in succeeding text, are ethylene oxide (EO) and nitrogen dioxide ($NO_2$). Portability should likewise be defined on a measure typical to armed forces: the highest weight that can be carried by two people, self-contained, minimal power draw, etc.

#### *EO*

EO is the most commonly used gas and third most commonly used method for sterilization (behind moist heat and irradiation) [4]. The gas is likewise a raw material with diverse applications in the plastics and food industries. However, EO by itself is a highly hazardous substance. At room temperature, it is an anesthetic gas and is flammable, carcinogenic, mutagenic, irritating, and carries with it a misleading sweet aroma. Likewise, a major safety issue with EO is the fact that its odor threshold is 500 ppm, with a National Institute of Health and Safety "immediately dangerous to life and health" value at 800 ppm. This is an extremely tight range, in addition to the fact that the U.S. Occupational Safety and Health Administration (OSHA) has set the permissible exposure limit to 5 ppm.

As a poison gas that leaves no residue on the items it contacts, pure EO is a disinfectant widely used in hospitals and the medical device industry to replace steam in sterilization of heat-sensitive tools and equipment. And it kills everything: spores, viruses, fungi, and bacteria. Despite the advantages, its toxicity and flammability make it difficult to work with as a sterilant.

The typical methods for EO sterilization are two-fold: the gas chamber method and the micro-dose method. The gas chamber method benefits from economies of scale in that a large chamber is typically flooded with a combination of EO and other gases used as dilutants, as EO becomes highly flammable past 3% concentration. Drawbacks of this method include the air contamination produced by the fluorocarbon dilutants, EO residuals on materials (condensation), and, most prominently in this instance, the nonexistent portability of this method.

The micro-dose method is a more reliable and economically feasible version of the gas chamber method. It stipulates the use of a bag containing a pure EO-liquid-filled ampoule that, upon activation, evaporates and diffuses through the containing bag into a second bag that contains the items to be sterilized. Once there, contact sterilization occurs at a specified temperature and humidity. Unfortunately, the specifications on temperature and humidity are required to prevent excess condensation of the EO from occurring. This psychrometric limitation would prevent the use of this method in the field, unless a temperature and humidity controller could be added to the system.

#### *$NO_2$*

$NO_2$ is a highly effective and rapid sterilant for use against a spectrum of common bacteria, viruses, and spores. The qualities that diminish EO's usage due to thermodynamic limitations do not inhibit $NO_2$ (i.e., it can operate in a closed environment at room temperature

prosthetic arm likewise is stable enough for push-ups and taps directly into his nerve system to provide individual finger feedback. Bob feels a great sense of independence and renewed strength due to his advanced wound care and recovery.

Thanks to the aforementioned advancements in the field of combat casualty care, there is a much greater chance that Bob will recover with a favorable psychological outcome. ■

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and ambient pressure). The lethality mechanism for the substance is the DNA destruction of the biological agent via nitration of the phosphate backbone, which kills the organism as it absorbs $NO_2$. This DNA degradation occurs at extremely low concentrations of the gas and carries with it a low boiling point, which likewise predicates that it will not condense in the majority of field operating environments. This fact implies that $NO_2$, unlike EO-based processes, requires no aeration to remove condensation from the work piece immediately following the sterilization cycle. It is likewise less corrosive and compatible with most medical materials and adhesives. In addition, because $NO_2$ does not diffuse as deeply into a material as EO does, the total sterilization and aeration time is significantly reduced from days to minutes or even less. Furthermore, the rapid aeration process allows for fewer residues on materials, and the residues themselves are not carcinogenic, cytotoxic, or teratogenic. This notion implies that materials can be handled immediately after the cycle has completed. Exhaust is handled by scrubbers, which are landfill-safe after saturation, side-stepping the hazardous materials limitations.

## ADVANCED PROSTHETICS

Prosthetics have endured a significant evolution over the last two centuries. Unfortunately, field amputations were all too common across the 19th century battlefronts. Even worse, during this era, the afflicted lacked adequate means of anesthetic and were forced to endure crude, painful, and often fatal measures at preserving life. The medical community at the time was aware of this fact, but the technology simply did not exist for a higher quality of care.

Fast forward to the 20th century, and suddenly a different picture begins to emerge. Electronics are made small. Transistors the width of a hair strand no longer seem curious to the layman. And what follows (beginning in the late 1970s) is a systemic and grand transition of technological evolution in the area of miniaturized electronics.

Although the 1970s was not the genesis decade for the great advancements in prosthetics we see today, this period did lay the foundation upon which the field built much of its applied technologies—namely, advancement in applied controls, miniaturized motors, and biological sensing modalities. At a glance, these technologies may appear unrelated, but together they formed the core of advanced prosthetics in the modern age.

Control systems are nothing new to engineering; however, the applications by which control theory can be applied are ever evolving. In particular, the field of biologic sensing is incredibly young and only beginning to be understood and explored. And its participation in the field of prosthetics is obvious: people are not machines; they are biologic entities that behave like machines. Their movements are guided by predictable kinematics, their musculature systems are similarly driven by a series of cables and hinges, and the signals that these pieces of biologic machinery receive are electrical in nature. Unfortunately, the analogy pretty much ends there. Where a pure machine signal is discrete in nature, a biological marker of a similar indication is highly nonlinear and unpredictable in a human subject.

Nonetheless, this fact has not stopped research from pressing forward, especially in the northeastern United States. Two universities—Johns Hopkins and the University of Pittsburgh—in collaboration through DARPA-funded efforts, have achieved great success through extended programs. These two programs are known as the Revolutionizing Prosthetics program (RPI, RPII, and RPIII [note that the numbers represent different phases of funding]) and the Hand Proprioception and Touch Interfaces (HAPTIX) program. Further up the chain, these dollars come from the Brain Research through Advancing Innovative Neurotechnologies (BRAIN) Initiative, which is sponsored by the White House to revolutionize the understanding of the brain and accelerate the development of new associated biological technologies.

In the field of neurologically controlled prosthetics (neuroprosthetics), when it comes to assessing biological data streams from the nervous system [5], two parameters are typically considered in obtaining the data: richness and invasiveness.

*Richness* describes how distinct a sensing modality is at representing a movement or motion. *Invasiveness* represents the qualitative measure of the ease by which a sensing platform may be applied and removed. The institutions of academia appear to be much more focused upon richness, and the limit of invasiveness has not yet been reached.

For example, spinal columns, as well as grey matter in the brain, have been tapped into, and direct nerve innervations have all been tested with varying degrees of success. These elements represent *high invasiveness*. On the other end of the spectrum is the array of pressure sensors, myoelectrics, and superficial electroencephalograms (EEGs), which do not penetrate the skin of the subject patient. These approaches fall under *low invasiveness* tactics.

Similarly, richness has its own spectrum. In the beginnings of neuroprosthetics (under the guidance of Dr. Andy Schwartz at the University of Pittsburgh), signals were noisy and poorly understood. In addition, repeated testing for the same action often yielded wildly different results, which can be attributed to the newness of the field as well as the poor understanding of the technology interface. It thus took many years of data analysis and pattern recognition algorithms to finally achieve a sense of how the brain and muscle system interact [6].

The relationship between richness and invasiveness is often one of direct proportion; increase one, and the other rises along with it. This phenomenon was observed in Dr. Schwartz's trials. While invasiveness in itself is not a bad quality for a sensing modality, it does come with its drawbacks. Most noteworthy is biocompatibility. This factor is related to how organic tissues and their associated immune system responses interact with the implanted material. A good analogy is that of organ transplantation. If everything is not just so, the host body will attack and destroy the newly implanted organ. In the instance of implanted sensing modalities, the most common result of this interaction between tissue and nonorganic material is scar tissue, which can lead to signal degradation and attenuation over time. Currently, the field has a razor-sharp focus on the *science* of understanding these sensing modalities rather than on the *engineering* of enhancing their long-term viability, accuracy, and biocompatibility.

It serves the investigation, due to the high variety in technologies and limb geometries/kinematics, to compartmentalize the approach such that upper limb (UL) and lower limb (LL) prosthetics are considered separately. Statistically speaking, the LL amputation is much more prevalent due to the combat association with the amputation procedure. Many more Warfighters returning from the battlefield are LL amputees [7]. UL amputations tend to be congenital in nature, and so users are typically more adapted to using their residual limb as a non-weight-bearing tool. Likewise, these amputations occur at varying lengths relative to another part of the body. With LL, they are measured with respect to the hip, and with UL, they are measured with respect to the shoulder. This notion breaks the types into several categories. LL types include above the knee (AK), below the knee (BK), and hip disarticulation. UL types include humeral, radial, and shoulder disarticulation.

That being said, consider the potential cost associated with a Warfighter discharged to injury via limb amputation. This cost includes a lifetime of care through the U.S. Department of Veterans Affairs (VA); loss of mobility, dignity, and independence; a wide assortment of potential negative psychological effects directly tied to the injury itself (e.g., post-traumatic stress disorder [PTSD]); and a Warfighter unable to assist in forward operating efforts. This last notion, if addressed by advanced prosthetics, would supply the Warfigher with re-captured independence, dexterity, and mobility; a greater psychological state of health afforded by a restored limb; and a significantly reduced cost per soldier to the VA office. By having an advanced restored limb, many or all of the negative cascading effects associated with enduring amputation could be negated.

Parallel but separate efforts in the field of advanced prosthetics have been ongoing since the late 2000s. What is interesting to note, however, is how unique these efforts are for UL and LL prosthetics. The geometries and kinematics associated with the human leg and the arm are vastly different. Virtually no identical technology can be applied from one side of the gap to the other. Accordingly, their applied technologies and involved industries/research efforts are distinct.

Three companies that specialize in advanced LL prosthetics are Otto Bock (Germany), Össur (Iceland), and Hangar Clinics (the United States). Each of these companies tended to develop at the outset of a war, where the local citizenry had a high prevalence of amputation. Accordingly, these companies have had their doors open for approximately a century or longer and have expanded their services beyond prosthetics (mostly into simplifying various disability scenarios). Typically, their research is conducted in house, and their technologies are proprietary. And collectively, most of their 21st century advances can be seen through computer-controlled knees and ankles, as well as unique flexible foot geometries to replicate a natural human gait.

Computer-controlled knees (such as that pictured in Figure 6) feature hydraulic systems that adjust the pressure of a fluid within the joints of the knee, providing the patient with counterweight, natural feel, and balance. These elements are critical for providing a stable platform on which the wounded Warfighter can rely in athletic scenarios. Similarly, computer-controlled ankles providing increasingly more degrees of freedom and platforms with greater foot flexion further enhance the natural feel of the limb and serve to create greater proprioception for the Warfighter wearing the leg [8].

As their histories of development have shown, the companies focused on LL are much more likely to collaborate with endowment foundations than

Figure 6: Thought-Controlled Knee.

with government institutions. This trend is likely to continue into the foreseeable future and lead to similar LL technologies across all three companies with discrete unique instances of deviation, depending on which foundation or post-academia researchers are working with the company at the time. Furthermore, technologies are starting to take shape that emulate the sensing philosophy of the UL research community in addition to these big companies beginning to expand into UL territory.

UL research has a different approach. Sponsored mostly under the umbrella of the BRAIN Initiative, a great amount of research has come from within the academic community via government research grants, sponsored by directed agencies such as DARPA. The UL research focus is especially directed toward implementing the brain to control advanced prosthetic equipment. As mentioned, the HAPTIX and Revolutionizing Prosthetics programs are the strongest efforts on this front.

## CONCLUSION

With all the technological advances occurring on the homefront, the time has come to bring battlefield medical care into the 21st century. What were once statistically fatal injuries can now be treated with advanced superficial wound care, internal hemostatic agents, portable sterilization, and advanced prosthetics to afford wounded Warfighters the opportunity to continue to live happy, healthy lives and, in some cases, return to defending their country. Collaborative research and large funding efforts in academic, industrial, and governmental spheres have begun to advance the state of technology toward human enhancement and extended longevity [9]. These platforms, which are mostly at stages between development and deployment, will require industrial efforts to scale up their usefulness, such as is being performed by DARPA and the National Institutes of Health (NIH) through the BRAIN Initiative. With further collaborative efforts on these fronts, these technologies will further preserve the livelihood and health of the forces fighting to defend their countries. ■

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## BIOGRAPHY

**JAKE MONTEZ** is a principal investigator and lead programmer for the Non-Destructive Evaluation (NDE) department at the Texas Research Institute, where he develops user interface and data acquisition software for NDE applications in composites, metals, and biologics. His 5-yr career has included developments in computational fracture mechanics (peridynamics), advanced prosthetics research and construction, high-performance computing enhancements, software optimization and automation routines, and biologic NDE. His current research areas include novel industrial transitions for academic technologies, additional biological NDE sensing modalities, and advanced prosthetics development. Mr. Montez holds a B.S. and an M.S. in mechanical engineering from the University of Texas at San Antonio.

**DTIC SEARCH TERMS:**
Combat Casualty Care

**RESULTS:** 41,700

- Military Operations, Strategy & Tactics (5,000+)
- Medicine & Medical Research (4,900+)
- Government & Political Science (4,500+)
- Military Forces & Organizations (3,600+)
- Foreign Reports (2,700+)
- Theses (2,500+)
- FBIS Collection (2,400+)
- Military Operations (2,400+)
- International Relations (2,000+)
- Warfare (2,000+)

*See page 16 for explanation ▸

# JOINT INTEGRATION TESTING OF SWARMING UNMANNED AERIAL VEHICLES

**By F. Patrick Filbert**

## INTRODUCTION

As technology improves, so does the capacity to expand a defensive perimeter to ever-increasing ranges, both horizontally and vertically. Identifying ways to penetrate this perimeter with assets and capabilities that do not require increasingly expensive solutions requires creative use of current and emerging technological advances. Potential adversaries understand that the United States is extremely advanced in its warfighting systems technology. This fact requires a thinking enemy to develop ways to keep America's advanced systems outside of the enemy's sphere of influence—specifically, to both deny and create an inability to gain access to specific areas of operation. In the current vernacular, this action is referred to as creating an anti-access/area denial (A2/AD) environment, which has, as its backbone, advanced integrated air defense systems (IADSs).

## A BIT OF HISTORY

The ability to provide a “layered” offensive capability with manned kinetic/nonkinetic payload armed aircraft has been in existence for some time. One relatively recent example involved a joint U.S. Air Force (AF)-Army helicopter team (Task Force Normandy), which used AF MH-53J/Pave Low IIIs to blind Iraqi IADS early warning radars with nonkinetic electronic attack and then Army AH-64/Apaches to destroy the radars with kinetic weapon strikes (e.g., Hellfire missiles, Hydra rockets, and 25-mm cannon fire) in the opening minutes of Operation Desert Storm to allow follow-on AF strike aircraft access through coverage “holes” in the Iraqi IADSs and to attack key targets further into Iraq [1]. Similarly, future use of an advanced wave of unmanned aircraft systems (UASs) equipped with electronic warfare (EW) payloads leading a subsequent wave of attacking aircraft from carrier strike groups is one potential way to enter and counter a potential adversary’s A2/AD environment.

However, while emerging EW payload testing on UASs is occurring, mating electronic attack (EA) payloads onto a coordinated semi-autonomous or fully autonomous swarm of smaller unmanned aircraft (UA) is still an emergent test environment effort. However, once such capabilities mature, being able to employ them requires that a foundational concept be in place. The Joint Unmanned Aerial Vehicle (UAV) Swarming Integration (JUSI) Quick Reaction Test (QRT) was directed on 27 February 2015 by the Deputy Director, Air Warfare under the authority of the Office of the Secretary of Defense (OSD), Director, Operational Test and Evaluation (DOT&E) to address such a foundational approach.

> While emerging EW payload testing on UASs is occurring, mating EA payloads onto a coordinated semi-autonomous or fully autonomous swarm of smaller unmanned aircraft is still an emergent test environment effort.

The JUSI QRT was established under the DOT&E’s Joint Test and Evaluation Program on 29 July 2015. It is co-located with the U.S. Pacific Command (USPACOM) J8 Resources and Assessment Directorate, at Camp H. M. Smith in Oahu, HI. The JUSI QRT reports to the AF Joint Test Program Office (AFJO) at Nellis Air Force Base, NV, and receives support from USPACOM J81 (the Joint Innovation and Experimentation Division). The JUSI QRT will develop, test, and validate a concept of employment (CONEMP) for the integration and synchronization of swarming UA performing EA in support of the Joint force against an advanced IADS (such as the one illustrated in Figure 1). The JUSI QRT effort is focused on a 2015–2020 timeframe to research and identify previous and ongoing swarm-related efforts while building a swarming UA community of interest, concurrent with CONEMP development.

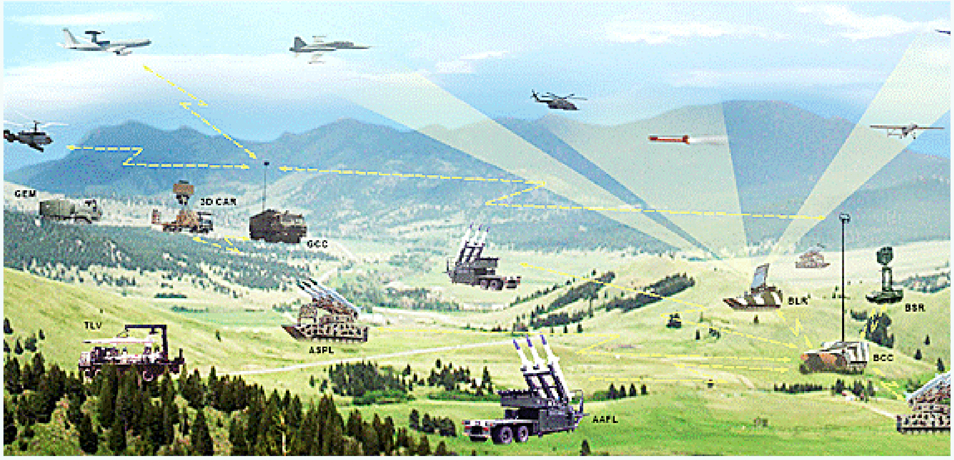

Figure 1: Notional IADS [2].

## ADVANCED IADSs AND HOW TO ADDRESS THEM: THE PROBLEM

Modern surface-to-air missile (SAM) systems are an integral part of advanced IADSs. These IADSs are, in turn, integral parts of a potential adversary's networked A2/AD environment. For the purpose of the JUSI QRT effort, an IADS refers to a networked system of adversary capabilities (e.g., a series of detection and tracking radars coupled with SAMs) not specific to one platform (e.g., an IADS on a warship by itself or a specific individual SAM, such as an SA-20).

> The JUSI QRT's resulting CONEMP will provide an effective operational context to inform requirements development, roadmaps, and—eventually—TTPs in several areas, including communication, automation, UA, and EA.

The Joint forces do not currently have adequate ways to fully plan, integrate, or synchronize the effects delivered by UA swarms (such as that pictured in Figure 2). This ability requires development and testing of a foundational CONEMP offering an effective planning methodology for delivering integrated effects of UA swarms against advanced IADSs protecting targets with threat SAM arrays.

Figure 2: Artist Concept of a Swarm (Defense Advanced Research Projects Agency) [3].

The Joint force has traditionally been over-reliant on standoff weapons (SOWs) and fourth/fifth-generation strike platforms to address the A2/AD challenge. UA swarms represent a potential additional approach, complementing existing platforms and weapons systems. Despite rapid technical advances in UA swarming development and demonstrations, the Joint force lacks an adequate CONEMP for operations requiring UA swarm-delivered effects. The lack of a CONEMP or other supporting documentation hinders requirements development, A2/AD countering, and precludes integration and synchronization with the rest of the Joint force.

## APPROACH TO ADDRESSING THE PROBLEM

Combat-capable and -survivable UA with the capability to perform swarming functions are a new but quickly growing aspect of modern warfare. The JUSI QRT will take the first step to characterize, develop, and evaluate a CONEMP for using multiple UA of various sizes to deliver coordinated EA to enable other weapons and platforms (e.g., various types of SOWs, decoys, jammers, and fourth/fifth-generation platforms) access to counter A2/AD approaches. With the short lifespan of the JUSI QRT—1 year —the effort will focus on CONEMP development supported by a series of modeling and simulation (M&S) runs over the course of three test events.

Integrated support by experienced M&S personnel of the Johns Hopkins University's Applied Physics Laboratory (JHU/APL) during each of the test events will enable the QRT to gain data collection for the equivalent of hundreds of swarm flights, thus providing a cost-saving aspect concurrent with data analysis to support CONEMP development. JHU/APL will provide M&S and analysis of the execution of UA with EA payloads against scenarios developed to test the UA's ability to deliver desired effects against an advanced IADS as part of an A2/AD environment.

The resulting qualitative and empirical data, once analyzed, will enable the JUSI QRT Team to assess findings,

conclusions, and recommendations to revise the CONEMP between each test event with JUSI QRT's first test event, which was concluded on 20 November 2015. Additionally, upon completion of each test event, a Joint Warfighter Advisory Group (JWAG) will be convened to receive test event results—the first JUSI QRT JWAG occurred on 9 December 2015. As the QRT process continues, it will lead to development of a finalized swarming UA CONEMP to provide the link to requirements development and capability integration for the Joint force to have a distributed approach to complement existing solutions focusing on fourth/fifth-generation strike platforms and SOWs.

## THE WAY AHEAD

At the end of the JUSI QRT, the resulting CONEMP will provide an effective operational context to inform requirements development, roadmaps, and—eventually—tactics, techniques, and procedures (TTPs) in several areas, including communication, automation, UA, and EA, to deliver intended effects. The CONEMP will also serve to help focus future Department of Defense and industry investment. Future considerations related to swarming UA with EA payloads may include development, testing, and validation of TTPs for UA with EA payloads. Such TTPs will further reinforce the use of swarming UA by empowering the commander to develop standards in the areas of manning, equipping, training, and planning in the Joint force. In the interim, the JUSI QRT-developed CONEMP will provide planners, trainers, and their supporters with a starting point for employment of this capability. ■

## ACKNOWLEDGMENTS

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## DTIC SEARCH TERMS:

UAV Swarm

**RESULTS:** 2,200

- Military Operations, Strategy & Tactics (385)
- Pilotless Aircraft (385)
- Drones (334)
- Cybernetics (309)
- Theses (246)
- Algorithms (238)
- Unmanned (232)
- Computer Programming & Software (225)
- Symposia (177)
- UAV (177)

*See below for explanation ▸

## BIOGRAPHY

**PATRICK FILBERT** is the JUSI QRT Subject-Matter Analyst for UAS. During his 24-year Army career, he has held command and staff positions from platoon through Joint staff in the United States, Europe, the Balkans, Korea, and the Middle East. His post-military career has focused on developing counter-UAS procedures, serving as an intelligence analyst in USAF units, and serving as a project manager for USPACOM's Socio-Cultural Analysis effort. He holds a bachelor's degree in history from the University of Hawaii and a master's degree in strategic intelligence from American Military University.

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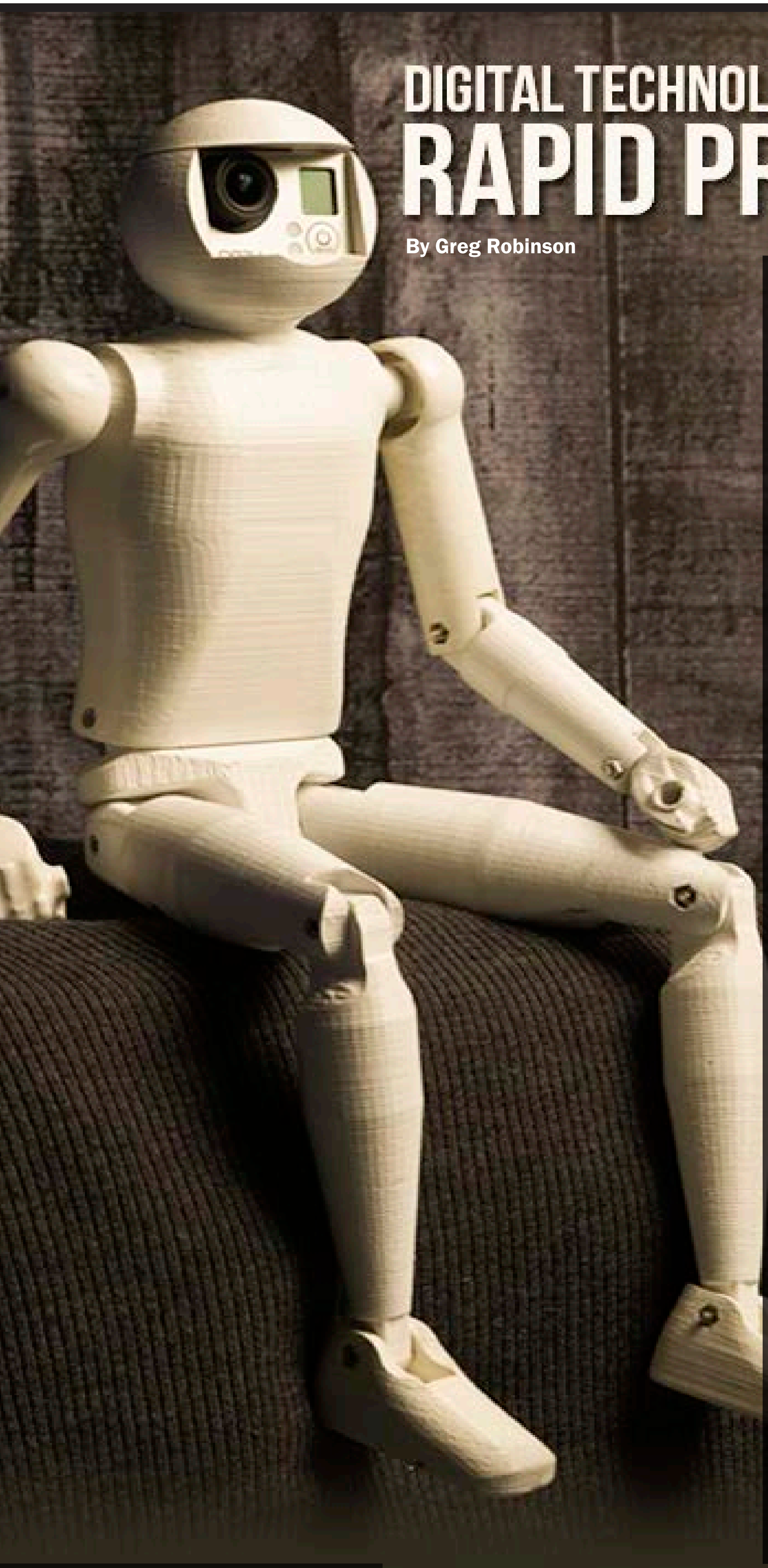


# DIGITAL TECHNOLOGIES AND RAPID PROTOTYPING

**By Greg Robinson**

## INTRODUCTION

The current digital revolution is affecting almost every aspect of our lives. Many of the revolutionary changes, such as our latest mobile phones and the emergence of driverless cars, are obvious. Other changes, while much less visible, are no less important. The impact on product development has been especially profound. In particular, the emergence and popularity of digital, three-dimensional (3-D) technologies, such as computer-generated solid models and additive manufacturing (3-D printing) techniques, have greatly expedited the preparation of prototypes. Likewise, subtractive manufacturing techniques, such as computer numerical control (CNC) milling and laser cutting, have made prototype generation faster and less expensive, although these techniques have not received as much recent attention as additive manufacturing. But in either case, all of these production improvements are enabling multiple iterations of cost-effective prototypes to be made, which in turn has facilitated the development of exquisitely optimized manufacturing designs. And the solid model that results from these designs is the starting point of the "digital thread" that provides the digital data link through manufacturing and sustainment in model-based engineering (MBE) [1]. MBE is a process that is increasingly being adopted by many DoD and related organizations (including the National Defense Industrial Association [NDIA]) to manage the manufacture of complex products.

Rapid prototyping is defined as a group of digital techniques that facilitate the quick fabrication of a prototype physical part or assembly from a 3-D computer file. The first rapid prototyping technology was developed more than 30 years ago, when the first 3-D printer was invented [2].

**"Buster," the Hoverbike Scale Model Mannequin**

Since then, many other 3-D printing techniques have been developed. These 3-D printing technologies, where a part is built up layer by layer, are collectively known as additive manufacturing. Other 3-D prototyping techniques, such as CNC milling and computer-controlled laser or water-jet cutting, are collectively referred to as subtractive manufacturing. With subtractive manufacturing, material is removed from a block or sheet until only the part remains. It is important to note that, in practice, it is often necessary to supplement digital prototyping techniques with manual methods, especially in the early stages of prototype development [3].

## MANUFACTURING AND THE 3-D MODEL

MBE is a concept being adopted by many organizations to manage the manufacture of complex products. A 3-D computer-aided (CAD) model is the official data record and forms the starting point of the previously mentioned digital thread. It is produced during the concept and design phases of manufacture and will progress through the manufacturing process to the product's end of life (see Figure 1). Currently, two-dimensional (2-D) blueprints are often used to officially track changes while "unofficial" 3-D models are created from these as needed, with all the inefficiencies that this approach entails. Therefore, 3-D model development, aided by the creation of iterations of prototypes during the concept and design phases of an MBE manufacturing process, is increasingly important.

## PROTOTYPE COMPUTER MODEL DEVELOPMENT

A 3-D CAD model is required before either additive manufacturing or subtractive manufacturing techniques can be used to create a physical prototype that is suitable for evaluation. High-quality solid modeling CAD programs, such as SOLIDWORKS, PTC Creo Elements/Pro, and Autodesk Inventor, have greatly decreased the time needed to create 3-D models. A solid 3-D model is assumed to have volume, and all the faces of the model are connected to other faces. Solid-modeling software usually has the ability to test structural integrity of the model using finite element analysis (FEA) and to perform other analyses [4]. Because the models are feature-based, their geometry can easily be changed to accommodate design enhancements.

A 3-D CAD model may be developed from "scratch" from design requirements, or it may be reconstructed from existing blueprints. Often, these blueprints do not represent the part exactly as the part has been adjusted or adapted during previous production runs. In some cases, only a physical part is available, which must be captured and adapted to meet current requirements (see Figure 2). To create a 3-D CAD model from an existing part of any complexity requires the use of either a contact or noncontact coordinate measurement machine (CMM).

A contact CMM could be a fixed-bridge CMM, an articulated measurement arm, or a laser tracker. All of these CMMs touch the part to make the measurement and collect individual points or streams of points. Particularly useful for model creation from these types of point measurements is feature-based reverse engineering (RE) software, such as DezignWorks or Point2CAD, which facilitates creation of CAD models from parts using measurement arms.

A smaller part is generally scanned with a noncontact CMM, such as a laser scanner or a structured light scanner. A laser scanner, which is often attached to a measurements arm, projects a laser line onto the part, which is captured by a sensor offset from the projector. The projected line is distorted by the part's surface topography, thus providing information about its curvature. The line scans are referenced into the global coordinate system by the encoder readings on the arm. In the case of a structured light scanner, a 2-D pattern is projected onto the part surface, and the pattern's distortion is captured by an offset image sensor. A surface point cloud is then computed from this distortion.

Point cloud data are generally collected and integrated in specialized

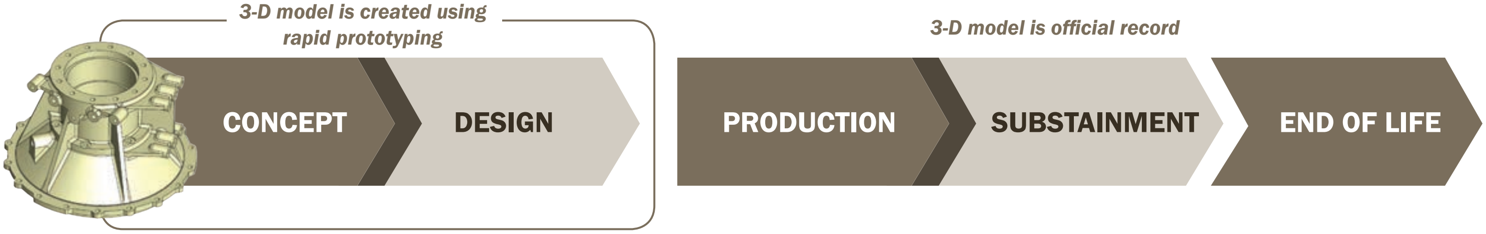


Figure 1: Model-Based Engineering (MBE).

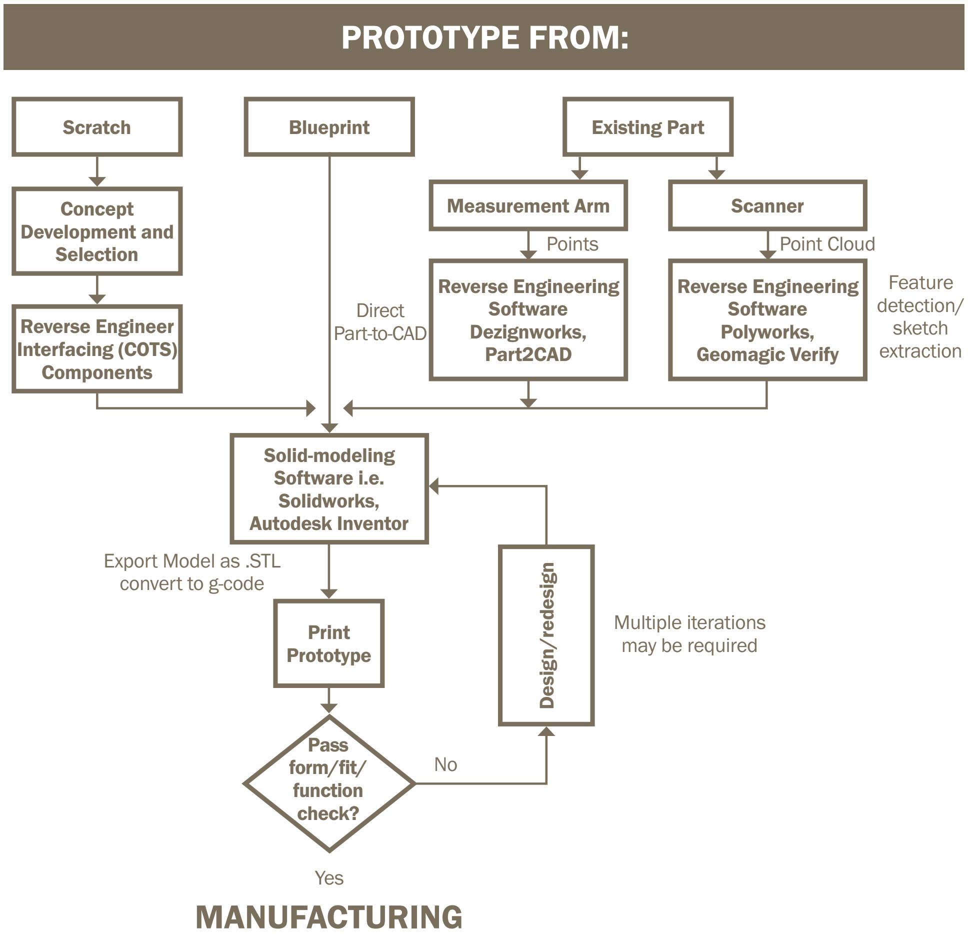


Figure 2: Prototype Development From Scratch, Blueprint, or Existing Part.

RE software, such as PolyWorks or Geomagic Verify. The points are processed to reduce noise and remove duplicate and erroneous data and converted into a more compact polygonal model. It is usually necessary to extract the geometric primitives from the polygonal models and to replace freeform surfaces with CAD-friendly lofted or Non-Uniform Rational Basis Spline (NURBS) surfaces. The model can then be exported to solid-modeling CAD software for adjustment and numerical simulations.

## CREATING THE PROTOTYPE

Once a digital model has been generated, the first prototype can be produced using either additive or subtractive methods. As mentioned previously, additive manufacturing builds up the part layer by layer whereas subtractive manufacturing creates the part by cutting away unneeded material.

## ADDITIVE MANUFACTURING (3-D PRINTING)

The basic process of creating a prototype using additive manufacturing is straightforward. The CAD file must be converted into an appropiate file format, usually stereolithography (STL). In the process of generating an STL file, the 3-D model's geometry is converted into a series of planar triangles, which are closer together in areas of curvature and further apart in flatter areas. The STL file is then imported into 3-D printing software, where it is sliced into 2-D sections so that it can be printed layer by layer. The resulting file contains the low-level program (G-code) that provides instructions to the printer. The exact form of the file depends on the particular technology of the printer and may include printing support material to prevent overhanging sections warping while the printing material cures.

Additive manufacturing has some important advantages for prototype creation. In general, parts can be quickly and (for small parts) inexpensively made, which encourages the creation of multiple iterations so that the optimum design requirements can be achieved. Additionally, complex parts are as easily produced as simple ones because they are all produced in the same manner, layer by layer. And printed parts can easily be fitted with electronic or mechanical components.

However, additive manufacturing does have some restrictions. The range of materials from which parts can be printed is limited, as is the size of parts that can be produced by typical commercial printers. And the cost of a 3-D printed part increases rapidly with size.

The following sections detail some common technologies that are categorized as additive manufacturing.

### ***Stereolithography (SLA)***

SLA, the pioneering 3-D printing technology, works by focusing an ultraviolet (UV) laser onto a bead of UV-curable resin to create a 2-D cross-section on the build platform. The platform is then lowered so the next layer can be cured. SLA printers produce extremely smooth parts with almost no stepping between the layers because of the high precision of the focused UV layer. Parts produced by SLA printers are particularly useful when the detail of the prototype is required to closely resemble the final, mass-produced part. The voids in the center of a part are typically filled with additional resin, and parts may require additional finishing/curing after the print has been completed.

### Fused Deposition Modeling (FDM)

The predominant solid-based 3-D printing technology is FDM, which works by extruding material layer by layer. The print head outlines the base layer of the object and then fills in the contour. After the first footprint layer is printed, the print head is raised slightly and deposits the second layer. The printer continues depositing one cross-sectional layer of the object after another (as illustrated in Figure 3). High-end FDM printers can produce large parts for prototyping. Parts can be made from plastics, generally acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Overhangs are supported by layers of temporary material, which is easily removed once the print is complete. To achieve smoothness, parts must be post-processed by hand.

### Powered Bed Printing

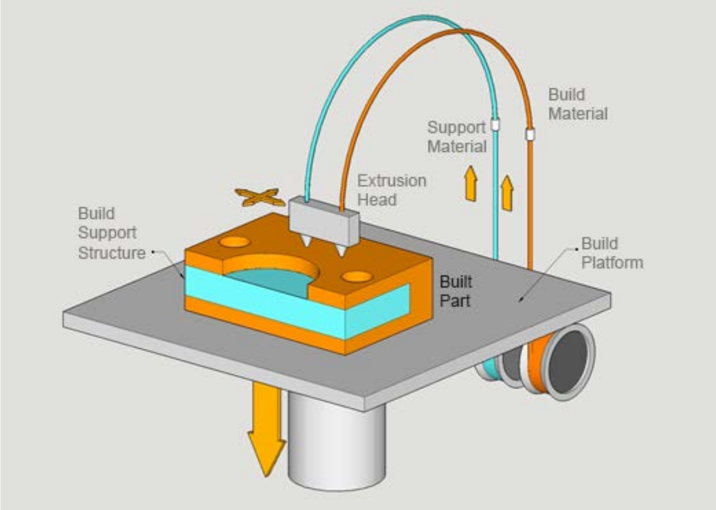
Powder bed printers work by spreading powder on a bed and then solidifying the layer with a liquid binder. There are many variations of this technology, but the most common one is the inkjet printer, which prints (colored) binder into the powdered material instead of ink. By using multiple print heads, it is possible to print in multiple colors. Overhangs, which may be a problem in other types of printing, are supported by the underlying powder. However, the prints tend to be brittle and require considerable cleanup to get rid of excess powder. In a similar manner to SLA prints, voids in the print are filled with powder.

### Selective Laser Sintering (SLS)

SLS—and, similarly, direct metal sintering (DMLS) and selective laser melting (SLM)—use high-powered lasers to melt powdered particles. As illustrated in Figure 4, the powdered material is laid down and melted by the laser, and then the next layer is added. No binding material is required, and parts can be created out of numerous types of materials, such as metals, ceramics, and plastics. Further, the resulting parts can be as strong as conventionally manufactured parts. However, DLS, DMLS, and SLM printers are expensive and use potentially dangerous materials that require careful handling.

### Polyjet Printing

Polyjet printers deposit a layer of UV-curable resin onto the print bed, which is instantly cured with a UV light, located on the print head. Overhangs are supported with gel, which is easily washed away after the printing is complete. The parts produced are strong and can include different colors and materials when produced with the appropriate resin. Many types of resin are available, and the print can resemble any material, from hard plastic to rubber. For example, a hard plastic inner shell, covered by a soft grip or protective layer of a rubber-like material, can be printed.



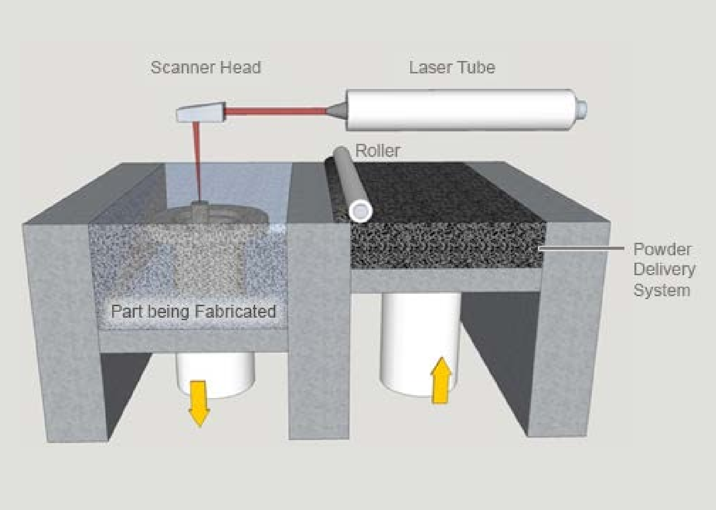


Figure 3 (left): Fused Deposition Modeling.
Figure 4 (right): Selective Laser Sintering.

## SUBTRACTIVE MANUFACTURING

Digitization has also profoundly enhanced milling and cutting capabilities, although this method has not captured the popular imagination to the same extent as 3-D printing or additive manufacturing. High-quality 3-D or sheet metal prototypes can be created directly from a processed computer model.

### *CNC Milling*

Milling machines in their simplest form consist of a motor called a spindle that spins an end mill, which cuts away material from a block until the desired part remains. This block of the material is attached to a platform that can move in three or more directions with respect to the end mill. The operator removes material in pockets, revealing one feature at a time. Digitization has resulted in the replacement of many of the tasks of an operator with a computer and the creation of CNC mills.

The CNC milling operation is controlled by computer-aided manufacturing (CAM) software. Increasingly, CAM programs are sold as a module that works within solid modeling programs, such as Creo Elements/Pro or SOLIDWORKS. This software takes the 3-D model and processes it to create a series of instructions for the mill. However, CNC mill operation requires a considerable amount of skill and experience, with much operator interaction being required, depending on the material and the shape of the part being made.

When equipped with a suitable end mill, CNC mills can create parts from many materials, including steel, aluminum, titanium, wood, and plastic, making these mills highly versatile.

### *Computer-Controlled Laser Cutting*

Laser cutting has emerged as an exciting technology that is useful both for prototyping and manufacturing. High-powered lasers are able to quickly cut complex metal profiles. Smaller $CO_2$ lasers are sufficiently powerful to cut plastic and wood. Laser-cut parts are particularly suitable for sheet metal prototypes or may be part of the assembly used to create the prototype, depending on the application [2].

## COMPARING ADDITIVE AND SUBTRACTIVE TECHNIQUES

A CNC mill, equipped with the appropriate end mill and cooling system, is capable of making parts in many more materials than 3-D printers. It is also able to achieve extremely high dimensional accuracy. However, 3-D printers can create parts with a great deal of complexity. Depending on the 3-D printing technology adopted, internal geometry can be just as complex as external geometry. Furthermore, it is possible to print preassembled assemblies, such as the assembled chain shown in Figure 5.

Figure 5: Assembled Chain Printed With Polyjet Technology.

Additionally, CNC mills are capable of producing high-precision parts (less than 0.001 inch in size). On the other hand, the accuracy of 3-D printing relies heavily on the particular technology and is generally unable to meet the accuracy achievable by CNC mills. The general prototype iterative approach can be used to improve the accuracy of the part created by additive manufacturing. As shown in Figure 6, the part is printed and measured. The geometry of the solid model is then adjusted to compensate for those areas that are out of tolerance. The model is reprinted and selectively scaled until it provides a print of the required accuracy.

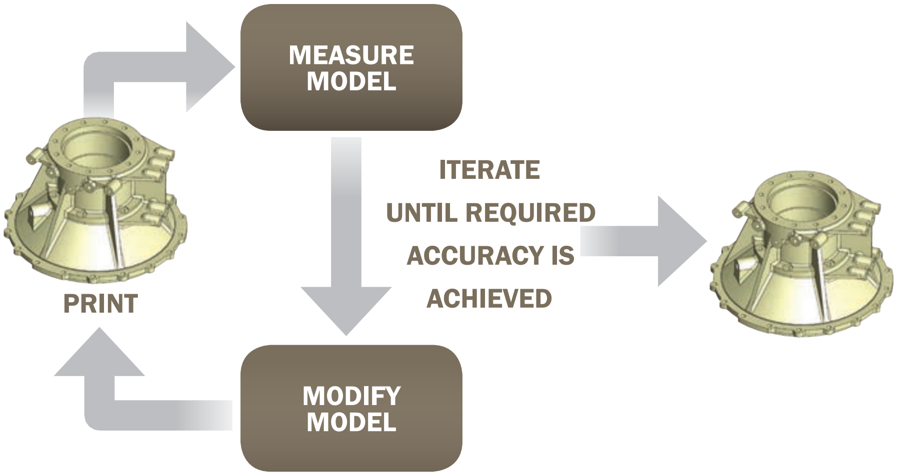


Figure 6: Iterating to Improve Printed Part Accuracy.

Machines that combine 3-D printing and CNC capabilities are becoming available. A part can be printed, and then select features can be machined for the highest accuracies.

A CNC mill, in the hands of an experienced operator, can produce smooth surfaces. Most 3-D printing techniques can as well; however, some 3-D printer techniques require post-processing to achieve a smooth finish.

## CHECKING THE PROTOTYPE

Once the prototype has been created, it is checked for form, fit, and function. If the part has been created with, for example, a powder printer, then it may be weak and/or brittle and thus not suitable for checking for function. In this case, resin casting may provide a part with sufficient strength to check function. A silicon mold can also be produced using the 3-D printed part and simple tools. With appropriately molded material, a strong functional part can be produced from a weak or brittle 3-D print.

> CNC mills can create parts from many materials, including steel, aluminum, titanium, wood, and plastic, making these mills highly versatile.

If the part does not meet one or more of the checks, then adjustments are made to the model and another prototype is created. This process continues until the part can be shown to meet the design requirements. Several iterations are usually required. CAD software reduces the time required for 3-D model adjustment, and prototype parts can be produced quickly and relatively cheaply using additive and subtractive techniques, thus living up to the name "rapid prototyping."

Once the prototype has met all of the product requirements, the part or assembly is ready to be manufactured from the finalized solid model. Manufacturing can take many forms, including 3-D printing, CNC milling, silicon molding, or injection molding, depending on factors such as the part's material, dimensional tolerances, and number of parts required.

## APPLICATIONS OF RAPID PROTOTYPING

The following two examples show how rapid prototyping was effectively used to develop 3-D solid models for products being developed under contract to Department of Defense (DoD) organizations. For these products, additive manufacturing was the most appropriate method of producing the prototypes to check form, fit, and function. For projects in which high-precision or extremely strong parts are required, subtractive manufacturing may offer a better solution. A third example is a 3-D printed "pilot," which provides scale and a camera mount for a prototype Hoverbike, currently under development for the DoD via a DSIAC Core Analysis Task (CAT) (see related Hoverbike article later in this volume). All of these projects are being conducted by the SURVICE Engineering Company's Aberdeen Technology Operation in Belcamp, MD.

## HAWKEYE LOW-COST SCANNER


Figure 7: Hawkeye Scanner With Battery Pack.

Hawkeye (shown in Figure 7) is a hand-held scanner currently under development for the U.S. Marine Corps as a joint venture between SURVICE and Corvid Technologies. The scanner is designed to be low cost by using a commercial-off-the-shelf (COTS) monochrome sensor and infrared (IR) laser projector scanner system. It can be used to perform battle damage assessment in the field, enabling Marines to determine if a combat vehicle has suffered structural damage.

The sensor and electronics components were reverse-engineered with a measurement arm in Part-to-CAD software (DezignWorks) so that the scanner housing 3-D computer model could be designed to accommodate them. The prototype housing was then printed using the SLA additive manufacturing technique in a material called Somos NeXt LV Grey, which is a highly durable material similar to a traditional thermoplastic. The housing was painted black with speckle for cosmetic purposes. Finally, the product name was silk-screened onto the upper housing component (as shown in Figure 8), and a connector was built into the scanner housing so that it could connect to a Microsoft Surface Pro 3 tablet for scan data processing.

A COTS high-capacity battery is included with the system to ensure that the scanner can be used in the field for extended periods. However, the battery was initially designed for office use and was not sufficiently rugged for use in the field. The battery was reverse-engineered using a laser scanner, and a rugged protective housing was designed in two sections: a rigid plastic inner section and a rubberized shell. The prototype case was printed on a Polyjet printer, which has the capability of printing material of two textures and colors (as shown in Figure 9).

Small adjustments are currently being made to the scanner housing and battery case solid-models to ensure that they are suitable for injection molding. After the initial expense for the preparation of the aluminum molds, many high-quality housings can be produced at low cost by injection molding, thereby meeting one of the design requirements.

However, before the mold is created (using subtractive manufacturing techniques), the final designs will be 3-D-printed and used to create silicon molds for resin casting. This step will have two purposes. It will allow the design to be checked before the high-cost molds are produced, and it will allow the production of a small number of parts (from 10 to 25) that can be used for assembly procedures development before the larger volume of injection molded parts become available.

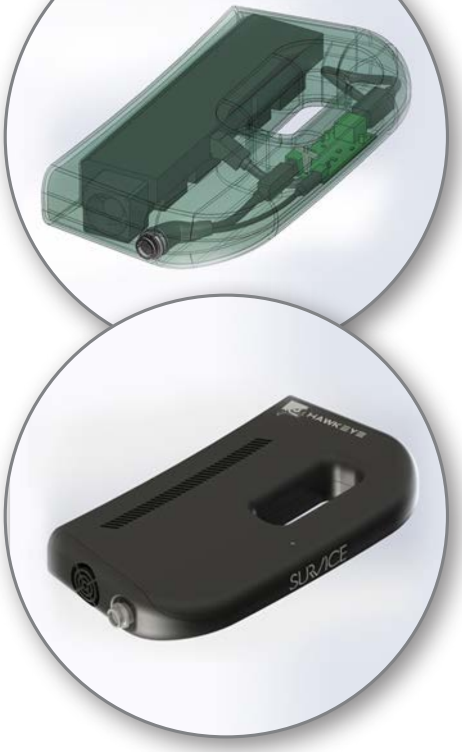


Figure 8: Hawkeye Scanner Housing Wireframe (middle) and Rendered Model (bottom).

## AIRCRAFT DAMAGE LOGGER

SURVICE developed the aircraft damage logger to use photographs to measure the size of defects in the engine ducts of stealth tactical fighter aircraft of the U.S. Air Force. High-performance computational algorithms are required to run on the mobile processing unit, quickly exceeding the computing capability of the included COTS computer tablet. Therefore, custom hardware was developed to provide complementary computational capabilities. In addition, the hardware includes supercapacitor technology, which powers a 6,000-lumen light-emitting diode (LED) flash to illuminate the measurement area, as well as projected lasers, which provide scale to the area. The unit housing the computer tablet and the electronic board must protect from shock and moisture so that the logger can be used in challenging environments. The front and rear views of the case, as well as the internal

Figure 9: Hawkeye Rendered Battery Pack Case Model (left) and Polyjet-Printed Two-Material Battery Case (right).

electronics, are shown in Figure 10. The rear view of the logger (center) also shows the protected port that is required for downloading the raw and processed data.

Prototypes of the case were printed using a Polyjet 3-D printer. The case was printed out of two types of material, a photopolymer known as digital ABS (acrylnonitrile butadiene styrene), which forms a protective high-quality plastic shell. The shell was overprinted by a rubber-like material, TangoBlack FLX973, which provides shock protection as well as grip for the device.

Once the final design was developed, a small number of loggers (approximately 10) were required to be manufactured. The most economical way to produce these loggers was by resin casting. In addition to having a far lower setup cost than injection molding, resin casting has many resin varieties, ranging from extremely soft to extremely hard. These resins are also heat-, water-, and impact-resistant and can also be colored as desired using pigments.

Silicon molds for resin casting are created directly from 3-D printed parts, and therefore resin casting forms are a highly useful and complementary technique to additive manufacturing. These master parts must be carefully prepared for the molding process by removing any residual imperfections, such as layering artifacts and scratches. This removal may be accomplished, for example, by coating the part with automotive primer, followed by hand-sanding. In addition, texturing can be added through the 3-D printing process or by post-processing. Special care must be taken with the finishing process because any residual flaws in the masters will show up in the resin-casted parts.

Figure 10: Aircraft Damage Logger Front (left), Rear Showing Camera and Flash (center), and Internal Electronics (right).

The next step in the resin casting process is the creation of the silicon molds. Molds are created by attaching a 3-D printed part to a base and placing a frame around it. Registration objects such as nonporous plastic bars are also placed on the base so that positive and negative molds can be registered together. The silicon material is poured around the part and allowed to cure, creating the negative mold. Small cones and cylinders are glued to the 3-D printed part to make provision for fill holes for pouring resin into the mold as well as for venting displaced air. Mold release is applied to the negative mold, and an extension is added to the frame. An additional layer of silicon is added to create the positive mold.

An ABS stimulant resin was used to cast the inner case. Once the resin is mixed, and before it is poured into the mold, it is placed in a vacuum chamber so that any bubbles are removed from the mixture. The positive and negative molds are placed in position, and the resin is poured into the void between the two through the fill holes. Resins generally cure at room temperature. The inner case is then removed from the mold and is ready to be overmolded in a negative mold made from a 3-D print of the combined inner and outer case. The cast inner case is installed in its matching locations in the mold, and the voids between the case and the mold are filled with a rubber stimulant resin. Because of the low volumes required, silicon molding thus presents an economical solution for manufacturing the Aircraft Damage Logger.

## HOVERBIKE PILOT

The Hoverbike, a joint venture between SURVICE and Malloy Aeronautics, is a new class of tactical reconnaissance vehicle (TRV) currently in development for the DoD [5]. The vehicle, a one-third-scale prototype, shown in Figure 11, is designed to carry a single pilot and fly at a range and altitude similar to a traditional small helicopter, potentially transforming the way U.S. troops operate in difficult terrain. Its small size and potentially high maneuverability mean it could operate in far tighter spaces than a larger rotor-wing aircraft. Also, the military variant of the aircraft is expected to be able carry several hundred pounds of cargo in addition to the pilot.

In support of the Hoverbike development, a 3-D scale model of the civilian version of the Hoverbike was created. This model includes a model of the Hoverbike's pilot, fondly referred to

Figure 11: FDM-Printed Components on Hoverbike Scale Model.

as Cyborg Buster. The pilot, which was designed to be printed on a consumer-grade FDM 3-D printer, is approximately 22 inches high and has semi-articulated movement in its shoulders, elbows, hips, knees and ankles. It provides scale to the prototype, showing how an adult person would look on a full-sized Hoverbike, and it also functions as a highly adjustable camera mount. Figure 12 shows a GoPro camera installed into the pilot's head so that video footage can be captured from a pilot's-eye perspective. This is an example of how simple 3-D printing can be used to complement prototype development.

## CONCLUSION

Digital technologies, including solid-modeling, 3-D printing, CNC milling, and computer-controlled laser cutting have revolutionized prototyping in recent years. Modeling software is becoming less expensive and easier to use, and its ability to evaluate characteristics such as structural strength is becoming more sophisticated. Additionally, virtual models can be rapidly and economically tested for form, fit, and function by rapidly produced physical prototypes comprising sophisticated materials. Thus, these robust 3-D models are forming the origin of MBE's digital thread, which will continue to be critical to the future of increasingly complex manufacturing in the United States. ■

*Mr. Mark Butkiewicz and Mr. Rob Baltrusch of SURVICE's Applied Technology Group and Mr. Joel Witman of the SURVICE's Metrology Group provided assistance in the preparation of this article.*

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## BIOGRAPHY

**GREG ROBINSON** is Deputy Manager of the SURVICE Engineering Company's Metrology Group. He has more than 20 years of experience providing metrology services to DoD and commercial customers. His areas of expertise include metrology support for hydroelectric power generator refurbishment, proton beam therapy machine installation, and nuclear accelerator alignment; and he has managed Small Business Technology Transfer (STTR) and Small Business Innovation Research (SBIR) for the DoD and U.S. Air Force. Mr. Robinson has a B.S. in Land Surveying from the University of Natal, South Africa, and an M.S. in Geomatics from the University of New Brunswick, Canada.

Figure 12: Hoverbike Scale Model With Video Camera Installed.

**DTIC SEARCH TERMS:**
Rapid Prototyping

**RESULTS:** 79,100

- Computer Programming & Software (1,700+)
- Other (1,700+)
- SBIR (Small Business Innovation Research) (1,500+)
- SBIR Reports (1,400+)
- Symposia (1,400+)
- Prototypes (1,312+)
- Electrical & Electronic Equipment (1,000+)
- Medicine & Medical Research (1,000+)
- Test & Evaluation (923+)
- Aircraft (900+)

*See page 16 for explanation ▸

### U.S. MILITARY EYEING FUTURISTIC

# HOVERBIKE TECHNOLOGY

By Mark Butkiewicz and Chris Malloy

**Figure 1: Tethered Test Flight of Original Malloy Aeronautics P1 Hoverbike Prototype (Computer-Generated Background).**

## INTRODUCTION

Sometimes science fiction has a way of becoming reality. From Buck Rodgers ray guns to Star Trek communicators, many technologies that were once the realm of science fiction have worked their way into the real world in one form or another. And the Hoverbike will soon be added to this growing list of technologies, with the successful testing of a prototype (shown in Figure 1) revealing that the feasibility of the concept is no longer relegated to science fiction.

## HISTORICAL OVERVIEW

The idea of a Hoverbike or similar type of personal hovercraft is not new. The military has been testing various concepts for many years, including the HZ-1 Aerocycle of the 1950s (Figure 2) and the VZ-8 Airgeep of the 1960s (Figure 3). However, these concepts never made it into production. The Aerocycle, which was one of the first personal hovercraft developed for the Army, was found to be too difficult to control by untrained infantrymen and thus was abandoned after early failures. Likewise, the Airgeep, which used twin 400-hp Turbomeca Artouste IIC turboshaft engines, was eventually abandoned in favor of further development of conventional helicopters, although several successful flight tests were performed.

Figure 2: HZ-1 Aerocycle Circa 1954.

Figure 3. Piasecki VZ-8 Airgeep Circa 1962.

But a lot has changed since the 1960s. A technical revolution has occurred over the past several decades that has ushered in an age in which the Hoverbike can become a reality as a low-cost and safe means of transportation over virtually any terrain. Some of the key technologies that are available today but not when these concepts were first envisioned include the following:

- ***Low-cost, low-power computer technology* –** While the older vehicle concepts had to rely on skilled pilots operating mechanical control vanes or using simple analog control methods, modern-day microcontrollers operate the Hoverbike. The flight control computer reads sensor data (from onboard gyroscopes and other sensors to user control inputs) and provides constant adjustments of rotor speeds in excess of 400 times per second. The combination of computational capability afforded by current low-power consumer electronic devices and robust flight control algorithms provides the dynamic control authority necessary for safe operation.
- ***High-density magnet technology* –** Samarium-Cobalt (SmCo) "rare earth" magnet technology, developed in the early 1970s, provides high-density magnetic fields that substantially increase electric motor efficiency and reduce both the size and weight of electric motors. Although the original SmCo magnets were brittle and costly, they have since been replaced with Neodymium (Nd) permanent magnets, introduced in the 1980s.
- ***High-efficiency motor controllers* –** Permanent Magnet Synchronous Motor (PMSM) and Brushless Direct Current (BLDC) motor controllers, with up to 97% efficiency, are now available, leveraging state-of-the-art microcontrollers to provide unmatched efficiency, reduced size/weight, and a price point that is a fraction of what was available a decade ago.
- ***Electric motors* –** Only in the last few years have there been commercially available lightweight and high-efficiency electric motors that have been designed specifically for direct drive-aircraft applications. These motors reduce weight through eliminating heavy and complex gearboxes, and using rare earth Nd permanent magnets, computerized numerical control (CNC) manufacturing, and sophisticated phase control algorithms.
- ***Composite materials* –** New composite materials and additive manufacturing technologies provide lower-weight structural components, which translate into higher overall vehicle efficiencies, less vehicle weight, and more useable payload-carrying capacity.

The combination of the aforementioned advances and the proliferation of commercially available components in each of these technology areas has provided a good foundation to develop new vehicle concepts, such as the second-generation Malloy Aeronautics Hoverbike concept (pictured in Figure 4). The Hoverbike represents the culmination of years of developing and combining these technologies into a new class of vehicle. It combines the design of the original P1 prototype with fly-by-wire electric-drive quadcopter technology. Its increased stability and redundancy, as well as its unmanned operation, make it ideally suited for military applications.

## BENEFITS OF THE HOVERBIKE CONCEPT

The second-generation Hoverbike concept implements all of the aforementioned advances in technology, while simultaneously incorporating survivability and reliability enhancements. Key features of the Hoverbike include the following:

Figure 4: Second-Generation Hoverbike Concept.

- ***Improved stability* –** The second-generation overlapping quad-rotor concept provides an inherently more stable platform than the original dual-rotor prototype, while maintaining ergonomic ingress/egress from the platform and providing shrouded ducting for protection to both passenger and vehicle. The unique and patent-pending overlapping rotor system is also an extremely stiff and efficient structure, providing additional payload capacity through weight savings and lower disk loading for the vehicle footprint.
- ***Improved survivability and reliability* –** The Hoverbike, through multi-engine redundancy and an innovative augmented-yaw control system, is able to maintain controlled and stable flight should a single rotor fail. Redundancy at the system and subsystem levels and the ability to have emergency egress provide a unique capability for this new class of vehicle.
- ***Adaptable chassis* –** Unlike traditional vehicles, which rely on drive shafts or similar methods to distribute power to the lifting system, the Hoverbike's distributed drive system and modular power systems allow for quick and easy reconfiguration of the center vehicle section for mission-specific purposes. Examples include medical evacuation (MEDEVAC), squad supplies and logistics, heavy sensors, and Special Forces roles.

> The Hoverbike's increased stability and redundancy, as well as its unmanned operation, make it ideally suited for military applications.

- ***Minimal training–*** The Hoverbike and its variants are designed to be low maintenance due to their simple and robust drive systems. The vehicle's fully autonomous capability can minimize the need for training, as the flight controls can provide varying levels of pilot input augmentation.

- ***Acoustic and radar signature –*** The Hoverbike has been designed to be a relatively small vehicle capable of safe, low-level flight. In addition to its small physical footprint and operation envelope (which is designed to be largely below radar), the Hoverbike features shrouded fans. The shrouds not only keep occupants and ground crew safe, but they also mask tip noise generated by the propellers.

- ***Power generation –***The multi-fuel-capable onboard generator can supply more than 70 kw of continuous power where and when it is needed. And when not being used for transportation, logistics, or surveillance, the Hoverbike can also provide useful onsite power.

- ***Logistics –*** Using the autonomous capability of the Hoverbike allows simple waypoint-to-waypoint navigation by relatively unskilled users. And the small size of the Hoverbike and the safe shrouded propellers allow supplies to be delivered where needed, and without the need for a larger runway or clearing (as shown in Figure 5). The use of the Hoverbike platform as an unmanned asset purely for materiel transport is an attractive application in and of itself. Bypassing the need to put highly trained personnel and expensive aircraft assets at risk, the Hoverbike can shuffle supplies directly to military units in remote locations.

## INITIAL RESEARCH AND DEVELOPMENT (R&D)

Under a preliminary R&D effort through DSIAC, a scale-model analysis of the Hoverbike concept and full-scale Hoverbike flight testing were conducted to evaluate the vehicle's suitability as a Tactical Reconnaissance Vehicle (TRV) that can avoid improvised explosive devices (IEDs) by hovering over roadways or avoiding them altogether.

Several 1/3-scale models of the Hoverbike and proposed TRV concept vehicle were built and tested to evaluate vehicle ground effects, drive train and air flow efficiencies (as shown in Figure 6), terrain handling, and flight controls. These models were used as an initial test bed to experiment on during design and development of full-scale modifications/testing.

The effort culminated with the construction of the full-scale Hoverbike vehicle, which was flight tested in and out of ground effect to analyze performance, stability, and the functionality and efficiency of the drive system. Figure 7 shows a weighted mannequin on the Hoverbike being remotely controlled to test the vehicle stability and control algorithms.

Figure 6: Scale Model Airflow Testing.

The overall result/conclusion from the DSIAC effort is that the Malloy Aeronautics Hoverbike concept, at the desired objectives of 400 lbs and 800 lbs of payload capacity, is feasible, with no significant technical hurdles required to achieve these objectives.

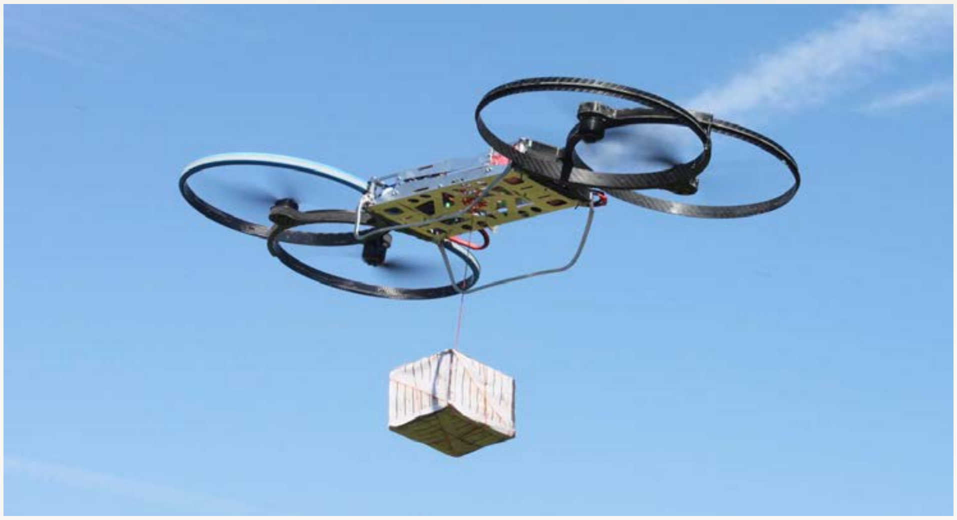

Figure 5: Hoverbike in Logistics/Sustainment Resupply Role.

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## CONCLUSIONS

The Hoverbike is a technology whose time has come. Just as smaller drones have seemingly invaded the airspace today, we may soon be establishing new "roadways in the skies" where this type of vehicle opens new avenues for logistics and transportation. Military commanders will have added flexibility in moving troops and supplies, and individual soldiers will have unprecedented personal maneuverability options. Furthermore, leaders of, say, humanitarian and emergency response efforts will have a new ability to move medical supplies and personnel into remote regions affected by earthquakes, hurricanes, and other natural disasters. Thus, we are now at a point where science fiction is poised to become reality, and the possibilities, like the skies themselves, are seemingly endless. ■

## BIOGRAPHY

**MARK BUTKIEWICZ** is the General Manager of the SURVICE Engineering Company's Applied Technology Operation. He has more than 30 years of engineering experience in military and space research and development, including his current support of Hoverbike development through a strategic partnership between SURVICE and Malloy Aeronautics. Mr. Butkiewicz holds a B.S. in mechanical engineering from the University of Maryland.

**CHRIS MALLOY** is the Managing Director of Malloy Aeronautics, and designer/inventor of the Hoverbike. He has more than 15 years of experience in engineering design and fabrication, with an emphasis on research and development and rapid prototyping. Mr. Malloy is also a licensed helicopter pilot, with experience as an aerial surveyor.

## DTIC SEARCH TERMS:

Hover Transportation Technology

**RESULTS:** 13,300

- Helicopters (3,158)
- Foreign Reports (1,454)
- Military Operations, Strategy & Tactics (1,201)
- Aircraft (1,131)
- Government & Political Science (1,118)
- FBIS Collection (923)
- Symposia (879)
- Test & Evaluation (846)
- Theses (757)
- Military Forces & Organizations (703)

*See page 16 for explanation ▸

Figure 7: Early Flight Control Testing of Full-scale Hoverbike Concept.

**Photo Credit: Lance Cpl. Kathy Nunez, U.S. Marine Corps.**

# LIGHTENING THE LOAD

## FOR THE MODERN MARINE

**By Capt. Anthony Ripley**

## INTRODUCTION

Dismounted U.S. Marines perform some of the most physically demanding missions, often requiring extensive situational awareness, overwhelming firepower, and considerable quantities of energy. Over the last 10 years, the Marine Corps has successfully achieved increased lethality and capability, but it has departed somewhat from its expeditionary, lightweight, fast-moving roots. Today's infantry battalions consume significantly more energy than their counterparts did a decade ago. In fact, since 2001, Marine Corps battalions have experienced a:

- 250% increase in radios
- 300% increase in information technology (IT)/computers
- 200% increase in the number of vehicles
- 75% increase in vehicle weight
- 30% decrease in vehicle fuel efficiency/miles per gallon (mpg) [1].

Marines have also become critically dependent on fuel, battery, and water logistics/resupply. This dependence has resulted in increased personal risk on the battlefield, especially for those Marines, soldiers, and civilians hauling fuel and water. And it has exacted a high toll. One Marine or civilian is injured in every 50 fuel/water convoys [2], and a buried explosive incident occurs in every 17 convoys. Consequently, for the individual Marine, the increased dependency on energy has meant an increase in overall weight carried, increased injury, and an increased dependence on resupply.

A typical dismounted Marine carries up to 20 lbs of batteries, in addition to his combat load, and requires 3 gal of water a day in an arid environment [3], equating to approximately 75 lbs of water for a 72-hr mission. The batteries and water alone add significant weight to an already heavy load (see Figure 1). These items also constrain lines of communication and limit the marine's ability to penetrate deeper into enemy territory. Accordingly, a practical solution is needed to address these problems.

## PROBLEM DESCRIPTION

Traditional approaches to modernization have often been to develop and incorporate power-consuming material solutions into dismounted forces operations without fully considering the overall impact on the individual Marine. Conversely, when systems are developed for aircraft or vehicles, similar constraints are clearly specified. These constraints—which include factors such as maximum gross weight, center of balance, size, weight, and power—are largely absolute. Accordingly, subsystems are developed within the boundaries of established trade space. And the reason is simple: if aircraft are too heavy, they don't fly. Likewise, if the weight on Marines is too heavy, they either function at a reduced capacity, or they break.

The Services have attempted to address the weight and power problem by developing lighter technologies, higher-energy density batteries, and renewable technologies. However, individual materiel prototyping has failed to deliver the widespread acceptance needed for adopting renewable energy-harvesting technologies, which are currently demonstrating the potential to significantly reduce the battery weight and resupply requirements of Marine Corps units.

| ITEM | WEIGHT (LBS) |
|---|---:|
| Silk Weight Undershirt | 0.37 |
| Protective Under Garment | 0.55 |
| Socks, Extreme Weather | 0.30 |
| Utility Belt | 0.25 |
| Flame Resistant Org. Gear (I&II) | 3.39 |
| Rugged All Terrain Boots | 3.12 |
| Plate Carrier w/ E-Side SAPI Inserts | 28.00 |
| Protective Over Garment | 2.15 |
| Multi-Purpose Bayonet | 1.60 |
| Holster | 1.70 |
| Complete Hydration System (100 oz water) | 10.19 |
| Intra Squad Radio AN/PRC-153 | 1.10 |
| LWH w/reversible cover | 3.50 |
| FROG Baclava | 0.20 |
| Chest Rig (w/ Magazine x7) | 9.40 |
| FROG Gloves | 0.18 |
| Knee and Elbow Pads | 1.60 |
| Ballistic Hearing Protection | 0.01 |
| Ballistic Eyewear Set | 0.32 |
| Hand Held Flashlight | 0.31 |
| Assault Pack | 5.51 |
| Pistol, M-9 | 2.50 |
| Improved Modular Tectical Vest | 11.00 |
| Rifle, Combat Optic | 1.00 |
| Night Vision Devices AN/PVS-14 | 1.00 |
| Illuminator, Infrared AN/PEQ-15 | 0.44 |
| Combat Assault Sling | 0.65 |
| M50 Gas Mask | 3.00 |
| Rifleman's Suite (Pouches) | 2.00 |
| Rifle, M16A4 (M-4 Shown) | 6.70 |
| **Total Weight** | **102.04** |

*NOTE: Loads typically increase for sustained operations.*

Figure 1: Typical Marine Assault Load [4].

To effectively provide energy solutions to the Warfighter, developers need to fully understand the energy consumption requirements. In the past, attempts to specify power requirements were performed simply by reviewing product data sheets and adding up the total power to determine the requirements. This approach has not accurately captured the tactical environment power usage profile for an individual up to the company level. For example, the PRC-117G radio has a specified power requirement of 55 W in one mode, but what is not specified is the power requirement for other operational modes, the duty cycle, and the length of time an operator will use it in each mode during various missions.

At an institutional level, the joint Services sometimes appear to have a questionable understanding of the actual power requirements and usage profiles that are necessary for a company in a tactical environment. This deficiency, along with the myopic evaluation of each individual technology solution, contributes to unchecked increasing power demands and, ultimately, an uninformed acquisition process. Instead of viewing each piece of technology individually, each piece should be evaluated against the individual, squad, platoon, or company "as a system," much like the requirements for the preceding aircraft example.

The Army has started using this approach with the creation of the Soldier as a System (SaaS) concept. This systems engineering approach ensures that requirements such as the maximum weight that the individual through the company (as a system) can carry, as well as individual- to aggregate-unit-level power requirements, are considered. Capability developers have suggested that dismounted Warfighters are considerably less effective when saddled with 190-lb loads and excessive power requirements. However, we continue to observe increasing weight and power requirements due to stove-piped technology development processes and organizations within the Services that are not using an SaaS approach.

## TWO-PRONGED APPROACH TO SOLVING THE PROBLEM

### *Dismounted Forces Energy Requirements (DFER) Integrated Product Team (IPT)*

The DFER-IPT is challenged with developing, promulgating, and incorporating energy-specific attributes for capabilities integration officers (CIOs) whose requirements result in solutions that are carried/employed by, or interface with, dismounted forces. The desired end state is to lighten the individual Warfighter load, improve energy performance, minimize the burdens of tactical resupply, and reduce overall costs to the Department of Defense (DoD).

The DFER IPT consists of representatives from the Army, Marine Corps, Office of Naval Research, Office of the Secretary of Defense, Marine Corps Systems Command, Capabilities Development and Integration, etc., and comprises the following four working groups:

- The Integration and Interoperability Working Group (IIWG)
- The Energy Sustainment Working Group (ESWG)
- The Mobility, Safety, & Survivability Working Group (MSSWG)
- The Energy Modeling Working Group (EMWG).

> A typical dismounted Marine carries up to 20 lbs of batteries in addition to his combat load and requires 3 gal of water a day in an arid environment.

The IIWG will establish a standard for electrical and mechanical interfaces for use by dismounted Warfighters to maximize interoperability and the ability to accept external power. The IIWG will also establish a standardized family of batteries to control battery proliferation.

The ESWG will provide the applicable guidance and determine the energy sustainment requirements that developers must consider, with respect to architecture and performance, to ensure future systems are integrated; impose the least possible physical burden for dismounted forces; minimize logistical resupply; and facilitate the harvesting, regeneration, and/or scavenging of energy.

The MSSWG will recommend mobility metrics for worn and carried dismounted forces power systems, as well as metrics to control hazards to the individual and retain dismounted forces survivability through testable system performance measures.

Lastly, the EMWG will assist the IPT and requirements and acquisition professionals with defining energy performance considerations early in the development of new equipment and upgrades to legacy capabilities.

Together, these working groups will tackle a significant problem and in the end provide constraints that will bound the size, weight, and power requirements of future dismounted systems. The DEFR IPT is targeting the middle of fiscal year 2016 to wrap up its efforts.

### *The Joint Infantry Company Prototype (JIC-P)*

The JIC-P (illustrated in Figure 2) is a joint effort between the Army and the Marine Corps (led by the Marine Corps Expeditionary Energy Office [E2O]) that is planned to address many of the problems discussed herein. The 18–24-month effort is aimed at lightening the load and reducing the size, weight, and power requirements of dismounted systems. It will provide the Marine expeditionary rifle company with a unique, self-sustainable capability set that enables dismounted multi-day operations in an austere environment while informing the DFER-IPT. The program will include a company concept of operation development, modeling, technology development, integration, and large-scale testing and evaluation.

The evaluation will start small but grow to include a side-by-side evaluation of

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25 Vest Power Managers (VPM) and 25 Integrated Soldier Power and Data Systems (ISPDS) with 50 kinetic-energy-harvesting backpacks, 50 kinetic-energy-harvesting knees, 50 lightweight photovoltaic panels, and 100 conformal rechargeable batteries. A side-by-side comparison of the Marine Corps VPM and the Army ISPDS will inform the joint community and play a crucial role in determining the future small unit power architecture for the Marine Corps. This effort will be accomplished through a collaborative partnership between the Naval Surface Warfare Center Dahlgren (NSWCD), the Natick Soldier Research and Development Engineering Center (NSRDEC), the Army, and the Marine Corps. ■

## REFERENCES

[1] Commandant of the Marine Corps. "United States Marine Corps Expeditionary Energy Strategy." p. 8, 5 March 2011.

[2] Commandant of the Marine Corps. "United States Marine Corps Expeditionary Energy Strategy." p. 7, 5 March 2011.

[3] U.S. Marine Corps. "Marine Corps Warfighting Publication 4-11.6, Petroleum and Water Logistics Operations." 19 June 2005.

[4] Jim Smerchanski. Marine Corps Systems Command Load Brief. 27 March 2015.

[5] Capt. Anthony Ripley. Joint Infantry Company Prototype Brief. 21 July 2014.

## BIOGRAPHY

**CAPT. ANTHONY RIPLEY** is currently serving as the Science and Technology Lead for the Marine Corps Expeditionary Energy Office. His more than 20 years of military service includes serving as an Aviation Warfare Systems Operator and Search and Rescue Swimmer in the U.S. Navy, as well as serving as a Maintenance Materiel Control Officer, Assistant Aircraft Maintenance Officer, Airframes and Aviation Life Support Systems Division Officer, and HAZMAT officer in the U.S. Marine Corps. His service has also included multiple deployments to the Persian Gulf, Iraq, and Afghanistan. Capt. Ripley holds B.S. degrees in criminal justice and sociology from the University of Idaho, as well an M.S. in management and certifications in energy and defense systems analysis from the Naval Postgraduate School.

## DTIC SEARCH TERMS:

Dismounted Soldier Load

**RESULTS:** 10,600

- Military Operations, Strategy & Tactics (2,406)
- Military Forces & Organizations (1,274)
- Army Personnel (1,186)
- Test & Evaluation (993)
- Military Operations (929)
- Combat Vehicles (850)
- Logistics, Military Facilities & Supplies (839)
- Warfare (798)
- Army Operations (734)
- Army Training (726)

*See page 16 for explanation ▸

**Figure 2: U.S. Army JIC-P System [5].**

# CONFERENCES AND SYMPOSIA

## JANUARY 2016

**Tactical Power Sources Summit**
25–27 January 2016
Sheraton Pentagon City
Washington, DC
**http://www.sae.org/events/gim** ▸

**Tenth Symposium on Performance of Protective Clothing and Equipment: Risk Reduction Through Research and Testing**
28–29 January 2016
Grand Hyatt San Antonio
San Antonio, TX
**http://www.astm.org/SYMPOSIA/filtrexx40.cgi?+-P+MAINCOMM+F23+-P+EVENT_ID+2772+-P+MEETING_ID+95831+sympotherinfo.frm** ▸

## FEBRUARY 2016

**Marine West**
3–4 February 2016
Marine Corps Base
Camp Pendleton, CA
**http://www.marinemilitaryexpos.com/marine-west.shtml** ▸

**AAS Guidance and Control Conference**
5–10 February 2016
Beaver Run Resort
Breckenridge, CO
**http://aas-rocky-mountain-section.org** ▸

**2016 Human Systems Conference**
9–10 February 2016
Waterford at Springfield
Springfield, VA
**http://www.ndia.org/meetings/6350/Pages/default.aspx** ▸

**Development, Affordability and Qualification of Complex Systems**
9–10 February 2016
The University of Alabama in Huntsville
Huntsville, AL
**https://vtol.org/events/development-affordability-and-qualification-of-complex-systems** ▸

**26th Space Flight Mechanics Meeting**
14–18 February 2016
Embassy Suites Napa Valley
Napa, CA
**http://www.space-flight.org/docs/2016_winter/2016_winter.html** ▸

**AFCEA WEST Conference and Exhibition**
17–19 February 2016
San Diego Convention Center
San Diego, CA
**http://westconference.org/West16/Public/Enter.aspx** ▸

**Air Force ISR Industry Day**
25 February 2016
Engility Heritage Conference Center
Chantilly, VA
**http://www.afcea.org/calendar/eventdet.jsp?event_id=26122** ▸

## MARCH 2016

**2016 Live Fire Test and Evaluation**
1 March 2016
The MITRE Corporation
McLean, VA
**http://www.ndia.org/meetings/6390/Pages/default.aspx** ▸

**ASNE Day 2016**
2–3 March 2016
Hyatt Regency Crystal City
Arlington, VA
**https://www.navalengineers.org/events/individualeventwebsites/Pages/AD2016.aspx** ▸

**Ground Robotics Capabilities Conference and Exhibition**
2–3 March 2016
Waterford at Springfield
Springfield, VA
**http://www.ndia.org/meetings/6380/Pages/default.aspx** ▸

**31st Annual National Test and Evaluation Conference**
2–3 March 2016
The MITRE Corporation
McLean, VA
**http://www.ndia.org/meetings/6910/Pages/default.aspx** ▸

**Eighteenth Annual Directed Energy Symposium**
7–11 March 2016
Uptown Marriott
Albuquerque, NM
**http://www.deps.org/DEPSpages/DEsymp16.html** ▸

**Directed Energy Education Workshop**
9–10 March 2016
Uptown Marriott
Albuquerque, NM
**http://www.deps.org/DEPSpages/EduWksp16.html** ▸

**AUSA ILW Global Force Symposium and Exposition**
15-17 March 2016
Von Braun Center
Huntsville, AL
**http://ausameetings.org/globalforce** ▸

**National Geospatial-Intelligence Agency Industry Day 2016**
16 March 2016
NGA Campus East
Springfield, VA
**http://www.afcea.org/events/nga/16/welcome.asp** ▸

**Smart Structures/NDE 2016**
20-24 March 2016
JW Marriott Las Vegas Resort & Spa
Las Vegas, NV
**http://spie.org/conferences-and-exhibitions/smart-structuresnde** ▸

**TechNet Air 2016**
22-24 March 2016
Henry B. Gonzalez Convention Center
San Antonio, TX
**http://events.afcea.org/Air16/Public/Enter.aspx** ▸

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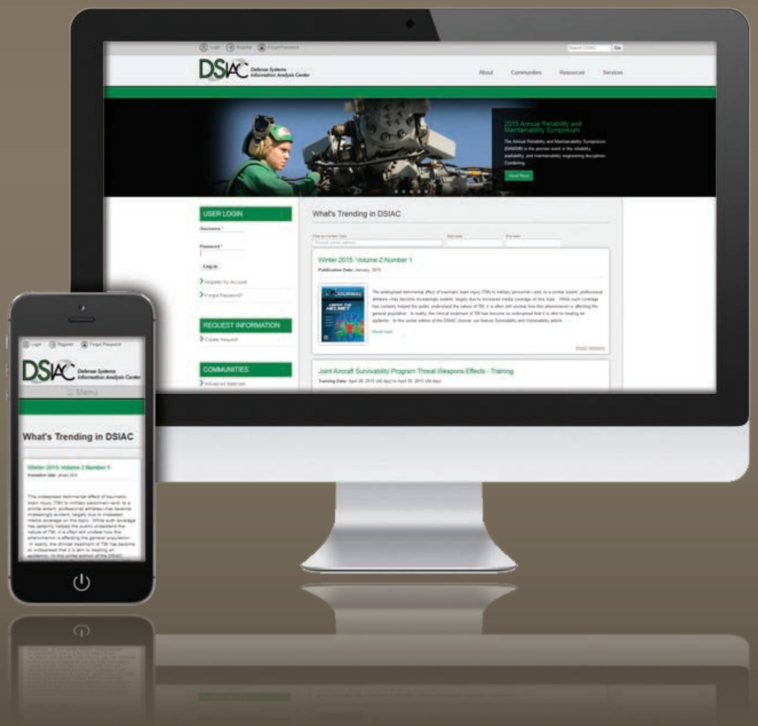

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