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May 2014

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Supplement to *NASA Tech Briefs*

May 2014

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SPECIAL ISSUE
Unmanned Vehicle & Robotics Technology

Navigating Regulatory Compliance for UAV Electronics Development

Simulating Lightweight Vehicles Operating On Discrete Terrain

UUV Developments for Defense and Commercial Applications

The Evolution of Tactical Robots

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A U.S. Air Force MQ-1 Predator unmanned aerial vehicle (UAV) conducts a mission over hostile terrain. The future use of UAVs in civil airspace raises a host of regulatory and safety issues that must be addressed before UAVs can be adapted to commercial applications. To learn more, read the feature article on page 6.

U.S. Air Force photo by Lt Col Leslie Pratt

Unmanned Vehicle and Robotics Technology

Welcome to a very special issue of *Aerospace & Defense Technology*.

When our publisher asked me if there were any areas of the defense industry that warranted additional coverage, I didn't have to think twice. "Unmanned vehicles and robotics," I said. It seems like you can't pick up a newspaper – or tablet computer – today without reading about a drone strike somewhere or a robot being used to detect IEDs.

Growing up as a child of the 50s and 60s, robots and unmanned vehicles were the stuff of science fiction and fantasy. Even in the 1970s, when I was in engineering school, robots were little more than characters in Hollywood movies. In 1973, the movie Westworld created a futuristic theme park where, for $1,000 a day, adventurous tourists could interact with lifelike robots in any of three themed worlds – ancient Rome; medieval Europe; or the Wild West. Pretty cool…until something went wrong and the robots turned into homicidal maniacs. It was a lot more fiction than science, particularly for a young man studying technology.

Fast forward almost 40 years. According to statistics compiled by the International Federation of Robotics (IFR), approximately 168,000 industrial robots were sold worldwide in 2013. IFR also predicts that 28,000 robots, including unmanned aerial vehicles (UAVs), will be sold for defense applications between 2013 and 2016. Perhaps the best indication of the market's potential, however, is the fact that in December 2013, Google purchased Boston Dynamics, a robotics company with strong ties to the Defense Advanced Research Projects Agency, a.k.a. DARPA.

On the unmanned vehicles front, research by Frost & Sullivan determined that in 2013 the US Department of Defense's unmanned aerial systems market generated revenues of $4.97 billion. Barring significant budget cuts, they predict that this market could generate as much as $6.53 billion in 2018.

Exciting? No doubt. That's why we've put together this special issue. In the following pages you'll get a good overview of some of the cutting-edge technology that's ensuring U.S. superiority in unmanned vehicle and robotics technology.

For example, late last year Amazon CEO Jeff Bezos made headlines by announcing plans to someday deliver parcels using a fleet of drones. And Amazon isn't the only company looking to commercialize what has been, until now, mainly military technology. There's just one problem. Commercial drones flying in civil aviation airspace would have to comply with all sorts of rules and regulations that the military doesn't have to deal with, not the least of which is safety certification. In "Navigating the Regulatory Compliance for UAV Electronics Development", a team of experts from General Atomics Aeronautical Systems, Logicircuit, LDRA Certification Services, and FAA Consultants explains what's involved in certifying unmanned aerial systems (UAS) for civil aviation.

The military also utilizes a broad array of unmanned ground vehicles (UGVs) for a multitude of missions from remote surveillance to countering improvised explosive devices (IEDs). Most of these vehicles must operate on uneven terrain like sand and loose soil, which presents certain design challenges. In "Simulating Lightweight Vehicles Operating On Discrete Terrain", a team of authors from the University of Wisconsin-Madison and U.S. Army TARDEC explains some of the computer modeling techniques used to overcome these challenges.

Another area of intense growth for both military and commercial applications is unmanned undersea vehicles (UUVs). According to Jeff Smith, CEO of Bluefin Robotics, research into UUV technology actually began back in 1957 and has grown to the point where there are now 74 different companies/institutions producing about 185 different UUVs. To see what else he has to say about this market, read "UUV Development for Defense and Commercial Applications".

Closely related in some ways to UGVs are tactical robots, which can range in size from small tracked/wheeled vehicles weighing several hundred pounds down to handheld, throwable devices that can serve as a soldier's eyes and ears in dangerous situations. LTC (Ret) Charlie Dean, who now works for QinetiQ North America, gives us a brief overview of where this market came from and where it's going in his article "The Evolution of Tactical Robots".

And last but not least, a key technology vital to all aspects of unmanned vehicle and robotics operation is command and control. As I learned from watching Westworld, the last thing the world needs is out-of-control robots or drones. In "Next Generation Antenna Design", Kathleen Fasenfest, an electrical engineer with TE Aerospace & Marine, explains some of the new materials and processes being used to improve antenna design.

So there you have it. Those feature articles, along with some interesting application stories and exclusive tech briefs you won't find anywhere else, should give you a good feel for what constitutes state-of-the-art technology in unmanned vehicle and robotics design today. Enjoy!

Bruce A. Bennett
Editor

The New Home for
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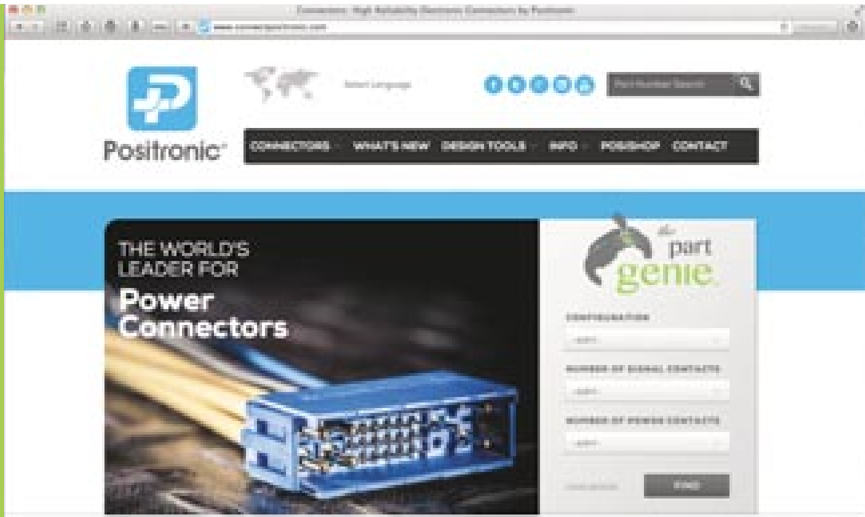

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Navigating Regulatory Compliance for UAV Electronics Development

Unmanned Aerial Vehicles (UAV) deliver sophisticated capabilities with tremendous cost advantage over traditional methods. While this technology has evolved from military missions, civil and commercial sectors are beginning to realize many of the same remote sensing benefits. However, one of the main barriers to rapid full-scale commercial growth is the concern for safety. As a myriad of certification agencies scramble to keep up with the unique demands of this fast-growing industry, one thing is clear – where applicable, pertinent certification standards for manned aircraft are starting to apply. For the complex electronics that provide the brains of these systems, this means a swift move towards compliance with DO-178C for software and DO-254 for hardware development.

UAV Evolution into the Civilian Domain

Not long ago, talk of UAV systems was reserved for the intelligence community. Today, the mainstream media is reporting on Amazon's plans to use "drones" for 30 minute deliveries. It is clear that UAV systems have progressed rapidly in the past two decades. These sophisticated machines have branched out from their military roots to offer an endless array of commercial and civil possibilities, from border surveillance to fire control, police work, aerial mapping, and so on. An estimated $8 billion industry by 2018, huge potential lies ahead for these magnificent systems.

However, several key challenges stand in the way. First is the complex and uncertain certification landscape. Second is the necessary shift in both mindset and processes from the developers of these systems themselves.

The Certification Landscape

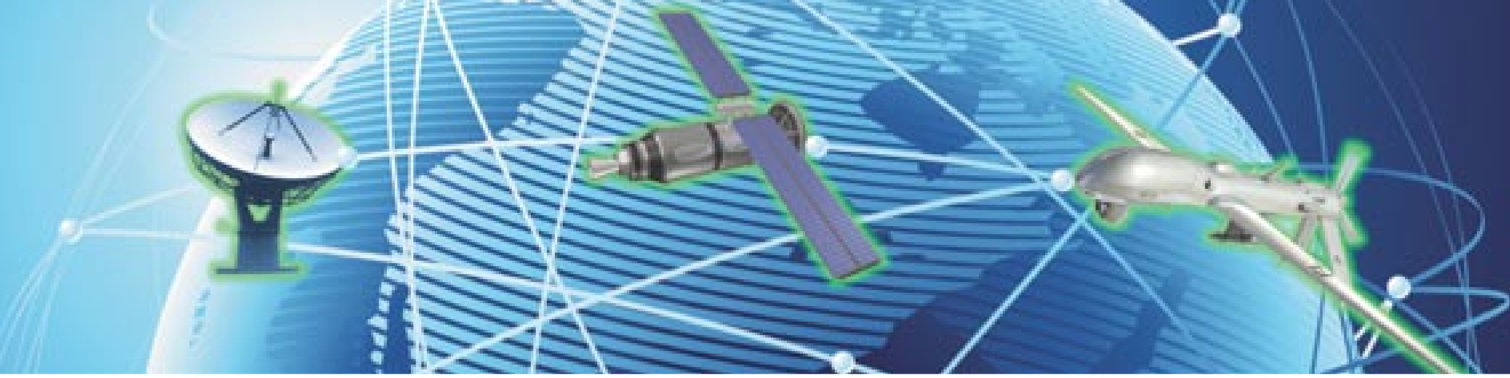
The UAV technology boom of the past two decades offered the military tremendous benefit in both budget and life savings. But in this world, accomplishing the "mission" is always the primary agenda. Safety, while a consideration, is a secondary objective as budget is available. Nonetheless, UAVs had to meet the pertinent military airworthiness guidance (e.g., MIL-HDBK 516B and MIL-STD-882E). However, as missions began morphing into possible civil applications, contracts started including requests for more robust compliance to civil airworthiness standards. Meanwhile, civil aviation agencies took notice of the Unmanned Aerial Systems (UAS) phenomena as well. What they noticed was that UAS (the term used by policy makers) include not only the vehicle itself, but also the control segment and data link – two very important differences from manned aircraft that complicate certification considerations.

A topic of discussion and concern for years, UAS certification policy has only recently gained significant momentum. At an international level, the ICAO (a special agency of the United Nations chartered with the safety of international aviation) published Circular 328 covering unmanned systems. This document states a UAS should demonstrate equivalent levels of safety as manned aircraft, and thus, meet the pertinent federal rules for flight and equipment.

At the US national level, in 2012 Congress passed a bill that mandated the Federal Aviation Administration (FAA) create a plan for allowing UAS into commercial airspace. This past November, the FAA responded by issuing the "Integration of Civil Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) Roadmap." It sets forth a list of actions required for the safe integration of UAS into the NAS. In addition to referencing the ICAO's statement, and declaring a harmonization strategy, the FAA also referenced the work of the RTCA (a non-profit industry organization that acts as a Federal Advisory Committee to the US government). RTCA Special Committee 203 (SC-203) has produced numerous documents addressing unmanned aircraft. Among them is DO-320, which states that UAS will require design and airworthiness certification to fly civil operations.

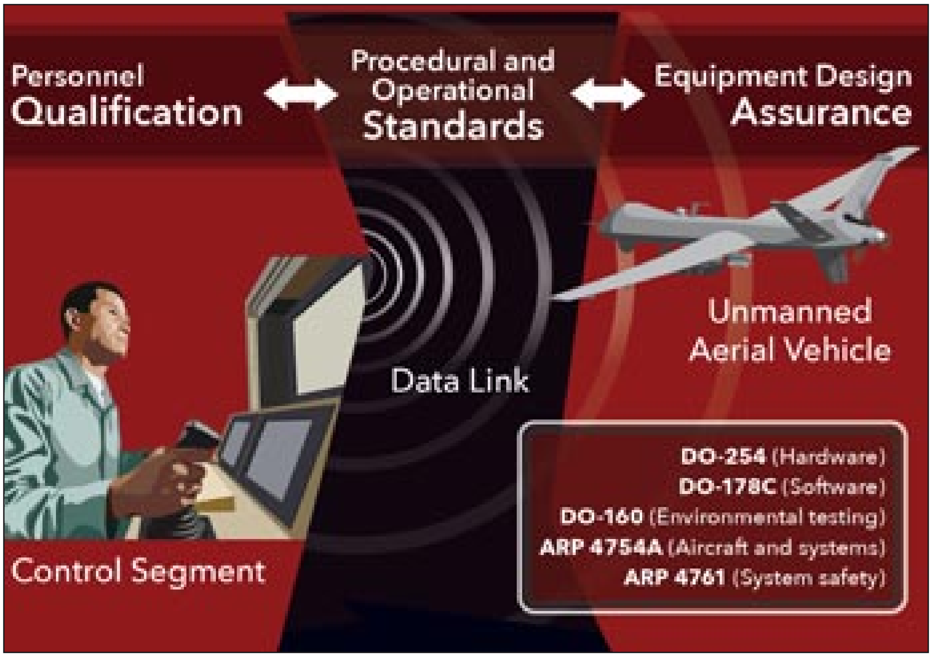
The FAA roadmap is, in essence, maturing the acceptance of UAVs from their current "experimental" standing (which allows them to fly limited missions) to requiring standard airworthiness type certificates (TCs), which will enable broader use and full integration into the NAS. In determining what is required, the FAA is leveraging existing pertinent policy and regulation, while simultaneously identifying unique needs and concerns of UAS.

From a safety perspective, if UAS must conform to the same rules and levels of safety as manned aircraft, given their relative size and weight, they would have



to comply with the Code of Federal Regulations Part 14, subpart 23 (14 CFR 23). This regulation covers airworthiness of commuter aircraft. From an equipment perspective, the main concerns are adherence to subparts 23.1301 (function and installation) and 23.1309 (equipment, systems and installation). The primary guidance that addresses development of the complex electronic systems in compliance to these federal rules includes RTCA/DO-178C ("Software Considerations in Airborne Systems and Equipment Certification") and RTCA/DO-254 ("Design Assurance Guidance for Airborne Electronic Hardware"), along with several other aircraft, systems and safety standards.

To complicate things, it may not just be the "airborne" systems that require compliance. The UAS brain is divided between the UAV itself



Regulatory Compliance Concerns of Unmanned Aircraft Systems.

UAV development is driving miniaturization of multi-function, multi-core avionics assemblies.

(which requires onboard "sense and avoid" systems) and the control segment – with the data link between the two playing a crucial role. Not only do these new system aspects need development assurance considerations, they are also pushing the technology adoption envelope in terms of complexity of both hardware and software (a challenging area for the policy makers, even in manned systems today).

An Industry Paradigm Shift

For the UAS manufacturers of Medium Altitude Long Endurance (MALE) and High Altitude Long Endurance (HALE) aircraft, primary design and development grew out of the Department of Defense's rapidly developing mission capabilities. The applicable certification criteria or airworthiness requirements were derived from MIL-HDBK-516 which employed a variety of standards, both civil and military. For these manufacturers, developing technology is a core capability. Developing in a regulated and highly controlled manner, however, was limited to applying appropriate manned standards until the FAA developed UAS policy, rules and regulations. With civil applications presenting themselves as a viable market opportunity, certification becomes a primary business objective with structure and oversight by the FAA replacing pure technological development and self-certification by the military.

For more than 10 years, General Atomics Aeronautical Systems, Inc. (GA-ASI) company leaders have envisioned the growing opportunity of civil applications and understanding of civil certification implications engaging in both process and outlook adjustments. Using a four phased approach, which includes awareness, training, implementation and enforcement, design teams now are in various stages of compliance with both DO-178C and DO-254. But understanding what compliance means can be complex, as both of these standards themselves have been evolving and changing. Many UAS stakeholders have been involved in industry technical groups such as RTCA SC-203 (disbanded) and the new SC-228 working group to address technical and operational challenges to integrating UAVs into the National Airspace System (NAS).

Complying with DO-178C and DO-254

The Code of Federal Regulations mandates that aircraft systems perform their intended function under any foreseeable operating condition. For the airborne software and hardware to comply with this rule, DO-178C and DO-254, respectively, have been developed, invoked, and are evolving as necessary.

DO-178 has been governing airborne software development for the better part of 30 years. As software complexity increases, so have both the requirements and solutions. Newly expanded and revised DO-178C presents additional compliance challenges over its predecessor DO-178B. For example, DO-178B required code coverage metrics be collected during requirements-based testing (which exercises the software's "intended function") to ensure sufficient testing of the code's structure. DO-178C adds data coupling and control coupling coverage, which are only now feasible due to test automation and technology advances not commercially available in 1992 when DO-178B was released.

On the hardware side, DO-254 compliance has been a moving target since its inception. While the original document has not changed since its finalization in 2000, interpretation has evolved significantly. Written to provide objectives for the development life-cycle of all electronics from component to line replaceable unit (LRU), in 2005, it was invoked but re-scoped to apply only to "complex custom micro-coded components." In 2008, Order 8110.105 clarified numerous aspects related to the new scoping and *The Conducting Airborne Electronic Hardware Reviews: Job Aid* was published to provide certification authorities guidelines for consistent interpretation during audits. In 2012, EASA published "Certification Memorandum SWCEH-001", which harmonized with the previous FAA documents, but also stepped beyond them in several key areas.

In addition to harmonization challenges, technology advances in both hardware and software are challenging the guidance as well. The policy makers are truly scrambling to grasp and modify the policy as quickly as technology is evolving. UAS developers will likely feel the brunt of this policy confusion as they are pushing the technology adoption envelope, but perhaps can also serve in driving acceptance of newer technologies into the certification realm.

Insight From a Leader

GA-ASI, as a leader in this transition, has gained valuable insight with the reapplication of military UAVs to civilian applications. Certification efforts have included applying relevant manned aircraft standards, both military and civil, and leveraging experience in technological areas such as data links and ground control stations, and, participating in technical industry organizations to develop a path forward while waiting for the FAA to provide final rules and regulations.

To fly a civil mission means creating a civil aircraft, which requires a type certificate (to ensure safety and design assurance, enable insurance, etc.). So internally, organizations must ensure everyone starts with a view of what needs to be accomplished - verifying the certification basis and performance requirements. This starts with assuring the system requirements are both mission and airworthiness focused. Then analyzing existing development processes against the DO-178C/254 objectives and take incremental steps towards the necessary organizational improvements. Meanwhile, any open challenges necessary to achieve the final outcome – type certification – would need to be addressed. Overcoming this challenge means opening new doors of opportunity for this industry, and developers play a big role in making that happen. Policymakers too will play a crucial role in supporting industry growth by firmly clarifying the needed certification requirements. The industry is already moving ahead in anticipation.

This article was written by Michelle Lange, Logicircuit, Inc. (Alpharetta, GA); Scott Olson, General Atomics Aeronautical Systems, Inc. (Poway, CA); Bill St. Clair, LDRA Certification Services (LCS) (Phoenix, AZ); and Todd White, FAA Consultants (Lakewood Ranch, FL). ***For more information, visit http://info.hotims.com/49745-500.***

Reseachers undertook the task of simulating a light autonomous vehicle negotiating a pile of rubble.

Simulating Lightweight Vehicles Operating on Discrete Terrain

Engineers increasingly rely on simulation to augment and, in some cases, replace costly and time consuming experimental work. However, current simulation capabilities are sometimes inadequate to capture phenomena of interest.

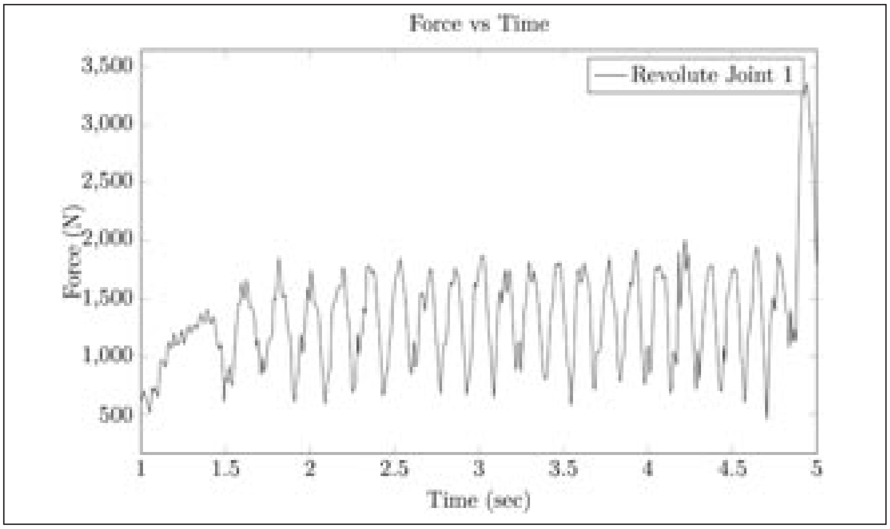
In tracked vehicle analysis, for example, the interaction of the track with granular terrain has been difficult to characterize through simulation due to the prohibitively long simulation times associated with many-body dynamics problems. This is the generic name used in this case to characterize dynamic systems with a large number of bodies encountered, for instance, when one adopts a discrete representation of the terrain in vehicle dynamics problems.

However, these many-body dynamics problems can now capitalize on recent advances in the microprocessor industry that are a consequence of Moore's law, of doubling the number of transistors per unit area roughly every 18 months. Specifically, until recently, access to massive computational power on parallel supercomputers has been the privilege of a relatively small number of research groups in a select number of research facilities, thus limiting the scope and impact of high performance computing (HPC).

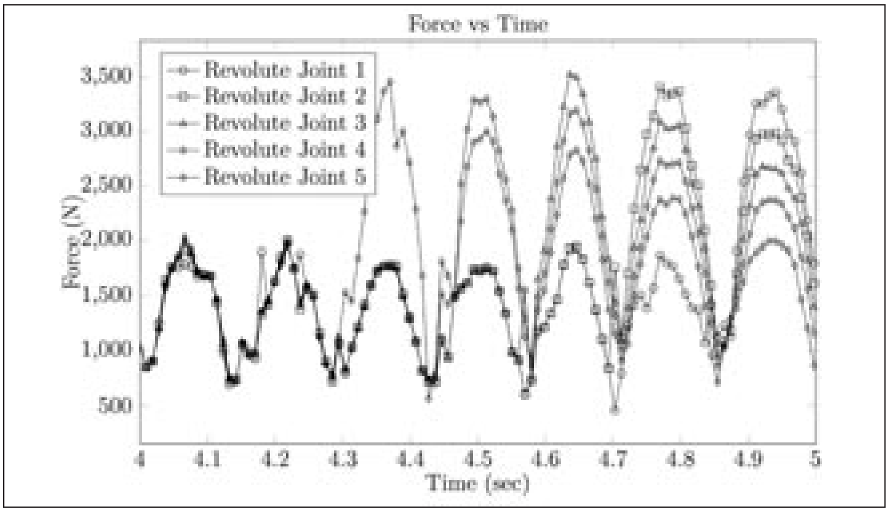
To illustrate the versatility of the simulation capability, the vehicle was assumed to be equipped with a drilling device used to penetrate the terrain. Shown is a cut-away image of the drilling tool.

This scenario is rapidly changing due to a trend set by general-purpose computing on graphics processing unit (GPU) cards. Nvidia's CUDA (compute unified device architecture) library allows the use of streaming multiprocessors available in high-end graphics cards. In this setup, a latest generation Nvidia GPU Kepler card reached 1.5 Teraflops by the end of 2012 owing to a set of 1536 scalar processors working in parallel, each following a SIMD (single instruction multiple data) execution paradigm.

Despite having only 1536 scalar processors, such a card is capable of managing tens of thousands of parallel threads at any given time. This overcommitting of the GPU hardware resources is at the cornerstone of a computing paradigm that aggressively attempts to hide costly memory transactions with useful computation, a strategy that has led, in frictional contact dynamics simulation, to a one order of magnitude reduction in simulation time for many-body systems.



Magnitude of forces in one revolute joint after the track has dropped onto the flat surface. Transient behavior was observed when the torque was applied to the sprocket at 1s and the track shoe connected to this joint came into contact with the sprocket at 5s.



Magnitude of force experienced by five revolute joints as their associated track shoes go around the sprocket.

The challenge of using parallel computing to reduce simulation time and/or increase system size stems, for the most part, from the task of designing and implementing many-body dynamics specific parallel numerical methods. Designing parallel algorithms suitable for frictional contact many-body dynamics simulation remains an area of active research.

Some researchers have suggested that the most widely used commercial software package for multi-body dynamics simulation, which draws on a so-called penalty or regularization approach, runs into significant difficulties when handling simple problems involving hundreds of contact events, and thus cases with thousands of contacts become intractable. Unlike these penalty or regularization approaches where the frictional interaction is represented by a collection of stiff springs combined with damping elements that act at the interface of the two, the approach embraced by researchers at U.S. Army TARDEC and University of Wisconsin-Madison draws on a different mathematical framework.

Specifically, the parallel algorithms rely on time-stepping procedures producing weak solutions of the differential variational inequality (DVI) problem that describes the time evolution of rigid bodies with impact, contact, friction, and bilateral constraints. When compared to penalty methods, the DVI approach has a greater algorithmic complexity, but avoids the small time steps that plague the former approach.

One of the challenging components of this method is the collision detection step required to determine the set of contacts active in the many-body system. These contacts, crucial in producing the frictional contact forces at work in the system, are determined in parallel.

The engineering application used to demonstrate this parallel simulation capability was that of an autonomous light tracked vehicle that would operate on granular terrain and negotiate an obstacle course. To further illustrate the versatility of the simulation capability, the vehicle was assumed to be equipped with a drilling device used to penetrate the terrain. Both the vehicle dynamics and the drilling process were analyzed within the same HPC-enabled simulation capability.

The modeling stage relied on a novel formulation of the frictional contact problem that required at each time step of the numerical simulation the solution of an optimization problem. The proposed computational framework, when run on ubiquitous GPU cards, allowed the simulation of systems in which the terrain is represented by more than 0.5 million bodies leading to problems with more than one million degrees of freedom. The numerical solution for the equations of motion was tailored to map on the underlying GPU architecture and was parallelized to leverage more than 1500 scalar processors available on modern hardware architectures.

Simulation Gets on Track

The simulation of the unmanned vehicle captured the dynamics of a complex system comprised of many bilateral and unilateral constraints. Using a combination of joints and linear actua-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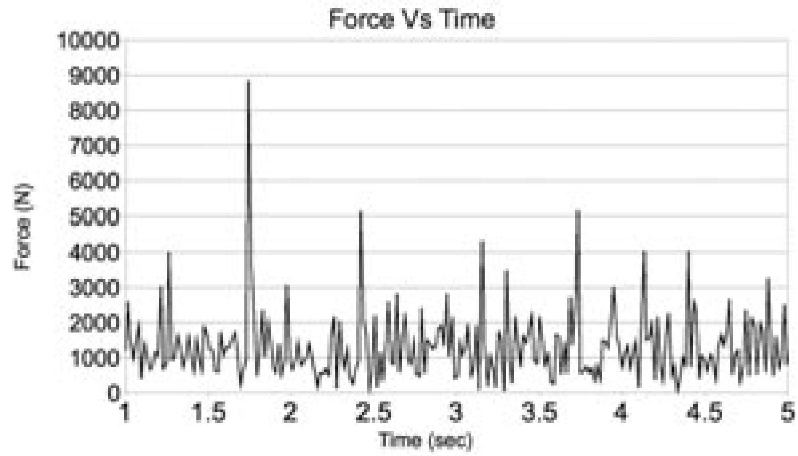
tors, the tracked vehicle model was created and then simulated navigating over either flat rigid terrain or deformable terrain made up of gravel-type granular material. The vehicle was modeled to represent a small, autonomous lightweight tracked vehicle that could be sent to another planet or used to navigate dangerous terrain.

There were two tracks, each with 61 track shoes. Each track shoe was made up of two cylinders and three rectangular plates and had a mass of 0.34 kg. Each shoe was connected to its neighbors using one pin joint on each side, allowing the tracks to rotate relative to each other only along one axis. Within each track there were five rollers, each with a mass of 15 kg, and one idler and one sprocket, both with a mass of 15 kg.

The chassis was modeled as a rectangular box with a mass of 200 kg and moments of inertia were computed for all parts using a CAD package. The purpose of the rollers is to keep the tracks separated and support the weight of the vehicle as it moves forward. The idler is necessary as it keeps the track tensioned. It is usually modeled with a linear spring/actuator but for the purposes of demonstration it was fixed to the vehicle chassis using a revolute joint. The sprocket is used to drive the vehicle and



Magnitude of force experienced by one revolute joint on granular terrain. The tracked vehicle was simulated as it moved over a bed of 84,000 granular particles.

was also attached to the chassis using a revolute joint.

Torque was applied to drive the track, with each track driven independently of the other. When the sprocket rotates, it comes into contact with the cylinders on the track shoe and turns the track with a gear-like motion.

The track for the vehicle was created by first generating a ring of connected track shoes. This ring was dropped onto a sprocket, five rollers, and an idler, which was connected to the chassis using a linear spring. The idler was pushed with 2000 N of force until the track was tensioned and the idler had stopped moving. This pre-tensioned track was then saved to a data file and loaded for the simulation of the complete vehicle.

Tracking Results

In this simulation scenario, the tracked vehicle was dropped onto a flat surface and a torque was applied to the sprocket to drive it forward; the forces on several revolute joints connecting the track shoes were analyzed as they traveled around the sprocket.

Transient behavior was observed when the torque was applied to the sprocket at 1s and the track shoe connected to this joint came into contact with the sprocket at 5s. The oscillatory behavior of the joint forces could be attributed to several factors.

First, the tension in the track was very high; there was no spring/linear actuator attached to the idler, so high tension forces could not be dampened. Second, the combination of a high pre-tensioning force (2000 N) and lack of a linear actuator on the idler resulted in high revolute joint forces.

The forces in the joint were highest when the track shoe first came into contact with the sprocket. As the track shoe moved around the sprocket, the force decreased as subsequent track shoes and their revolute joints helped distribute the load. It should be noted that the gearing motion between the track shoes and the sprocket was not ideal as it was not very smooth. In a more realistic model, forces between track shoes would be overlapping so that the movement of the tracks would be smoother and the forces experienced by the revolute joints would be smaller.

The tracked vehicle was simulated moving over a bed of 84,000 granular particles. The particles were modeled as large pieces of gravel with a radius of .075m, and a density of 1900 kg/m^3. A 100 N·m torque was applied to both sets of tracks to move the vehicle. Note that unlike the case where the vehicle moves on a flat section of ground, the forces experienced by the revolute joints are much noisier. Individual grains move under the tracks as the vehicle moves causing large vibrations to travel through the shoes. These vibrations would be reduced when modeling a more compliant terrain material that could dissipate energy on contact.

Results and Future Work

Researchers succeeded in expanding parallel simulation capabilities in multibody dynamics. The many-body dynamics problem of interest was modeled as a cone complementarity problem whose parallel numerical solution scales linearly with the number of bodies in the system. These developments have directly resulted in the ability to simulate complex tracked vehicles operating on granular terrain.

The parallel simulation capability was demonstrated in the context of an application that emphasized the interplay between light-vehicle track/terrain dynamics, where the vehicle length becomes comparable with the dimensions associated with the obstacles expected to be negotiated by the vehicle.

The simulation capability was anticipated to be useful in gauging vehicle mobility early in the design phase, as well as in testing navigation/control strategies defined/learned on the fly by small autonomous vehicles as they navigate uncharted terrain profiles.

In terms of future work, a convergence issue induced by the multi-scale attribute of the vehicle-terrain interaction problem needs to be addressed. Additionally, technical effort will focus on extending the entire algorithm to run on a cluster of GPU-enabled machines, further increasing the size of tractable problems. The modeling approach remains to be augmented with a dual discrete/continuum representation of the terrain to accommodate large scale simulations for which an exclusively discrete terrain model would unnecessarily burden the numerical solution.

This article is based on SAE International technical paper 2013-01-1191 by Dan Negrut, Daniel Melanz, and Hammad Mazhar, University of Wisconsin-Madison, and David Lamb, Paramsothy Jayakumar, and Michael Letherwood, U.S. Army TARDEC.

UUV Developments for Defense and Commercial Applications

Autonomous Undersea Vehicles (AUVs), also commonly referred to as Unmanned Undersea Vehicles (UUVs), have a history dating back to 1957 with the Special Purpose Underwater Research Vehicle (SPURV) developed by the University of Washington's Applied Physics Laboratory. Academia and special government programs drove the early decades of research but advancements were slow. Throughout the 1960s, 1970s, and 1980s, more explosive growth came for the Remotely Operated Undersea Vehicle (ROV) market which had two primary advantages: they were operated via a tether that provided power for the vehicle and man-in-the-loop control.

In the late 1980s and early 1990s, advancements were made under the Massachusetts Institute of Technology's Sea Grant AUV Laboratory in the design of lower cost, autonomous vehicles that leveraged available technologies in commercial computer processing coupled with lower power ROV sensors. In 1997, Bluefin Robotics spun out of the MIT AUV Laboratory to focus on commercial development of AUVs. Several competing firms also were formed in this timeframe, giving the primary, commercially-spurred market between 15 and 20 years of experience. Several of the large US defense contractors such as Boeing, Lockheed Martin, and Northrop Grumman predated this period for AUV development, but their focus was primarily defense and the US Navy's budgets dropped steeply in the early 2000s for AUV development. The 2000s saw slow but steady growth across the markets which included US and International Defense, Scientific, and Commercial.

Since the 2010 timeframe, the market has grown significantly as the US Navy released three large ($50M to $100M) multi-year programs for AUVs and oceanographic gliders; commercial oil and gas expanded to deeper fields off South America, Africa, and Asia; and environmental monitoring requirements grew. Further growth is anticipated in the defense markets as the US Navy shifts its focus back toward maintaining open sea lanes from supporting two decades of a land war and as international navies look to expand their maritime capabilities. Earlier this year, retired Marine Corps Gen. James Mattis, the former head of US Central Command (CENTCOM), credited a countermining exercise in 2012 in which 29 nations participated as a leading reason for Iran to back away from their threats of mining the Straits of Hormuz. On the commercial and scientific front, market growth is driven by increased utilization of ocean resources to support the world's population growth as energy, natural resources, and food needs increase substantially. Approximately 80% of the world's population lives in close proximity to the ocean and 90% of its global trade traverses the seas.

The growing demands are illustrated by the many new US and international AUV providers that have entered the market in addition to numerous academic institutions in the past 5 years. At the time of this article, the Autonomous Undersea Vehicles Application Center (AUVAC) catalogs 185 different AUVs from 74 different companies or institutions.

Environmental Challenges

The undersea environment is extreme and has many parallels with space exploration. It's an expensive environment to operate in as support ship costs can be in the multiple tens or even hundreds of thousands of dollars per day. Vehicle systems must be highly reliable as maintaining them remotely can pose challenges for parts and labor and can cause mission downtime leading to extended ship expenses. Temperature extremes can range from hot, on deck predeployment in 120 degrees to below zero at depth or in the arctic.

Some of the environmental challenges are much more daunting than space.

Class	Diameter (inches)	Displacement (lbs.)	Endurance High Hotel Load (hours)	Endurance Low Hotel Load (hours)	Payload (ft^3)
Man-Portable	3-9	< 100	< 10	10-20	< 0.25
Lightweight	12.75	~ 500	10-20	20-40	1-3
Heavyweight	21	< 3,000	20-50	40-80	4-6
Large	> 36	~ 20,000	100-300	>> 400	80-150

Table 1. UUV classes defined by the US Navy Master Plan

Lack of line of sight to satellites makes precision navigation and high bandwidth communications to the vehicles much more difficult, if not impossible. And the pressure extremes can be formidable when operating at depth. The oceans cover 70% of the Earth's surface with an average depth of over 12,000 feet (3,600 m). An AUV depth rating to 20,000 feet (6,000 m) allows it to operate on the majority of the ocean floor except for the trenches, which extend to the deepest place on the planet – Challenger Deep in the Mariana Trench, at nearly 36,000 feet (11,000 m). The pressure at 20,000 feet is over 9,000 pounds per square inch (psi), and nearly 16,000 psi at Challenger Deep. Considering, for scale, that the average SUV weighs 4000 lbs, this pressure is equivalent to multiple SUVs stacked on every square inch of vehicle surface at depth.

AUV Applications and Classes

The driving applications for the vehicles vary greatly between the defense and commercial/scientific markets but the sensor needs and even vehicle systems can often be flexible enough to address both markets. By example, a Navy may require a side scan sonar, or even a synthetic aperture sonar, to survey an operational area to determine if an undersea minefield is present. A commercial survey provider for the oil and gas industry would use an equivalent survey vehicle to determine if a site were suitable for a pipeline or a laydown area for subsea processing. With the right sensors and behaviors, AUVs can address a wide range of applications from survey, to inspection, to even intervention. Figure 1 depicts typical vehicle uses for both commercial and defense needs.

In an effort to provide industry guidance and drive commonality of systems and purpose, the US Navy published a series of UUV Master Plans that focused industry on 4 vehicle classes based on size and prioritized mission areas. Table 1 provides the AUV classes from the US Navy Master Plan for typical torpedo shaped AUVs. Endurance, payload volume, and vehicle complexity/capability commonly increase with vehicle size.

Most of the world's AUVs, whether designed for commercial purposes or defense, can be categorized into these basic vehicle classes, but typical endurances and payload sizes can vary from what was published in the UUV Master Plan. For example, the heavyweight Knifefish UUV under development by Bluefin for the Littoral Combat Ship's Mine Warfare Mission Package has a payload of over 30 ft^3. And the Naval Research Laboratory's Reliant UUV (the precursor to Knifefish) recently completed a 109 hour mission from Boston to New York (310 miles). Straightforward concepts exist to extend this demonstrated capability to ~600 hours (almost 2000 miles in range) with a heavyweight class AUV. As more large AUVs enter service and become more common, these payload volumes and endurances will extend even further.

The Navy prioritized missions to be accomplished by AUVs shown in Table 2 from the Master Plan. They also mapped how these mission areas would be satisfied by vehicle class. These missions would likely be considered common for other nations developing AUVs for defense applications.

Current Developments

With the growth of the AUV market in the past several years, there has been a healthy mix of production and development efforts in both commercial and defense. One unique class of vehicle that has emerged is a hybrid AUV/ROV that combines the traditional AUV capabilities with thin fiber optic tethers that allow for real-time data transfer and manual intervention similar to ROVs (Figure 2).

In 2011, Bluefin Robotics was awarded the production contract for the Mk19 Hull UUV Localization System (HULS). This provided an AUV capability to the Navy for inspection of ship hulls for mines or contraband that removed the need to deploy dive teams to inspect ships. The coverage rates were better than what divers could do in turbid waters and the robot could ensure complete coverage of the ship hull. The tether provided real-time access to the streaming sonar imagery in the event the vehicle identified a threat so that divers could then respond. It also provided for manual control of the vehicle to allow the support diver to more thoroughly investigate a target remotely. Bluefin is currently working on adding manipulation to this platform, leveraging the tether for remote operation.

Priority	UUV Mission Area	Man-Portable	Lightweight	Heavyweight	Large
1	Intelligence, Surveillance, Reconnaissance	Special Purpose	Harbor	Tactical	Persistent
2	Mine Countermeasures	VSW/SW SCM / RI Neutralizers	OPAREA Clearance	Clandestine Recon.	
3	Anti Submarine Warfare				Hold-at-Risk
4	Inspection / ID	HLD / ATFP			
5	Oceanography		Special Purpose	Littoral Access	Long Range
6	Communication / Navigation Network Nodes	VSW / SOF	Mobile CN3		
7	Payload Delivery				SOF, ASW, MCM, TCS
8	Information Operations		Network Attach	Submarine Decoy	
9	Time Critical Strike				(see Payload Delivery)

Table 2. UUV Mission Areas defined by the US Navy Master Plan

This concept has parallels in ground robotics where explosive ordnance teams utilize the robot for mine neutralization, thereby taking the technician out of harm's way. This class of vehicle has commercial applications for ship hull inspection and critical harbor infrastructure. In addition, Bluefin has a significantly larger (1-ton) system in final testing for much deeper rated (4,000m) inspection and light intervention.

The small AUV market is an area of growing interest, particularly for defense and scientific applications. For defense, these vehicles can provide low-cost countermeasure capabilities for torpedo defense and mine neutralization. Additionally, the small diameters (3 to 5 inches typical) provide less drag, thereby reducing the propulsion requirements for either fast-moving, or low-speed, greater persistence applications. With lower power processing advancements, these systems will be more and more capable as the personal electronics markets advance.

Bluefin has recently completed design updates to both its man-portable and lightweight class vehicles, improving the operating depths, navigational accuracies, and payload flexibility of these systems. Both the commercial and defense markets for these classes of vehicles are growing with numerous programs being released.

The heavyweight AUV space has seen significant growth in the past several years, both in defense and commercial applications. For defense, Bluefin is completing initial development testing of

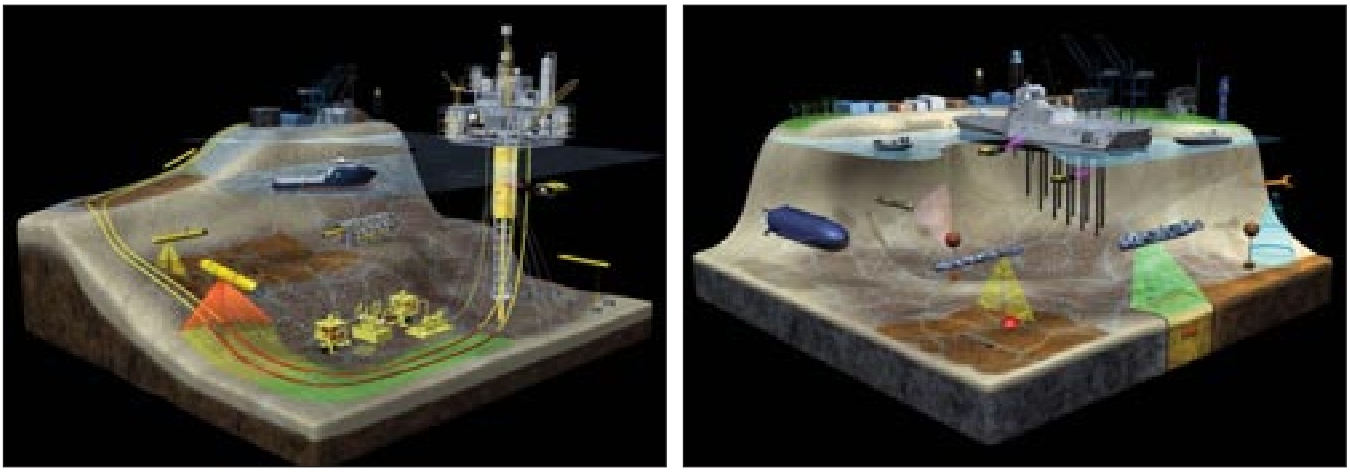


Figure 1. Similar AUV capabilities are required for Commercial (left) and defense (right) applications.

DARPA's Distributed Agile Submarine Hunting (DASH) program with a deep rated UUV with extended persistence. Additionally, Bluefin was awarded the vehicle design effort for the Knifefish UUV which will be entering sea testing this summer. Commercially, Bluefin supported global operations from commercial survey, to the hunt for Amelia Earhart, to under-ice operations in the arctic. A recently delivered 4,500m rated commercial heavyweight AUV employs a synthetic aperture sonar with a 1000m swath. This class of AUVs will see increasing applications as more advanced energy technologies are integrated to extend their persistence further.

On the large vehicle front, Bluefin is supporting its parent company Battelle and partner, the Columbia Group, in the development of Proteus Large UUV (Figure 3). This vehicle is a dual mode vehicle that can operate with divers or fully autonomously. Bluefin provides the autonomy, navigation, mission planning and subsea pressure tolerant batteries to this vehicle which has over 300 hours of in-water testing and operation accumulated as of this printing.

This article was written by Jeff Smith, CEO, Bluefin Robotics (Quincy, MA). ***For more information, visit http://info.hotims.com/49745-501.***

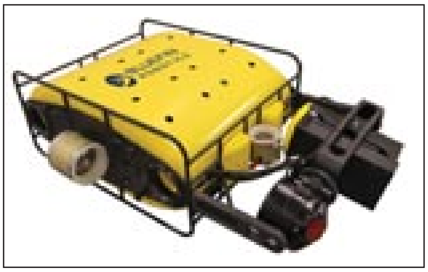


Figure 2. Hovering AUV

Figure 3. Proteus – Large Dual Mode Undersea Vehicle


The retractable arm of the TALON enables the safe removal of explosive ordnance such as improvised explosive devices. (Photo: Photographer's Mate 1st Class Robert R. McRill, U.S. Navy)

The Evolution of Tactical Robots

The lessons of yesterday and today are driving tomorrow's robotic programs.

A revolution in Unmanned Ground Vehicles (UGVs) is taking place today that focuses on formalizing the permanent integration of ground robots into military organizations within the U.S. Department of Defense and other nations' military forces as well. Similar activities are likewise cementing the relationship of UGVs to first responder organizations as ground robots continue to prove that they save lives.

The future of ground robotics is bright. Tactical UGVs will increasingly influence not only military and law enforcement operations, but other industries as well. While the most common uses for UGVs today are in providing remote reconnaissance and defeating improvised explosive devices (IEDs), robots have supported combat operations for decades. In fact, the forefathers of today's UGVs were used as assault weapons in World War II.

Early History of Tactical Robots

The story of tactical robots began in 1939 when a French inventor, Adolphe Kégresse (1879 - 1943), invented a lightweight tracked vehicle for delivering demolitions. Following the German invasion of France in May 1940, and the subsequent occupation of Paris, Kégresse's prototype was discovered by the Germans, who employed the Borgward Company to develop what would become the Sd.Kfz.302 "Goliath". This was the beginning of remotely controlled tactical vehicles and robots as they are known today.

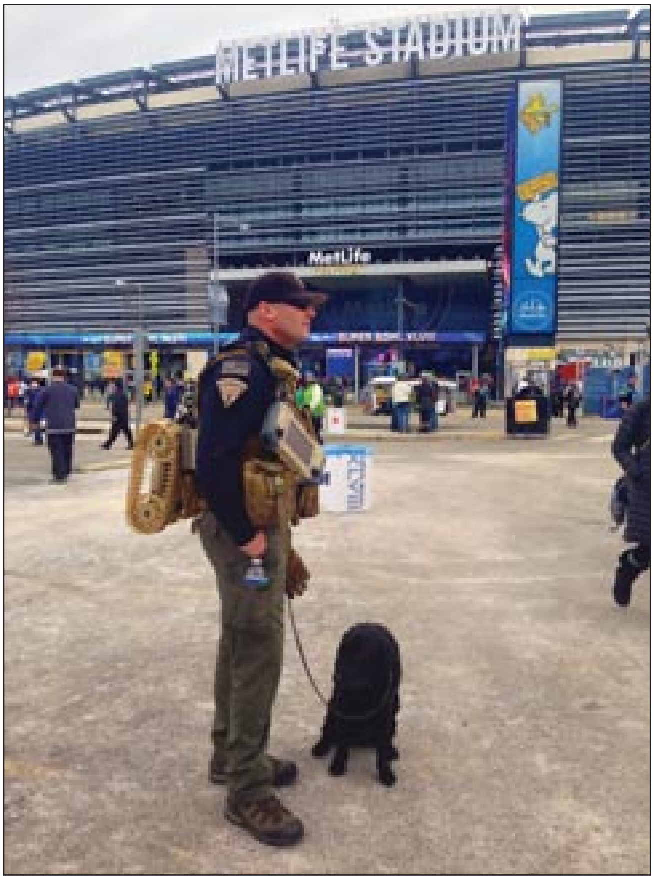
The Germans focused on remotely delivering demolitions with their small (Sd.Kfz.302/303 "Goliath"), medium (Sd.Kfz.304 "Springer") and heavy (Sd.Kfz.301 "Borgward IV") remotely controlled explosive charge carriers, even creating complete units based on manned and unmanned vehicles teaming together. To make use of captured Allied vehicles, the Germans at times added remote control kits to vehicles such as the Vickers Armstrong Universal Carrier, and loaded these with explosives.

The British experimented with several dozen small amphibian robots called "Beetles", but these swimming/crawling robots, also designed to deliver explosives, likely never saw combat. The Russians employed radio controlled "teletanks" based on control kits added to their standard T-18, T-26, T-38, BT-5 and BT-7 tanks. The battle of Kursk (Jul-Aug 1943) saw both the Germans and the Russians using remotely controlled vehicles against one another. By the end of the war, perhaps as many as 10,000 remotely controlled ground vehicles were used by the Germans and Russians alone.


A TALON robot inspects a suspected improvised explosive device. Robots such as TALON allow warfighters to clear routes quickly without having to wait for Explosive Ordnance Disposal teams to do so. Advancements in LDTO technology are making it possible to control these systems even further removed from the battlefield, increasing Soldier standoff distance. (U.S. Army photo by SGT Giancarlo Casem.)

Today's Warfighter

Following World War II, UGVs saw sporadic use until 2001, when combat operations in Afghanistan and then Iraq began necessitating the employment of large quantities of ground robots to help defeat the widespread use of IEDs. Military robots earned their battle stripes, establishing themselves as essential equipment for modern warfare. QinetiQ North America's medium sized TALON® robot, for example, has been



Massachusetts State Police officer wearing a Dragon Runner 10 robot during Super Bowl XLVIII at MetLife Stadium in New Jersey.

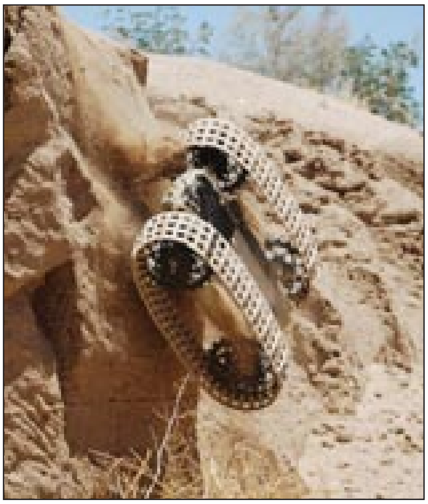
heavily used by U.S. and ISAF forces to destroy more than 50,000 IEDs in Iraq and Afghanistan. These TALON robots, numbering close to 5,000 systems fielded to date, are widely employed by military Explosive Ordnance Disposal (EOD) teams and Combat Engineer route clearance teams to locate and defeat IEDs. TALONs are the most widely used counter-IED robots in the world, and are often equipped with cutting-edge optics, sensors and tools for locating and defeating IEDs.

Small and large robots alike have also played critical roles in Afghanistan and Iraq. The smallest robots, lightweight and throwable, enable a squad to see beyond its current span of observation and into what was formerly dead space, enhancing situational awareness and unit safety. Some small robots employ modular arms and can be used to attack IEDs.

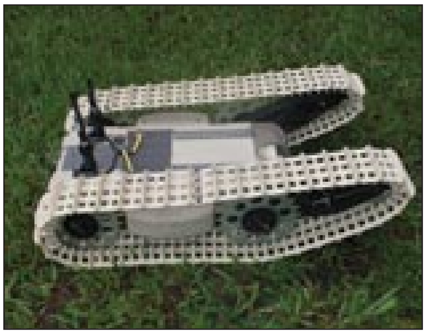
Large robots are used to assist with route clearance missions and even to autonomously carry supplies. These robots are often equipped with advanced sensors to assist with either autonomous navigation or localization of IEDs and other threats before small units are placed in harm's way.

First responders in the U.S. and overseas are learning from the combat lessons of employing UGVs to safeguard personnel in dangerous situations. Civilian bomb squads in the U.S., for example, are required to have robots in their response kits for investigation of possible threats. The first responders' robots are

Over 3,500 TALON robots have supported troops in Iraq and Afghanistan, destroying more than 50,000 IEDs and saving countless lives.



Small enough to fit inside a rucksack but tough enough to be thrown, the Dragon Runner 10 micro unmanned ground vehicle is a lightweight, compact, multi-mission remote platform developed for supporting small unit dismounted operations.



The Dragon Runner 20 gives users the ability to literally see around corners and into tight spaces, providing a flexible solution to ordnance disposal, reconnaissance, inspection and security in military and first responder applications.

often the same types of UGVs that the military is using in combat, due to the machines' proven track record in battle. Fire departments and SWAT teams are likewise picking up on the utility of UGVs and many departments today are already employing ground robots, often with sensors that were previously hand delivered.

Smaller, Lighter and More Versatile

As the wars in Afghanistan and Iraq progressed, the demand for small, lightweight counter-IED robots grew. The increasing frequency of IEDs interdicting dismounted patrols necessitated that EOD (Explosive Ordnance Disposal), engineer and infantry squads often had to carry robots on their backs. This was a challenge, if not an impossibility, with the medium-sized robots purchased earlier in the war. With evolutions in smaller, more capable radios, motors, computers, batteries and electronics over the past decade, rapid efforts were undertaken to develop and field rugged, lightweight, counter-IED robots. These easily transported systems added versatility and safety to small unit operations.

First responders are also experiencing a growing need for lightweight robots, largely learned after the Boston Marathon bombing in April 2013. While medium and large UGVs were heavily used in Boston, Cambridge and Watertown during the response to the attack, wearable robots proved their unique value as bomb squad members worked their way through congested streets to address discovered threats. These lessons are influencing current police operations as well as their planning for future law enforcement missions. Recently, quick response teams of bomb technicians employed at Super Bowl XLVIII wore Dragon Runner robots from QinetiQ North America on their backs.

The Future of Robotics

As UGVs continue to evolve, the revolution underway is taking the modern lessons learned from Afghanistan and Iraq, where 8,000-10,000 robots have been used by coalition armies, and creating enduring core programs to address both the current needs of these forces and their future requirements. These core programs will equip units with UGVs in standardized sizes and capabilities as doctrinally assigned equipment, not emergency equipment, and establish formalized training, maintenance, repair and replacement processes.

Core programs will address the needs of military forces, and perhaps first responders, for the better part of the next decade and longer. There will be ever increasing requirements for common components and software, modularity of payloads, commonality of controls, unmanning of supply vehicles and even the arming of UGVs, all the while minimizing costs and simplifying maintenance and repair. Advanced sensors will play an ever-increasing role in enabling these future robots to far better sense their surroundings, avoid collisions, detect threats, increase safety and add speed to operations. Communications systems will continue to evolve and soon all UGVs will be part of a common network where key information is seamlessly pumped to adjacent units as well as up and down the chain of command. Unmanned aircraft and ground robots will also be paired through advanced communication protocols and small unit situational awareness will increase dramatically.

The U.S. Army is exploring options to increase the combat effectiveness of smaller units through robotics, while remaining an agile, dominant force. As robotic systems further evolve to meet the needs of this changing dynamic, so too will the training and logistic needs of the warfighters who command, employ or sustain these robot-enabled fighting formations.

Though little is known about him in the U.S., Adolphe Kégresse, who invented the first tactical robot, has an enduring impact today as UGVs continue to provide ever increasing utility at extended ranges, enhancing safety and situational awareness while performing mission critical tasks.

This article was written by By LTC (Ret) Charlie Dean, Director of Business Development, QinetiQ North America (Shrewsbury, NJ). ***For more information, visit http://info.hotims.com/49745-502.***

Next-Generation Antenna Design

Materials and Processes Enable New Possibilities for Unmanned Systems Command & Control

Unmanned vehicles are finding increasing usage in military engagements, not only for aerial applications but also for ground and underwater missions. Modern antenna designs can increase unmanned vehicle fuel efficiency through reduced antenna size, increased antenna conformality, and reduced antenna weight. For airborne UAVs, time on station is a critical mission parameter directly influenced by payload weight and aerodynamics. For unmanned ground vehicles, increased antenna conformality reduces the likelihood of accidental damage that occurs with externally protruding antennas.

As designers look toward smaller and more capable UAVs, SWaP-C (size, weight, power, and cost) requirements necessitate smaller, lighter, more power-efficient components and subsystems built using modern manufacturing methods. With every subsystem as a candidate for SWaP-C improvements, small savings on subsystems can add up to significant overall savings for a platform.

Recent advances in materials and fabrication technologies are now enabling improved antenna designs with reduced size, weight, aerodynamic drag, and cost. Key innovations influencing next-generation antenna designs include composite materials and novel selective metallization processes. These innovations combine to allow cost-effective realization of three-dimensional antennas that are mechanically robust and can withstand harsh environmental conditions.

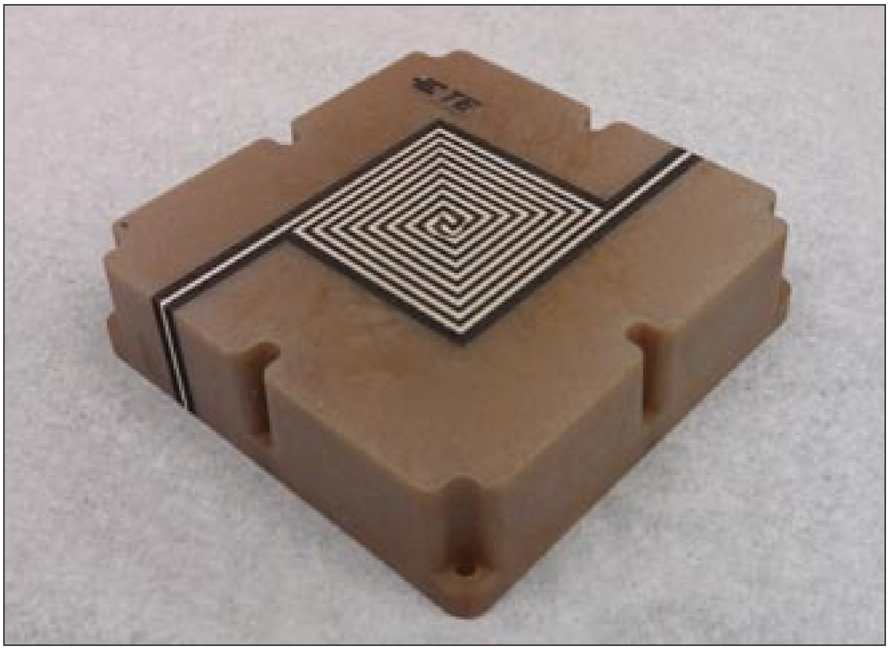


Figure 1. Conductive coatings can be flexibly and precisely applied to composite substrates. (Source: TE Connectivity)

Composites

A typical thermoplastic composite begins with high-performance engineered polymer to which fillers are added to enhance characteristics. For unmanned vehicle applications, the polymer is likely to be a high-temperature moldable thermoplastic, such as grades of PPS, PEI, or PEEK. Composite materials are strong and can be tailored to provide impact resistance, tensile strength, flexural strength, and other desirable properties. However, the choice of composites is affected by operating temperature and fluid resistance requirements, so a good understanding of the expected temperature extremes and environment of the antenna is necessary when designing composite parts.

Carbon fiber reinforced composites are addressing the need for lightweight, cost-effective, mass-producible electrically conductive parts. Conductive composites typically offer a 30 to 40 percent weight savings over aluminum parts. For antenna applications, use of carbon fiber composites range from ground planes to enclosures.

Glass fiber composites are moldable and offer an economical solution for producing radomes and antenna substrates. Typical radomes are formed using E-glass reinforcement for economical designs or quartz fiber reinforcement when low loss is critically important. Glass fiber composites offer thinner, lighter parts than non-fiber reinforced designs. Glass fibers also increase the dielectric constant of most composites, enabling antenna size reduction when these composites are used as substrate materials. Composite materials can also be engineered to provide "designer" dielectric constants through the addition of various filling materials, such as hollow glass microspheres, conductive particles, or foaming agents.

For both carbon fiber and glass fiber composites, fiber length is an important design parameter. Longer fibers offer more strength but reduced ability to manufacture small features. Moldable long-fiber composites allow significant thickness reductions while maintaining equivalent strength of short fibers. Continuous-fiber reinforcements are attractive for further weight reduction on designs with large, smooth features.

3D Selective Metallization

The typical method of metallizing specific shapes on 3D surfaces is selective plating. This process requires labor-intensive application of physical masks to the surface of the part followed by a multi-step plating process. Because of the high labor content, selectively metallized parts are usually relatively expensive.

Alternative processes include laser direct structuring (LDS) and two-shot molded interconnect devices (MID). Both allow cost-effective 3D metallization, but both are constrained by the range of available substrate materials. In addition, injection molds are required for both these processes, increasing non-recurring expenses and lead times.

To overcome these substrate limitations, TE Connectivity has developed a process for selectively metallizing 3D surfaces of arbitrary substrate materials. The process starts with the application of a sprayable conductive coating to the surface of the part. Next, this coating is cured by radiative or thermal processes. Finally, the coating is ablated to the desired pattern using a computer numerical control (CNC) laser. This process results in 3D conformal shapes with metallization resolutions as fine as 100 microns and allows molded or machined parts to be used as substrates.

This 3D selective metallization process can be applied to a wide range of substrates – including plastics, chemically resistant composites, glass, ceramic, and metals – with acceptable adhesion, a temperature range from -65°C to +200°C, and corrosion resistance. The metallization is also durable and withstands shocks, vibration, fluids, and salt spray to the levels required for most aerospace applications. This process enables rapid development and manufacture of robust 3D antennas for harsh environments.

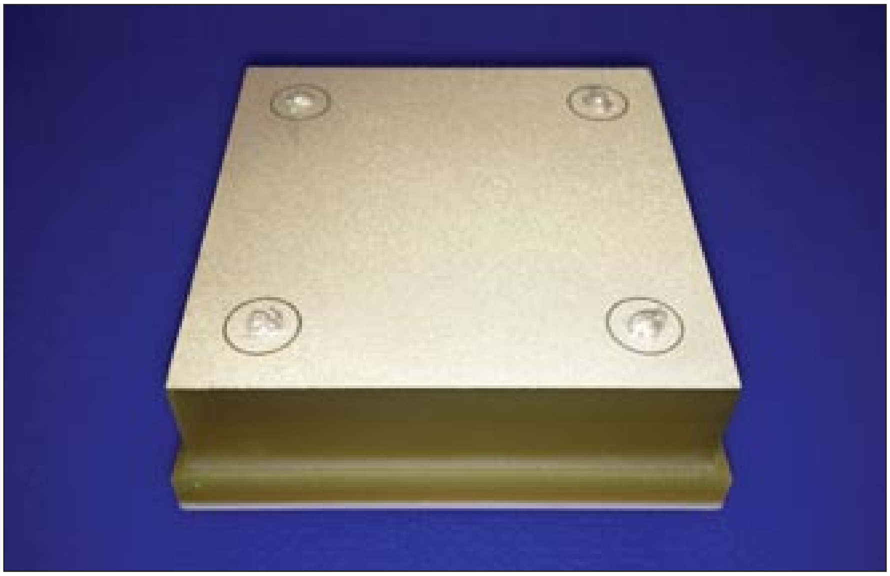


Figure 2. Moldable modular antenna design using a glass-fiber reinforced composite substrate and conductive coating. (Source: TE Connectivity)

Figure 3. Modular antenna array, which exhibits wide use of composite materials and conductive coatings in its construction. (Source: TE Connectivity)

Application to Antennas

Composites and 3D selective metallization technologies offer paths to reducing the size, weight, and cost of antennas for unmanned vehicle applications. Composites offer a great approach for building moldable, mass producible, inexpensive antenna substrates. These substrates can have arbitrary shapes and even include mechanical mounting provisions. This technology offers the antenna engineer design flexibility not afforded by traditional substrate materials.

Selective metallization through conductive coatings can offer a good solution for creating circuit traces on composite parts which would more typically be etched using standard circuit board techniques. The conductivity of some conductive coatings can approach the conductivity of bulk copper, adding only minimal loss to the circuit while enabling more cost-effective manufacturing. However, this selective metallization process is particularly useful when applied to the manufacture of three-dimensional circuit topologies. Three dimensional RF couplers and direct circuit connections to antennas now become realizable through this technology.

Within the antenna assemblies, aluminum parts can account for a large

Intro Cov ToC

portion of the total assembly weight. Composite ground planes offer 30-40 percent weight savings over traditional aluminum parts, with high manufacturability and often significant potential cost savings. Metal inserts can be provided for secure captivation of the antenna to the unmanned vehicle platform. Composite ground planes can be conductively coated if necessary to provide improved electromagnetic interference (EMI) shielding, grounding, or lightning strike protection performance. When the original aluminum parts require significant machining time to fabricate, composite ground planes can be quite cost competitive.

Traditional radome manufacturing involves hand layups of multiple material layers – a tedious, slow, and costly process that becomes difficult when intricate radome shapes are required. Recent advances in long glass fiber and continuous glass fiber composites offer approaches for achieving thinner, lighter weight radomes using injection molding. The ability to mold strong, lightweight radomes represents a significant change in the economics of antenna design and fabrication. When required, 3D selective metallization can provide lightning diversion or frequency selectivity features to these radomes.

In addition to the other advantages mentioned, conductive coatings also offer the possibility of printing antennas directly on structural composite parts of unmanned vehicles. As unmanned vehicles move toward incorporating composite body panels, conductive coatings offer an approach for functionalizing their surfaces. Antennas, RF traces, and DC wiring can now be directly printed onto components of the vehicles, rather than existing as standalone parts. This approach enables unprecedented integration of antennas into unmanned vehicles.

The Future of Antennas Has Arrived

Conductively-coated composite technology enables the cost-effective manufacture of novel antennas with reduced size, weight, and cost. Injection molded composites offer an attractive approach for mass producing antenna substrates and radomes. Selective metallization with conductive coatings allows the creation of three-dimensional antennas, circuit traces, and ground plane structures. These processes combine to offer electrically and mechanically robust antennas and arrays in conformal, lightweight form factors suitable for next-generation unmanned platforms.

This article was written by Kathleen Fasenfest, Senior Electrical Engineer, Antenna Products, TE Aerospace Defense & Marine (Berwyn, PA). ***For more information, visit http://info.hotims.com/49745-503.***

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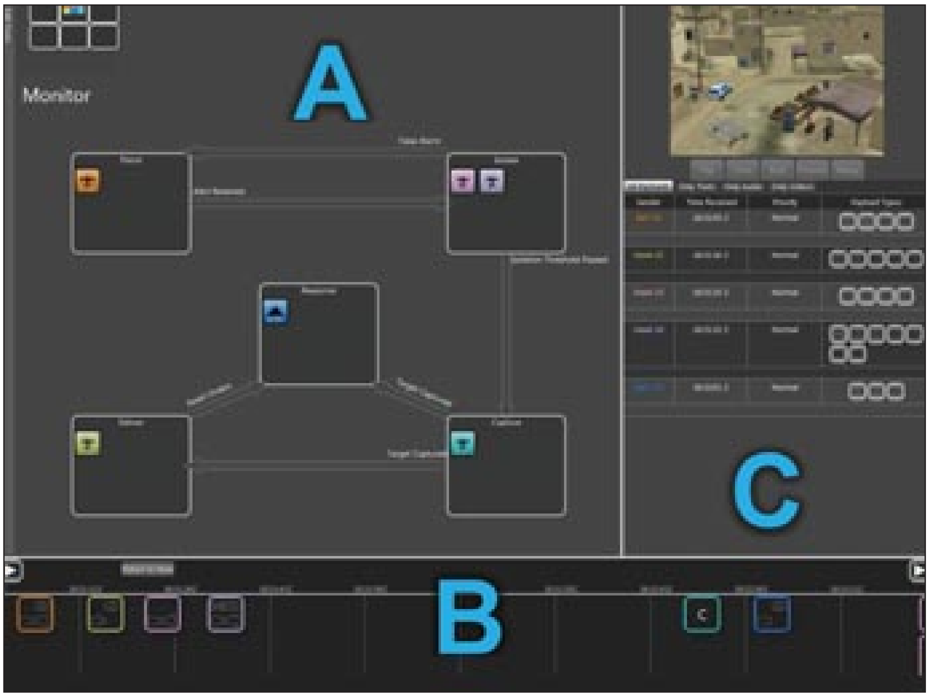
Supervisory Control State Diagrams to Depict Autonomous Activity

This method will enable a human operator to monitor, inspect, and manipulate activities of multiple UAVs, including situation assessment, decision-making, planning, and actions.

Air Force Research Laboratory, Wright-Patterson AFB, Ohio

The military seeks to enable agile and adaptive mission management and control for a team comprised of unmanned aerial vehicles (UAVs), unattended ground sensors (UGS), dismounted warfighters with mobile control stations, and an operator located in a central control station. With UAVs equipped and authorized to re-plan and act without human input, the challenge is developing methods for a human operator to sufficiently monitor, inspect, and manipulate the UAVs' activities, which include goal-directed task selection, situation assessment, decision-making, planning, and actions.



The L-PRISM and its three components: A) the State Diagram, B) the Timeline, and C) the Payload Viewer.

In addition to providing more detailed information concerning the information processing and behavior of an autonomous system, there is a challenge to present the information in a manner that affords quick and accurate assessment of the multi-vehicle system. The goal of this work was to design concepts that can support the use of symbols and patterns in an attempt to support "at-a-glance" recognition of complex activities.

Hierarchical pattern-oriented state diagram concepts are being developed to represent the autonomous activities. Layered finite state machine diagrams combined with a control timeline and payload inspection display, collectively referred to as Layered Pattern Recognizable Interfaces for State Machines (L-PRISM), will be integrated with the multi-UAV control station's tactical situation map and system status information to assist the operator to not only be aware of the vehicles' locations and planned routes, but also their mission goals, associated tasks, and states to achieve the mission goals.

The L-PRISM concept is composed of three display components: A) the State Diagram, B) the Timeline, and C) the Payload Viewer (see figure). The State Diagram uses the conventions of finite state machine diagrams to represent the autonomous system activity to the operator in real time. The State Diagram depicts the autonomy through the state nodes and transition arcs of the diagram. State nodes are display elements that represent autonomous tasks, showing what the vehicle is doing. The transition arcs represent the specific criteria for changing tasks, showing why the vehicle may move to a new task.

Multiple vehicles can be displayed in one diagram to accommodate multi-UAV monitoring and control. The State Diagram simultaneously shows the state of each UAV in the mission through vehicle icons. Vehicle icons depict the vehicle type, identify the vehicle by its call sign and unique color, and provide a time-on-task clock. The autonomous system can only make task and sub-task changes that follow the transition arcs. For tasks that have no transition arcs, task changes can only be made by operators. In general, vehicle control within L-PRISM has the flexibility to support different levels of automation, as long as there is adequate communication with the particular vehicle(s).

L-PRISM uses a layered arrangement of nested state diagrams to provide representation of autonomous tasks at varying levels of abstraction. These levels of abstraction are expected to enhance understanding and management of autonomous activities in part by displaying connections between actions, plans, and goals.

The Timeline presents information on significant mission events and provides controls to review that information across the control station. An event is represented by a colored tile containing a letter or icon that depicts a vehicle task change or payload delivery. Colors match the vehicle color that is used throughout the control station, and icons show the type of payloads. Operators can proceed forward or backward in time to investigate the tasks and actions of the vehicles and rationale behind those actions.

The Payload Viewer displays a sortable list of mission-relevant data referred to as payloads. Typical payloads are images or videos from UAV sensors, but could be operator-generated images or videos as well. Additionally, all operators (i.e., dismounted warfighters with mobile control stations and the stationary central control station) can create and send text messages or "voice note" audio recordings as payloads.

L-PRISM is an evolving supervisory control display concept that shows promise for providing many of the desired attributes and features for displaying information on a highly autonomous multi-vehicle system.

This work was done by Michael Patzek, George Bearden, and Allen Rowe of the Air Force Research Laboratory; Clayton Rothwell of InfoSciTex Corporation; and Benjamin Ausdenmoore of Ball Aerospace. ***For more information, download the Technical Support Package (free white paper) at www.aerodefensetech.com/tsp under the Information Technology category.*** *AFRL-0227*

Aerodynamic Modeling of a Flapping Wing Unmanned Aerial Vehicle

This technique models phenomena specific to flapping wing flight, including unsteady effects, significant wing deformation, and extreme angles of attack during flight.

Army Research Laboratory, Aberdeen Proving Ground, Maryland

The phenomenon of flapping wing flight in nature has been studied for centuries. Recently, flapping flight for unmanned aerial vehicle (UAV) applications has become of interest. Flapping wing flight offers many potential advan-

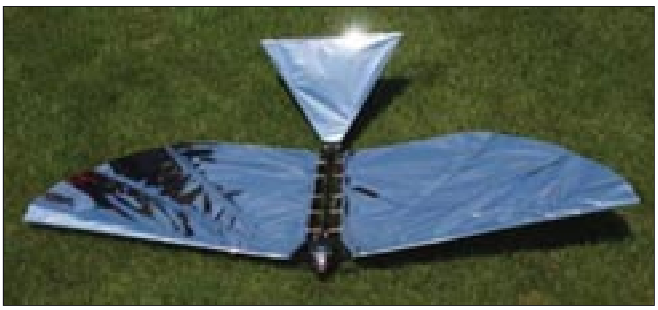


Figure 1. The RoboRaven bird-inspired Flapping Wing UAV .

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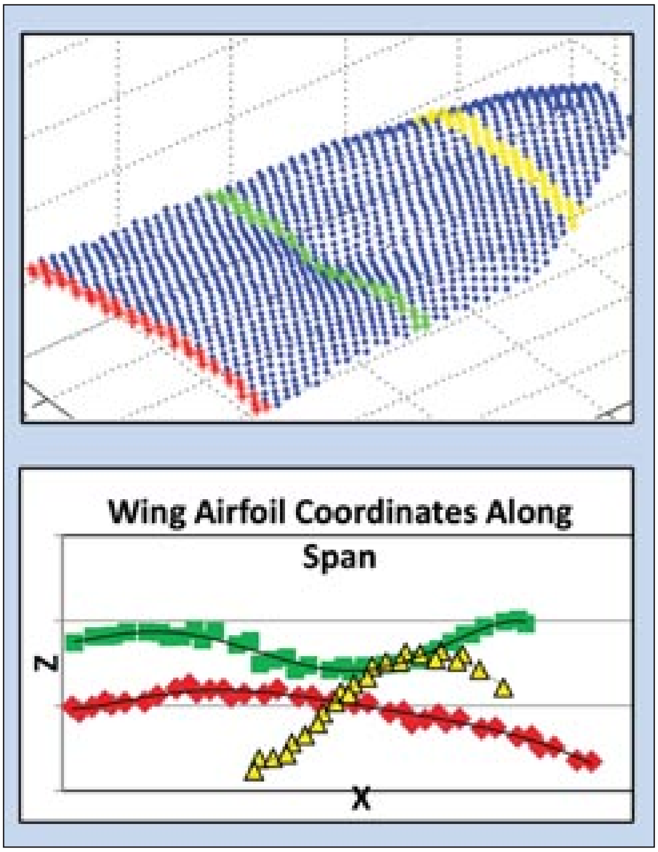

Figure 2. (top) Wing Chord Shapes along the span, and (bottom) two-dimensional airfoil shapes from the 3D wing scatter plots.

tages over traditional fixed- and rotary-wing aircraft. Fixed-wing UAVs have the advantages of long range and endurance, and high payload capabilities; however, they require high forward flight speeds and most configurations cannot hover, which makes them difficult to control in confined spaces.

Conversely, rotary-wing UAVs are highly maneuverable, can fly at lower forward speeds, and can hover, but generally have lower endurance times and are louder than fixed-wing UAVs due to high rotor tip speeds. The goal of using flapping-wing UAVs (FWUAVs) is to bridge the gap between fixed- and rotary-wing UAVs. FWUAVs have the potential to fly at lower airspeeds than fixed-wing aircraft, and most have the ability to hover, which enables FWUAVs to be flown in confined spaces. Compared to rotorcraft, FWUAVs tend to be quieter since the wing flapping speed is generally much slower than a rotor's rotation. This combination of maneuverability, hover capability, and stealthiness makes FWUAVs a potential choice for use in confined spaces.

This project is based on the bird-inspired FWUAV called the RoboRaven, which was designed and built at the University of Maryland (Figure 1). Bird-inspired flight is based on the forward posture of birds, where a forward velocity is required to maintain lift and the flapping motion is in a roughly vertical plane with respect to the forward velocity. RoboRaven has a wingspan of 0.9 m and a maximum chord length of ~0.3 m. The wings can move independently of one another, driven by two separate servos, which rotate the wings at approximately 3–4 Hz. In flight, the RoboRaven cruises at approximately 6.7 m/s, which is in the flight regime of Reynolds number ~120,000.

The goal is to improve upon the accuracy of existing FWUAV aerodynamic models to be used in the conceptual design process. FWUAV design is currently a sequential trial and error process, where engineers iterate through many different designs until reaching a desirable configuration. Aerodynamic models that can accurately predict flight forces enable designers to run through many iterations of design prior to building any prototypes.

The Blade Element Momentum Theory (BEMT) aerodynamic analysis was created using a combination of two aerodynamic theories: Blade Element Theory (BET) and momentum theory. In BET, the wing of a UAV is discretized across the entire span into chordwise "slices." Each of these slices experiences the flight forces of lift, drag, and thrust (in differential form). Because the wing is three-dimensional, each slice is really a small section with a width in the spanwise direction; however, it is treated as an airfoil with infinite span. Once all the differential forces have been calculated at each slice, integration is performed along the entire span to calculate the total forces on the wing.

Compared to BET, momentum theory is a much more simplified approach to calculating aerodynamic forces. In momentum theory, the momentum change of moving air deflected off a wing is used to calculate lift and thrust. When a wing is placed at an angle of attack, α, with respect to the forward velocity, U, it will deflect air downward at a velocity, w, called induced velocity. Induced velocity is ultimately used in momentum theory to calculate lift and thrust.

For a flapping wing, momentum theory analyzes the wings as a "partial actuator disk," where the disk's size is determined by the swept area of the wing flapping when viewing the UAV's frontal area. The momentum change of the air moving across this partial disk area is used to calculate thrust. Thus, in momentum theory, the entire wing flapping motion is represented by the partial disk area, as opposed to discretizing the wing along the span as in BET.

In both BET and momentum theory, there is one unknown variable, induced velocity, in the equations used for thrust calculation. When BET and momentum theory are used separately, induced velocity is either approximated using a function or is assigned a constant value as defined by the individual performing the aerodynamic analysis. BEMT solves this problem by combining the two equations for BET and momentum theory in order to solve for downwash velocity. Once downwash velocity is calculated, it is used in the BET analysis at each spanwise "slice" and forces are calculated.

This project accomplishes the goal of calculating the lift coefficient based on wing shape through the use of Digital Image Correlation (DIC) wing deformation scatter plots. These scatter plots are simple 3D representations of the wing, taken directly from DIC images of an FWUAV flapping in a wind tunnel. Once the 3D wing shape scatter plots have been obtained from DIC images, it is necessary to calculate the lift coefficient to be used in BET portion of the BEMT code (Figure 2). The experimental phase of this project was completed entirely via computer modeling in MATLAB.

This work was done by Justin Alexander Yang of the Army Research Laboratory. ***For more information, download the Technical Support Package (free white paper) at www.aerodefensetech.com/tsp under the Information Technology category.*** *ARL-0161*

Queuing Model for Supervisory Control of Unmanned Autonomous Vehicles

Human factors challenges have shifted from manually controlling individual unmanned systems, to supervisory command of multiple semi-autonomous systems.

Space and Naval Warfare Systems Center Pacific, San Diego, California

One critical aspect in developing a quantitative model of unmanned autonomous vehicle (UAV) operator and system performance has been to adopt a task-centric approach to interface design that entails an explicit representation of actions or tasks that need to be performed by the operator. The representation of work in terms of a task serves as a trace in the system that enables designers to track workload in addition to the task progress and flow of tasks among team members. In supervisory control, the focus is the flow of tasks (work) through a system that is composed of human servers and automated servers (software agents).

Quantitative models and methods that analyze dynamic systems of flow have been developed in the domain of queuing theory. This research may be extended to include supervisory control of unmanned vehicles. In this analysis, the "customers" to the queue are tasks that must be serviced by the human and

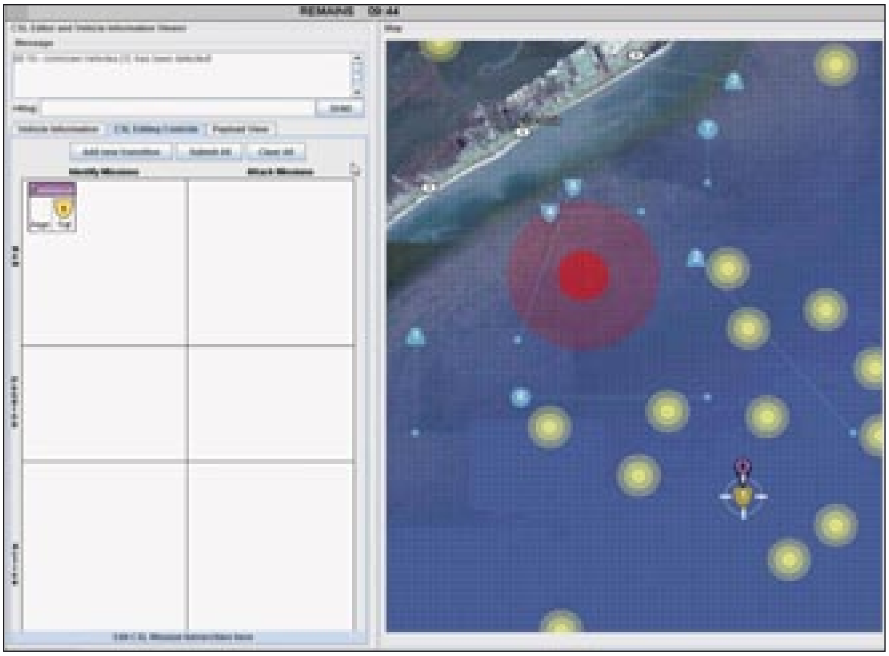

Figure 1. The interface for the RESCHU SP Simulation. The operator's display is composed of two main windows placed side-by-side.

Figure 2. A picture in the Payload view allows the operator to visually identify the contact as a friend or foe. Once identified as an enemy, the contact may be assigned a UUV to attack it.

software servers. The servers are human operators, software agents, and UVs.

In addition to physical platforms, autonomous agents working as virtual team members are prevalent tools for accomplishing missions. The coordination of actions and interactions among unmanned autonomous systems, manned systems, and a command group will be essential to accomplishing these future missions. A new problem must be addressed: How to maintain an adequate workload to avoid information overload and resulting loss of situation awareness.

The Research Environment for Supervisory Control of Heterogeneous Unmanned Vehicles (RESCHU), developed by MIT, was designed to test supervisory control tasks such as surveillance and identification. This simulation was modified by adding: 1) a complex mission scenario with an asset to protect and multiple simultaneous enemies to attack, 2) a highly automated system such as mission definition language (MDL), and 3) a highly heterogeneous team that is made of at least three different types of UVs. The new version of the simulation is called RESCHU SP.

In the RESCHU SP scenario, a single operator supervises a team of unmanned air vehicles (UAVs), unmanned surface vehicles (USVs), and unmanned underwater vehicles (UUVs). The operator's task is to deploy the UVs to identify and destroy enemy contacts that are attacking an oil platform at sea. In addition to defending the oil platform, the operator must direct the UVs away from hazardous areas that cause damage to the UVs. The interface for the simulation is depicted in Figure 1.

The operator's display is composed of two main windows placed side-by-side. In one window, a geo-situational display depicts the spatial position of the UV assets as well as the oilrig, unknown contacts, enemy contacts, and the hazard areas. The second adjacent window is a three-tabbed pane window that contains the following displays: Vehicle Information, The Collaborative Sensing Language (CSL) Editing Controls, and a Payload View.

In order to protect the oilrig and the UV assets, the operator must engage in five tasks: Assign to identify an unknown contact, engage to identify an unknown contact, assign to attack an enemy, engage to attack an enemy contact, and hazard avoidance. The scenario is designed such that only USVs can identify unknown contacts, and only UUVs can attack enemy contacts. The UAVs fly in predetermined flight patterns that the operator can change to avoid hazardous areas.

The operator must first select an unidentified contact, and then assign a USV to identify it. Once the USV arrives at the unknown contact's location, the operator may engage the USV to identify the contact. This action brings up a picture in the Payload view that allows the operator to visually identify the contact as a friend or foe (Figure 2). Once identified as an enemy, the contact may be assigned a UUV to attack it. The sequence of actions to attack is analogous to the identification process. An enemy contact is assigned a UUV for attack. Once the UUV has arrived at the target's location, the enemy icon flashes and the operator may select the icon to be engaged to attack. Once engaged, the enemy is attacked and eliminated. Its icon disappears from the geo-situational display.

The relationships among the operator, the CSL, and the UVs, and the manner in which they must process tasks, may be modeled as a network of interactive queues. In an "open" queuing system, "customers" (tasks) arrive at each of the servers. Some tasks are processed and leave the system, but other tasks may be passed from one server to another. Thus, tasks may sequentially arrive at different queues, be waited upon by different servers, and sometimes may "feedback" and return to a previous server before eventually leaving the system. Queuing theory provides quantitative tools to analyze the flow of tasks to and from each server. In addition, the overall performance of the network may be analyzed. All the components necessary to formulate and analyze a queuing system may be extracted from the RESCHU SP scenario.

This work was done by Joseph DiVita, Robert L. Morris, and Maria Olinda Rodas of Space and Naval Warfare Systems Center Pacific. ***For more information, download the Technical Support Package (free white paper) at www.aerodefensetech.com/tsp under the Information Technology category.*** *NRL-0061*

Real-Time, High-Fidelity Simulation of Autonomous Ground Vehicle Dynamics

Integrated simulation capabilities that are high-fidelity, fast, and have scalable architecture are essential to support autonomous vehicle design and performance assessment.

U.S. Army TARDEC, Warren, Michigan, and NASA's Jet Propulsion Laboratory, Pasadena, California

Integrated simulation capabilities that are high-fidelity, fast, and have scalable architecture are essential to support autonomous vehicle design and performance assessment for the Army's growing use of unmanned ground vehicles (UGVs). A mobility simulation of an autonomous vehicle in an off-road scenario was developed using integrated sensor, controller, and multibody dynamics models.

The JPL Rover Analysis, Modeling and Simulation (ROAMS) ground vehicle simulation framework is based on the JPL Darts/Dshell simulation architecture. ROAMS and the underlying architecture have been successfully demonstrated at JPL in several space scenarios where a high degree of mission complexity, real-time performance, and extensive sensor/actuator/control integration were necessary. ROAMS is unique in its integrated approach to straddling the multifunction, high-fidelity dynamics, sensors, environment, control, and autonomy models that are key attributes of future Army UGVs.

This work applies the ROAMS modeling approach to address the fidelity and speed bottlenecks for the Army's need to evaluate and test autonomous ground vehicles. This scalable architecture allows the adaptation and tuning of simulation fidelity across a very broad range (e.g. rigid/flex-body dynamics, sensor fidelity, dynamics/kinematics modes) needed for the multi-layered testing of complex autonomy behaviors.

This project developed and demonstrated an integrated simulation capability consisting of real-time, high-fidelity dynamics with control, sensors, and environment models in the loop for a representative autonomous vehicle. The simulator's architecture will allow the seamless selection of different fidelity levels and model parameters across the full modeling suite, and more importantly, provide analysts with a modular way to swap component models for varying vehicle/control/sensor behavior.

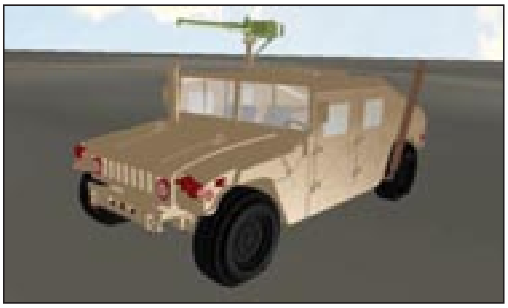

Figure 1. The HMMWV Simulation Model built in ROAMS.

Figure 2. The vehicle during the Lane Change Maneuver. Note the roll of the vehicle as it changes lanes.

The HMMWV suspension system is a variant of the common double wishbone suspension. These suspension systems have a large number of distinct bodies that are contained within a single kinematic closed loop. As a result, these suspensions have a large number of internal degrees of freedom, but due to the constraints imposed by them to a frame or chassis, they only have a single independent degree of freedom. For the HMMWV suspension modeling, three algorithmic techniques were tested and benchmarked to solve the multibody dynamics of the suspension system. While the HMMWV suspension model is the same, the difference among the three techniques is the number of constraints that are needed, which directly affects their resultant computational speed.

The HMMWV vehicle model built in ROAMS has essentially 15 degrees of freedom (DOF) after taking into account all the constraints on the system (Figure 1). Vehicle simulations were run in two main environments. The first was an urban environment; the second was an off-road

environment. In both cases, a graphical representation of the environment with a variety of tools was created. A digital elevation map was extracted from it for use in the vehicle wheel-terrain contact simulation.

The urban environment consisted of a 3D mesh model of a city. The vehicle off-road environment consisted of bumpy terrain (as opposed to the paved flat urban environment). To create the bumpy off-road environments, a digital elevation map was created and imported into the simulation. LIDAR was simulated using the simulator's graphics system.

Three distinct scenarios were performed.

- Scenario 1: Urban driving with navigation and obstacle avoidance. An urban terrain was used and a goal point a few hundred meters away was defined. The vehicle was left to drive towards the goal. The navigation system detected the raised edges of the road and avoided them.
- Scenario 2: Urban driving - lane change maneuver. The vehicle was driven in the urban environment, and an open-loop lane change maneuver was performed at speed to demonstrate the realistic nature of the vehicle dynamics (Figure 2).
- Scenario 3: Off-road driving teleoperation. The vehicle was driven at various speeds on off-road terrain with a few trees to demonstrate vehicle behavior.

The ROAMS HMMWV simulation successfully demonstrates that high-fidelity multibody dynamics, terrain models, sensors, actuators, control, and navigation in urban and off-road scenarios can be modeled and run at speeds that are useful for vehicle analysis and design purposes.

This work was done by Jonathan Cameron, Steven Myint, Calvin Kuo, Abhi Jain, and Håvard Grip of Jet Propulsion Laboratory, California Institute of Technology; Paramsothy Jayakumar, of the U.S. Army TARDEC; and Jim Overholt of the U.S. Air Force Research Laboratory. ***For more information, download the Technical Support Package (free white paper) at www.aerodefensetech.com/tsp under the Information Technology category.*** *ARL-0162*

Intro Cov ToC

Photovoltaic Thermography From the Air

Micro-Epsilon
Raleigh, NC
919-787-9707
www.micro-epsilon.com

Defective solar cells can destroy an entire module. Therefore, conducting regular inspections using thermography is a great way to perform preventative maintenance on photovoltaics installations. Any noticeable differences in temperature that are encountered can be used to reliably detect electrical, mechanical, installation and processing-related defects, including short circuits, inactive cells, moisture, and poorly soldered joints. As part of scheduled maintenance operations, thermography can provide valuable information for resolving warranty claims.

Inspections are normally performed in a non-contact, non-destructive manner from a safe distance using infrared cameras. One such camera is the new miniature thermoIMAGER TIM LightWeight IR camera from Micro-Epsilon, which can be mounted on a quadrocopter, a device that's similar to a small, remote-controlled helicopter with 4 blades. Design factors to consider when using an IR camera as part of flight operations include low weight, autonomous control and sufficiently high camera resolution to ensure high quality IR images.

The new system, which weighs just 350 grams, consists of a miniature IR camera and the NetBox mini PC. IR videos are stored on a microSD storage card in NetBox and can be launched directly through a button on the camera housing. The high resolution infrared camera offers an optical resolution of 382 × 288 pixels, with a thermal resolution of up to 40mK.

For Free Info Visit ***http://info.hotims.com/49745-505***

Unmanned Demonstrator Aircraft for Maritime Surveillance

Northrop Grumman
Falls Church, VA
703-280-2900
www.northropgrumman.com

The Northrop Grumman Corporation-built unmanned demonstrator aircraft used for maritime surveillance missions by the U.S. Navy recently surpassed 10,000 combat flying hours supporting intelligence-gathering missions in the Middle East. The Broad Area Maritime Surveillance Demonstration (BAMS-D) aircraft are currently flying 15 missions a month and allow fleet commanders to identify and track potential targets of interest using a specialized suite of surveillance sensors.

"BAMS-D has been extremely successful in providing a strategic picture to carrier and amphibious battle groups as they move through areas where we need more awareness," said Capt. James Hoke, Triton program manager with Naval Air Systems Command. "The BAMS-D aircraft started a six-month deployment in 2009 to demonstrate a maritime surveillance capability. Since then, they have continued to be used and have truly found their role in helping secure the safety of the fleet."

Based on the Global Hawk unmanned air system (UAS) designed for land surveillance, the BAMS-D systems were modified to work in a maritime environment. The aircraft regularly fly missions that are more than 24 hours long at high altitudes. The Navy is also using BAMS-D to understand how to best use the new surveillance capabilities for the MQ-4C Triton UAS. Currently under development, Triton uses an entirely new sensor suite optimized for a maritime environment.

"We've designed Triton to carry sensors that can monitor large ocean and coastal areas with a 360-degree field of view," said Mike Mackey, Triton program director with Northrop Grumman. "Coupled with anti-ice/de-ice capabilities and some structural strength improvements, the system will operate in a variety of weather conditions while providing a greatly improved surveillance picture to fleet commanders."

The Navy's program of record calls for 68 Triton UAS to be built. Northrop Grumman is the prime contractor for the program and is using two test aircraft to develop Triton's capabilities through 2016.

For Free Info Visit ***http://info.hotims.com/49745-506***

Additive Manufacturing of Small Tactical Munitions

Raytheon
Fullerton, CA
714-446-2315
www.raytheon.com

Solid Concepts Inc.
Valencia, CA
661-295-4400
www.solidconcepts.com

Raytheon is addressing the need for smaller tactical weapons that still incorporate all fundamental features for small tactical manned or unmanned aerial platforms with some help from additive manufacturing (a.k.a. 3D printing). Their newest tactical munition, named Pyros, is light, precise, and a serious weapon.

"Right now with Pyros we're looking at transitioning into full fledged production within the next year," says J.R. Smith, Senior Manager of Business Development at Raytheon, "and this is certainly one of the first times we've used additive manufacturing to go directly from prototyping to actually using additive manufactured parts on a production component."

Pyros utilized multiple additive manufacturing technologies during prototyping and into final production, including Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS). Both FDM and SLS offer high quality materials resistant to chemical and heat environments. FDM works via a heated nozzle which extrudes material layer by layer while SLS works via a bed of powdered nylon and a CO_2 laser which sinters material layer by layer. Both processes grow parts from the ground up, which affords part complexity that subtracting technologies like machining find difficult to emulate.

Smith, familiar with traditional precision machining, views additive manufacturing as a solution to the inhibitions of machining. His team has even experienced better tolerances from additive manufacturing than from machining. He says that the drilling and milling of computerized CNC machining centers is very costly. For complex parts, contends Smith, it's quicker and cheaper—especially with small tactical munitions like Pyros or even standard missiles—to use additive manufacturing to achieve good, tight tolerances.

The Raytheon engineering team worked hard to design Pyros for manufacturability and affordability, and that translated into using additive manufacturing early on in the project. For Pyros it was important to keep in mind the feasibility of assembling it fast. Additive manufacturing helps reduce manual labor by integrating features directly into the geometry (such as attachment features and fittings, mounting brackets, control surfaces), a difficult or impossible task to achieve in one simultaneous build when using machining. Additive manufacturing allows the team to consolidate multiple features into one part, and gives them full control over incremental changes in control surfaces and tolerances.

Pyros is built with fins upon its frame. These fins steer it toward its target via two frames of reference, a GPS and a semi-active laser seeker. "With 3-dimensional coordinates for its GPS, Pyros knows exactly where it's at, allowing us to direct Pyros within 3 meters of where we want to be," says Smith. "For moving targets, or targets within buildings, Pyros is equipped with a semi-active laser guidance system with demonstrated accuracy within one meter. A laser designator's energy reflected off the target is used by the seeker to guide Pyros. All this direction and information is processed simultaneously, making accurate fin movement in accordance with the GPS and laser information quite crucial to the success of its mission."

Raytheon worked with custom manufacturing company Solid Concepts on different components and iterations of Pyros, utilizing the prototyping and production capabilities of additive manufacturing. Smith says his team is looking to rework Pyros' guiding fins using additive manufacturing. As the control fins are imperative to guiding Pyros, experimenting with their control surfaces is on the forefront of future iterations.

Additive manufacturing has also played a role in weight reduction. Pyros is ideal for small UAS that have payloads ranging from 5 – 100 lbs or for manned attack and armed surveillance platforms. With the majority of Pyros' weight coming from its warhead, weight must be subtracted elsewhere. Material compositions of nylon, used in conjunction with Selective Laser Sintering (SLS), yield parts that are light but still strong and highly resistant to harsh environments while incorporating more features than machining could feasibly achieve in a single manufacturing instance.

For Free Info Visit ***http://info.hotims.com/49745-508***

Unmanned Ground Vehicle

RE2
Pittsburgh, PA
412-681-6382
www.resquared.com

RE2, Inc. recently announced that the company has been awarded additional funding by the Department of Defense to commercialize its high speed inspection robot called the ForeRunner. The ForeRunner unmanned ground vehicle (UGV) was developed under an Army Small Business Innovation Research (SBIR) program and the additional funding was awarded through the Robotics Technology Consortium as a Phase III SBIR with the Army's Tank and Automotive Research Engineering and Development Center (TARDEC).

The goal of this program is to provide the Army with unmanned ground vehicles and unmanned aerial systems (UAS) that are truly integrated and can be simultaneously controlled by a single operator from one control station, ensuring increased situational awareness and improved mission effectiveness.

"Our goal is to provide the Army with true unmanned systems teaming capabilities," stated Tim Davison, Chief Engineer at RE2. "This means, for example, that information gathered from a UAS, such as potential roadside threats, can be used by the UGV to safely guide a convoy."

During the Phase III commercialization effort, RE2 will focus on integrating the ForeRunner UGV with the Insitu Common Open-mission Management Command and Control (ICOMC2) ground control station. ICOMC2 will simultaneously control the ForeRunner and Insitu's Unmanned Aerial System (UAS). Insitu is a wholly owned subsidiary of The Boeing Company.

"Our team at RE2 has been working for several years to create truly modular unmanned systems and robotic manipulator arm payloads," stated Jorgen Pedersen, president and CEO of RE2. "Through this Phase III SBIR opportunity and in collaboration with Insitu we are able to validate and demonstrate the benefits of a truly interoperable system."

RE2 and Insitu will also co-develop the Joint Architecture for Unmanned Systems (JAUS) software plug-in for ICOMC2. JAUS is an interoperability standard within the DoD robotics community that enables unmanned systems, platforms, payloads, and control systems to communicate. JAUS enables interoperability between systems developed by different companies, allowing the DoD to procure the most appropriate modular open-architecture systems for current missions.

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