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REAL-TIME TASKING AND RETASKING OF MULTIPLE COORDINATED UAVs

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UAS: RQ-11B Raven®
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CONTENTS

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MESSAGE FROM THE EDITOR

ERIC FIORE

Looking for the proverbial needle in a haystack has always represented one of the greatest challenges to practitioners engaged in the science of finding something. Historically, this task required the mobilization of resources to make direct visual contact with the subject of interest. Today, we are in the midst of a technological revolution, not without its controversies, that is facilitating persistent surveillance and tracking of subjects of interest without the necessity for having a "man-in-the-loop."

But what if the need is to find something quickly over a vast area with little to no advance indication of where one would be searching or what they are searching for? Take, for example, the case of searching for someone or something that is lost in the wilderness, or even at sea. By their very nature, such occurrences are highly unpredictable. Once an incident is reported, assets are rapidly mobilized to "go out and find" the lost person or item. In this case, it typically involves mobilizing limited assets with observers looking for something that, visually, could be as small as a basketball. Consider the challenge of successfully covering a massive area, with limited assets, in a relatively short order.

In our feature article this quarter, Marjorie Darrah et al. discuss how teams of collaborating unmanned aerial vehicles (UAVs) can be commanded to autonomously perform a wide variety of complex missions with strongly coupled tasks, such as finding someone or something that is lost. The authors describe how the reliance on human operators can be reduced with the use of autonomous controllers on UAVs. Swarms of UAVs can be commanded to fly predetermined paths without the intervention of a pilot, thus minimizing the required amount of flight planning. Simply put, the operator designs the mission, and the software determines an optimized way to task the assets and provide the ground stations with the waypoints needed to direct the UAVs to accomplish the mission. This article discusses a small three-plane scenario that could be implemented with, for example, a swarm of Raven RQ-11s.

While the intelligence, surveillance, and reconnaissance (ISR) mission is currently the most widely applied capability for UAVs, it likely won't be long before rotor-based UAVs are widely augmented with vertical lift payload capabilities. Not only are commercial companies, such as Amazon, looking to disrupt the home and office delivery business with their plans to deliver parcels with drones, but the Department of Defense (DoD) is also looking to develop and field vertical lift UAVs to support the current mission primarily supported with manned helicopters.

Accordingly, Mark Coy's article focuses on the analytical framework, central characteristics, and system complexities for future advanced coaxial-rotor helicopter UAVs in swarm mission-flight. Mr. Coy discusses a preliminary analysis of the highly complex coaxial-rotor helicopter UAV swarm and reports on a modeling framework for swarm performance using system identification (ID) and cognitive physicomimetics mathematical techniques.

And to complete this issue's portfolio of autonomous systems articles, we have an article by Lt. Col. Jeffrey Lamport and Col. (retired) Anthony Scotto on countering the UAS threat. In this article, the authors discuss, from a Joint perspective, several contemporary challenges associated with identifying and managing UAS threats on the battlefield. And the battlefield is not the only area susceptible to the effects of nefarious UAS operators. Recent reports in the media suggest even the U.S. Capitol, nuclear facilities, correctional facilities, borders, and sporting venues are susceptible to this rapidly proliferating technology.

Hydroxyl-terminated polybutadiene (HTPB) is a critical material used in the rocket motor industry. And with a shrinking demand from the DoD, the viability of maintaining an adequate industrial base of this critical material has been a major and growing concern for the Defense industry. In our energetics article, Dr. Albert DeFusco discusses the 60-year history, current challenges, and the future of HTPB in the defense industry.

In our directed energy article, authors John Maynard and Ralph Teague provide a historical perspective of free space laser communications. Since the initial development of the laser, the potential for highly efficient high-data-rate communications using the laser has long been recognized. Free space optical communication using lasers offers significant advantages over radio frequency or microwave systems for both airborne and satellite platforms, for high-capacity trunk links, or for dedicated point-to-point links for high-data-rate sensors. Communications links using laser beams are inherently private and jam resistant. The short optical wavelengths allow extremely high antenna gains for establishing links over extremely long distances with transmitters and receivers that are the size of a shoe box. Nonetheless, after more than 50 yrs since the laser's introduction, as well as several major initiatives to mature system designs, the development of a full-scale operational free space laser communications link remains elusive, but interest is returning as a countermeasure to electronic warfare. ■

Atlas V rocket out of Cape Canaveral Air Force Station in Florida (Mike Killian / AmericaSpace)

HISTORICAL OVERVIEW OF HTPB

The Military's Preferred Solid Propellant Binder for a Half Century

By Albert DeFusco

BEGINNINGS OF HTPB IN THE DEPARTMENT OF DEFENSE (DoD)

For nearly 60 years, and at least two generations of scientists and engineers, hydroxyl-terminated polybutadiene (HTPB) has enjoyed a prominent place in the Defense business. Chemically similar to polybutadiene acrylonitrile (PBAN) and carboxyl-terminated polybutadiene (CTPB) [1], HTPB was recognized by rocket scientists as far back as the early 1960s as offering new opportunities to improved performance and enhanced mechanical properties [2]. First introduced by ARCO Chemical Company (Sinclair Petrochemicals, Inc.), HTPB also gained favor as the "Poly B-D Liquid Resin" of choice for many commercial applications, such caulks, foams, sealants, and adhesives [3]. These applications still exist today in the form of curable polyurethane (PU) systems of HTPB, along with its extensive use as a binder in rocket motor propellants and liners.

At the start, PUs based on HTPB and isocyanates showed many desirable features not attainable with other systems, such as excellent hydrolytic stability, compatibility with oil-type plasticizers (coined as "oil extendibility"), improved adhesion to substrates, and improved low-temperature properties, with embrittlement at or below -80 °C. The latter feature allowed scientists to extend the operational temperature range of rocket motors using HTPB binders, especially those destined for air-to-air tactical use.

The HTPB polymer has been the subject of extensive characterization across the world in terms of chemical structure, microstructure, and reactivity, as well as aging characteristics of PU networks [4, 5]. Devices as small as miniature model rockets and large-scale motors up to 93 inches in diameter (Castor 120®) are in use today because of the desirable properties, manufacturability, and versatility of HTPB propellants (when combined with an ammonium perchlorate [AP] oxidizer) [6].

The largest HTPB composite propellant motor ever produced was the Titan IV Solid Rocket Motor Upgrade (SRMU) strap-on booster, which was 10.5 ft in diameter by 112 ft long and weighed more than 770,000 lbs [7]. It was built by ATK between 1992 and 2001 for flights of the Air Force's Titan IVB launch vehicle through 2005, when it was retired. Aerojet also manufactured the 5 foot diameter by 56 foot long AJ-60A strap-on HTPB solid rocket booster for the Atlas V launch vehicle from 1999 to 2003. Orbital ATK's new GEM-63 booster is destined to replace the AJ-60A motor for future Atlas V launches, while an extended-length GEM-63XL is planned for use on the Vulcan launch vehicle [8]. Both strategic and tactical rocket motor propellants have been highly successful using HTPB for many years [9].

Both strategic and tactical rocket motor propellants have been highly successful using HTPB for many years.

THE STORY CONTINUES

The current producer and qualified supplier of Poly bd® resins is Cray Valley Hydrocarbon Specialty Chemicals, which is now owned by the French company TOTAL (see history in Figure 1) [10]. Cray Valley manufactures military grade HTPB at the original location in Channelview, Texas that was first established by Sinclair/ARCO in the 1960s. Cray Valley currently produces two forms of resins, R-45M and R-45HTLO [11], both of which are the only qualified materials in use by the DoD for a wide variety of rocket motor and warhead applications (see Table 1).

Due to the high demand for commercial HTPB (primarily R-45HTLO), Cray Valley has recently expanded and upgraded the Channelview, TX, facility. This move will help make the R-45M product more readily available to the Defense industry. At the time of this writing, rocket motor suppliers are in the process of requalifying Cray Valley R-45M with material made from the upgraded facility, and preliminary indications are positive, especially since there have been concerns over reproducibility over the past several years [12, 13].

CONCERNS AND CHALLENGES

With the shrinking demands from the DoD, the viability of maintaining an adequate industrial base of critical materials has been a major and growing concern for the Defense industry [14]. Qualifying second sources, and thus helping to eliminate the risky single-

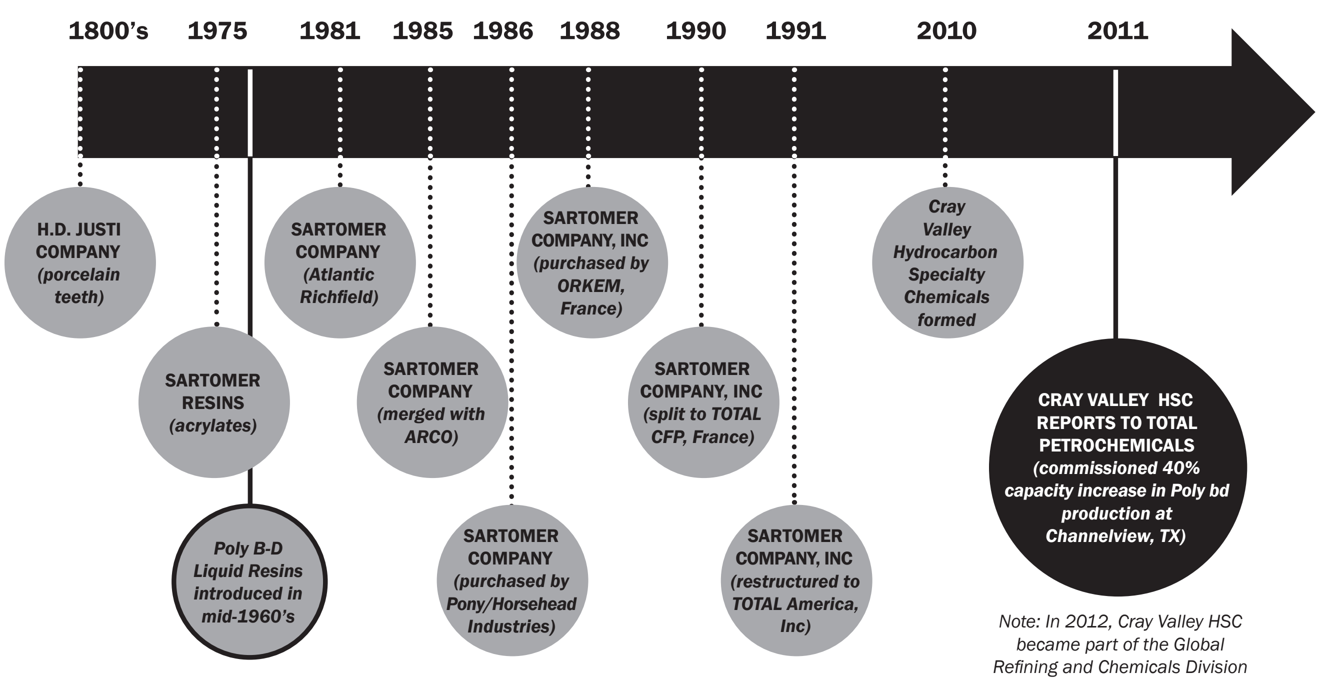


Figure 1: Cray Valley HSC Timeline.

Table 1: Characteristics and Use of Resins R-45M and R-45HTLO

Characteristic	R-45M	R-45HTLO
Primary uses	Rocket motor propellant and liner binder	Commercial use (adhesives, sealants, etc.); warhead explosive binder
Hydroxyl value (meq/g)[a]	0.7–0.80	0.7–0.85
Approximate equivalent weight (g/mole)	1,333	1,250
Approximate functionality	2.2–2.4	2.4–2.6

[a] Specification MIL-H-85497

source condition found with many critical Defense-related materials, is a top concern for the Office of the Secretary of Defense (OSD) as it strives to maintain and advance the U.S. ability to remain responsive in times of crises [15]. Recently, MACH I Incorporated has come forward to serve as a second source of HTPB, with its official product name HTPB-45M® [16]. This material is being manufactured by an Emerald CVC Specialty Chemicals Company plant located in Cuyahoga Falls, OH, and it easily meets current specification requirements. Supplying the Defense industry for more than 30 years with specialty chemicals, and working under Small Business Innovation Research (SBIR) and OSD contracts, the MACH I product is showing promise for this critical Defense material.

Additionally, the down-turn in the solid rocket motor (SRM) business outlook over the past several years has reduced future prospects considerably for propellant materials such as HTPB. As mandated by Public Law 110-181 (dated 28 January 2008), Mr. Robert Reed from the Office of the Under Secretary of Defense (OUSD) compiled a presentation entitled "Solid Rocket Motor (SRM) Congressional Interest" in 2009. This presentation was a synopsis of a report to Congress on SRM industrial capabilities in the United States [17]. The report contained industrial base information on space launch, strategic, missile defense, and tactical SRM business segments, including the down-turn in propellant and material needs that resulted from the completion of the U.S. Space Shuttle program, as well as subsequent reductions in SRM booster requirements.

Mr. Reed outlined, through the data extracted and compiled in Table 2, how the ongoing SRM businesses compared to one shuttle reusable solid rocket motor (RSRM). For example, to compensate for the loss of one shuttle RSRM, the Guided Multiple-Launch Rocket System (GMLRS) tactical business needed to increase by 5,121 units, an approximate 50% increase above quantity projections through 2012

Table 2: Comparing Space Shuttle RSRM to Other SRMs (Source: ATK and Aerojet)

Missile Program	Pounds of Propellant	Equivalent No. of SRMS to Equal One Space Shuttle RSRM
Space Shuttle RSRM	1,106,059	1
Trident II D-5	110,200	10
Minuteman III (MM III)	66,642	17
Ground Missile Defense (GMD)	43,469	25
Kinetic Energy Interceptor (KEI)	20,026	55
Patriot Advanced Capability-3 (PAC-3)	350	3,160
Guided Multiple Launch Rocket System (GMLRS)	216	5,121
Advanced Medium-Range Air-to-Air Missile (AMRAAM)	133	9,788
Hellfire	20	55,303
Javelin	3	368,686

NASA man-launched space systems a key player in large SRM sector and propellant subtier base.

[18, 19]. Because Presidential DoD budgets and projections for the past several years have been flat or declining, increased demand for materials such as HTPB is unlikely and may force large suppliers to comtemplate leaving the Defense business entirely.

Based on Mr. Reed's projections for SRMs through 2013, the anticipated quantities for HTPB amounted to less than 170,000 lbs annually for both major U.S. propulsion contractors, Orbital ATK and Aerojet Rocketdyne (see also Moore 1997 for past usage [20]). Figure 2 shows the missile procurement of these two contractors from 2007 through 2013.

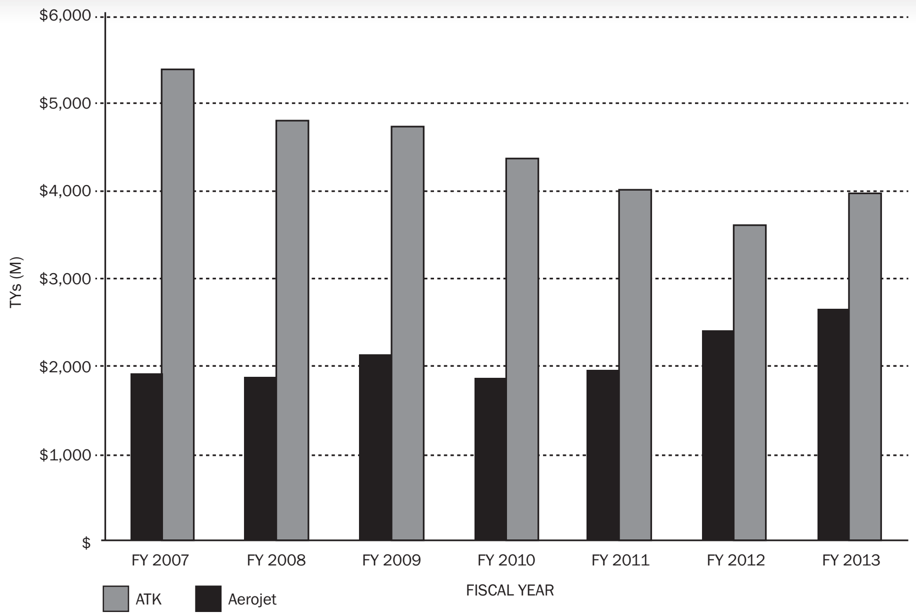


Figure 2: DoD Missile Procurement by Prime Contractor.

However, the HTPB polymer continues to find use around the world and in advanced rocket motors, such as those shown in the Table 3 [21]. SRM satellite launch vehicles from Japan and India, as well as hybrid rockets for Space Ships One and Two in the United States, are some of the applications. Combined with a peroxide oxidizer, the unique Dreamchaser spaceplane uses an HTPB hybrid rocket motor. One of the more exotic uses is in a hybrid rocket developed by NAMMO of Norway for a land speeder that originated in the United Kingdom [22]. The UK Ministry of Science Department of Innovation, Universities, and Skills is attempting to break the land-speed record with a vehicle known as Bloodhound SSC. The vehicle is being designed to reach a speed of 1,000 mph. This unique work is part of an education project designed to promote science, technology, engineering, and mathematics (STEM) to young students and requires the use of many talents in design, analysis, engineering, and testing across several institutions.

Table 3: International HTPB Rocket Motor Use

System	Subsystem	Rocket Type	Country of Origin	Reference
Satellite Launch Vehicle	Ariane V	Strap-on SRM	France (EADS/LV)	http://www.esa.int/Our_Activities/Launchers/Launch_vehicles/Boosters_EAP
Satellite Launch Vehicle	M-5 Rocket (aka M-v, Mu-5)	SRM	Japan (ISAS)	https://en.wikipedia.org/wiki/M-V (see also: https://en.wikipedia.org/wiki/JAXA)
Satellite Launch Vehicle	Polar Satellite Launch Vehicle (PSLV)	SRM	India (ISRO)	https://en.wikipedia.org/wiki/Polar_Satellite_Launch_Vehicle
Space Ship One and Space Ship Two	Hybrid Rocket With Nitrous Oxide	Hybrid Motor	United States (SpaceDev)	https://en.wikipedia.org/wiki/Hybrid_rocket (see also: https://en.wikipedia.org/wiki/SpaceDev)
Dreamchaser Spaceplane	Hybrid Rocket With Peroxide	Hybrid Motor	United States (SpaceDev)	https://en.wikipedia.org/wiki/Dream_Chaser (see: also: https://en.wikipedia.org/wiki/Sierra_Nevada_Corporation)
Bloodhound SSC Land Speeder	Hybrid Rocket With Peroxide	Hybrid Motor	United Kingdom	https://en.wikipedia.org/wiki/Bloodhound_SSC

LOOKING AHEAD

So what does the future hold for HTPB in the defense business? Although quantity demands may have diminished, the need for this highly effective polymer will not. HTPB has proven time and again to be the polymer of choice for systems in high-rate production, advanced development, and new research, especially in the area of AP-based rocket motor propellants and high-performance warheads. The future may show a need for specialized HTPB having performance not yet attainable, such as formulations with improved safety from thermal insult, higher toughness and strain capability, and expanded capability under extreme high and low temperature operation. The next 60 years may see dramatic shifts in Defense technologies, but highly successful materials such as HTPB are sure to remain important and useful for military applications. ■

REFERENCES

[1] Moore, Thomas L. "Polybutadienes Dominate for 40 Years." Chemical Propulsion Information Agency Bulletin, vol. 24, no. 2, March 1988.

[2] Hunley, J. D. "The History of Solid-Propellant Rocketry: What We Do and Do Not Know." AIAA 99-2925, Invited Paper at the 35th AIAA, ASME, SAE, ASEE Joint Propulsion Conference and Exhibit, Los Angeles, CA, 20–24 June, 1999.

[3] "Poly-BD Liquid Resins." Sinclair Product Data Bulletin Number 505, June 1967.

[4] Mahanta, Abhay K., and Devendra D. Pathak. "HTPB-Polyurethane: A Versatile Fuel Binder for Composite Solid Propellant." *Polyurethane*, edited by Dr. Fahmina Zafar, InTech, 2012.

[5] Strange, Karen L. (Ed.). "R-45M Characterization--1985 JPM Specialist Session." San Diego, CA, 10 April 1985.

[6] Aerocon Systems. "Estes Rocket Motors." http://aeroconsystems.com, accessed 2016.

[7] SpaceDaily. "ATK Gives Titan 4 a Solid Kick." http://www.spacedaily.com/news/booster-00b.html, accessed 2016.

[8] Wikipedia. "Graphite-Epoxy Motor." https://en.wikipedia.org/wiki/Graphite-Epoxy_Motor, accessed 2016.

[9] Purdue University. "Solid Rocket Motors." Purdue AAE Propulsion, https://engineering.purdue.edu/~propulsi/propulsion/rockets/solids.html, accessed 2016.

[10] Cray Valley. "Poly bd®." http://www.crayvalley.com/products/poly-bd-liquid-polybutadiene, accessed 2016.

[11] Cray Valley. "Poly bd® R-45HTLO and Poly bd® R-45M." Technical Datasheets, July 2010.

[12] Brady, Michael, and Robert Wardle. Personal communication with author. Orbital ATK, May 2015.

[13] Clark, Kerry. "Chemical, Physical and Aging Properties of HTPB R-45m Polymer." JANNAF HTPB Variability Workshop, CPIAC Abstract Number 2009-0105CM, 8 December 2009.

[14] Erwin, Sandra I. "Pentagon Running Out of U.S. Suppliers of Energetic Materials." http://www.nationaldefensemagazine.org/blog/Lists/Posts/Post.aspx?ID=1095, accessed 2016.

[15] Olson, David. "Critical Energetic Material Initiative." National Defense Industrial Association IM/EM Technology Symposium, Las Vegas, NV, 16 May 2012.

[16] MACH I Incorporated. "HTPB-45M®." Technical Information Sheet, to be published.

[17] Reed, Robert. "Solid Rocket Motor (SRM) Congressional Interest." December 2009.

[18] Pincoski, LTC Mark. "Precision Guided Missiles and Rockets Program Review." Presented at Precision Strike Annual Programs Review, 27 April 2007.

[19] George C. Marshall and Claremont Institutes. "Guided MLRS." http://missilethreat.com/missiles/guided-mlrs/, accessed 2016.

[20] Moore, Thomas. "Assessment of HTPB and PBAN Propellant Usage in the United States." Publication Number AIAA-1997-3137, American Institute of Aeronautics and Astronautics, 1997.

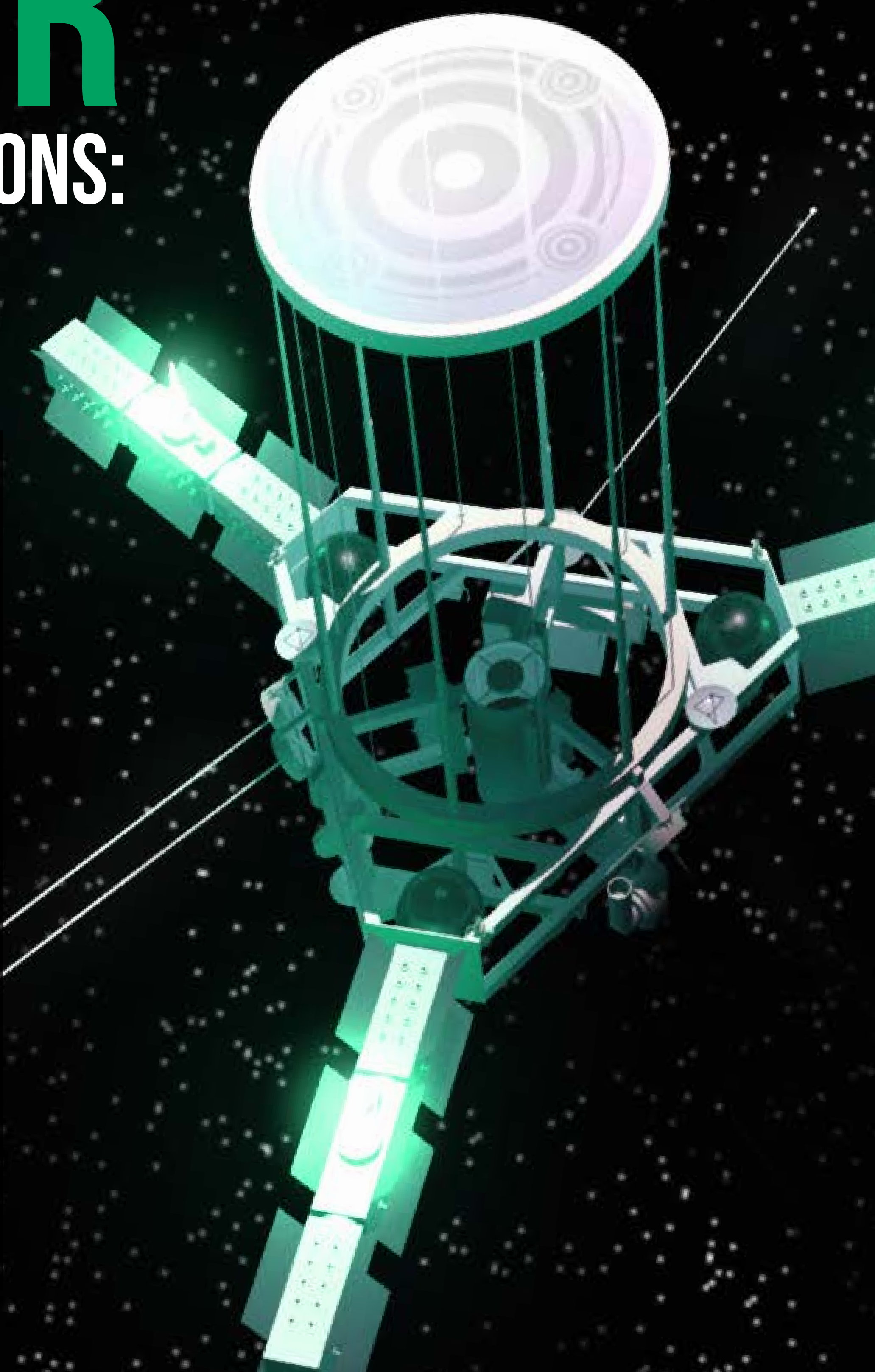
[21] Wikipedia. "Hydroxyl-Terminated Polybutadiene." https://en.wikipedia.org/wiki/Hydroxyl-terminated_polybutadiene, accessed 2016.

[22] Wikipedia. "Bloodhound SSC." https://en.wikipedia.org/wiki/Bloodhound_SSC, accessed 2016.

BIOGRAPHY

ALBERT DEFUSCO is currently a senior scientist at the SURVICE Engineering Company and a DSIAC subject-matter expert in energetic materials. He recently retired from Orbital ATK, where he spent 30 years in various capacities, including propellant and warhead formulating and energetic material synthesis. He also held various management positions in Orbital ATK's Program Office and Engineering Departments. He started his career as a National Research Council post-doctoral fellow under Dr. Arnold Nielsen at the Naval Weapons Center (NWC) in China Lake, CA, and also worked in NWC's Polymer Science Branch of the Research Department. Dr. DeFusco has a Ph.D. in organic chemistry from the University of Vermont and a B.S. in chemistry from the Worcester Polytechnic Institute.

Space probe design concept using optical rather than radio communication (NASA)



FREE SPACE LASER COMMUNICATIONS:

A Historical Perspective

By John Maynard and James “Ralph” Teague

INTRODUCTION

The potential for efficient high-data-rate communications using the laser has been recognized since its initial development more than 50 years ago. Free-space optical communications using lasers offer significant advantages over radio frequency (RF) or microwave systems for both airborne and satellite platforms, including high-capacity trunk links or dedicated point-to-point links for high-data-rate sensors. Communication links using laser beams are inherently resistant to both tapping and jamming. Short optical wavelengths allow high antenna gains for establishing links over extremely long distances and enable the use of shoebox-sized transmitters and receivers. Although several major initiatives have matured system-level designs, a full-scale operational free-space lasercom link is not yet available.

EARLY SYSTEM DEMONSTRATIONS: PROGRAM 405B

In 1971, the U.S. Air Force (USAF) initiated Program 405B to develop a system capable of demonstrating an unprecedented 1-Gbps data rate for a downlink comprising a geosynchronous satellite and a ground-based terminal. The program emphasized the development of critical technologies (laser modulation, pointing, acquisition, tracking, and signal detection) required to support a system design capable of operating from a geosynchronous satellite.

During the Engineering Feasibility Model phase of the program, two competing system approaches were developed, one based on coherent communications using the CO_2 laser (developed by Lockheed-Martin) and the other using short-pulse communications techniques employing the frequency-doubled Nd:YAG laser operating at 0.532 µm (developed by McDonnell-Douglas Astronautics). The Engineering Feasibility Model developed by McDonnell-Douglas successfully met program objectives, and thus McDonnell-Douglas was awarded the follow-on program in 1975 to develop the Space Flight Test System (SFTS) [1].

The SFTS program was to have developed and qualified a satellite terminal architecture that supported both a wideband (1 Gbps) downlink to a terrestrial ground station or to a receiver terminal in low-earth orbit. It was to have demonstrated the capability of critical technologies to survive and operate on orbit for a typical mission lifetime. A launch date was scheduled for 1979, however, shortly after the Preliminary Design Review in 1976, funding was reallocated at the Air Force Research Laboratory (AFRL), and the scope of the program was changed from a space-to-ground demonstration to an aircraft-to-ground demonstration [2].

Although the challenges of building hardware for an airborne demonstration were significantly reduced from the original scope of developing a terminal to operate in space, the technical difficulty of an air-to-ground link was in many ways significantly more difficult. The Airborne Flight Test System (AFTS) demonstration program transitioned the hardware originally intended for a satellite-borne terminal to a C-135 aircraft. The ground terminal (with a telescope aperture size of 48 inches) was initially located at the Airforce Test Station at Cloudcroft, NM, but it was transitioned to a facility (with a 14-inch telescope aperture size and a two-axis beam director) at White Sands Missile Range, NM (see Figure 1).

Figure 1: Airborne and Ground Terminal Platforms for the AFTS Demonstration at White Sands Missile Range, NM. Top: Airborne High-Data-Rate Transit Terminal Installed in KC-135 (With Ground-Based Test Equipment); Bottom: Airborne High-Data-Rate Ground Station Receiver Located at Cowan Site [3].

Several technological advances required for the original, space-based terminal were abandoned, including:

- A solar-pumped doubled Nd:YAG mode-locked laser.
- Radiation-hardened optics and electronics.
- A lightweight, gimballed beryllium mirror for precision pointing.

However, several significant advances in electro-optic technology were retained in the reduced-scope program, including:

- Low-noise silicon avalanche photodiodes (APDs).
- Wide-band precision fast-steering mirrors.
- A novel quaternary short-pulse modulation and communications data link format for high-data-rate transfer in a scintillating environment.
- A potassium-rubidium high-intensity discharge-pumped Nd:YAG laser for low-power operation.
- Diffraction-limited, beryllium telescope optics (with a 190-mm aperture).

Even though submicroradian tracking and pointing accuracy was not required to establish the link as part of the airborne demonstration, the pointing and tracking elements of the system were designed, built, and tested to meet the 0.6-µrad pointing accuracy required in an orbital environment. Because of the relaxed volume constraints, the program emphasized development of system architecture and electro-optical elements for the system (Figure 2).

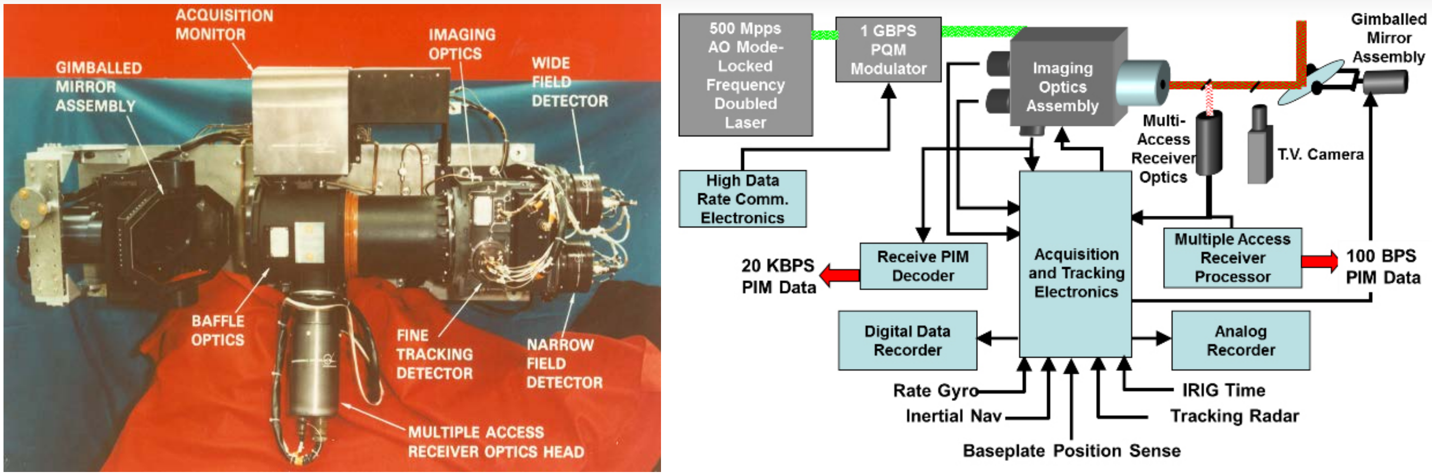


Figure 2: AFTS Electro-Optics Package (Left) and Overall System Block Diagram (Right) [3].

Overall, the program was highly successful in meeting the program objectives, including [3]:

- A diffraction-limited 5-μrad transmit beam from a beryllium optical telescope.
- Submicroradian wideband (300 Hz) tracking and pointing under simulated satellite dynamic environments.
- Low-noise, high-gain silicon APDs.
- A high-power (50-mW average output power) TEM00, mode-locked frequency-doubled Nd:YAG laser efficiently pumped with a potassium-rubidium, stable, high-intensity-discharge lamp.
- Near theoretical bit error rate (BER) performance of a 1-Gbps optical link.

In addition, although not an originally intended objective, a wealth of data was obtained regarding the performance of optical links from an airborne terminal operating through the aircraft boundary layer. Through collection of both scintillation and beam-wander data at both ground and airborne terminals, much was learned regarding the impact of aircraft boundary layer and link turbulence on design of lasercom terminals. These findings would prove valuable for later system applications.

THE LASER CROSS-LINK SYSTEM (LCS) FOR DEFENSE SUPPORT PROGRAM (DSP)

As the final AFTS air-to-ground demonstrations were concluding, studies were under way for modernization of legacy DSP systems. Since the initial DSP satellite launch in 1970, the DSP satellite system has provided the United States with ballistic missile launch detection. Originally deployed with three operational satellites—one generally over the Atlantic Ocean, another over the Pacific Ocean, and a third over Europe—the DSP provided early warning of missile threats to the continental United States. With the original constellation, the western satellite relied on remote ground terminals located on foreign territory to receive threat data, which were then relayed to the continental United States for processing and evaluation. The eastern satellite downlinked data directly to a U.S. ground station terminal. As part of the modernization effort, the USAF sought to eliminate the need to rely on foreign ground stations by establishing a cross-link between the two operational satellites. At that time, only two viable technologies existed for practical cross-linking between satellites in geosynchronous orbit: lasercom and 60-GHz RF communication. As part of the modernization effort, the USAF funded a trade study to assess 60-GHz vs. laser communications for the DSP laser cross-link implementation. Because of the relative maturity of lasercom technology, and because lasercom was considered the long-term solution for secure relay of U.S. intelligence data, this technology was selected for implementation of the LCS. In 1980, McDonnell-Douglas was contracted to develop a lasercom terminal for the DSP satellite [4].

McDonnell-Douglas conducted an initial trade study of two different optical cross-link technologies: a direct diode modulated link and a short-pulse-modulation format based on the Nd:YAG laser. McDonnell-Douglas engineers determined that the Nd:YAG-based link was the only technology exhibiting adequate maturity to satisfy the following requirements: rapid link acquisition, nuclear survivability, and operation with the sun in the receiver field of view. Consequently, McDonnell-Douglas was awarded a research, development, test, and evaluation (RDT&E) contract in 1980.

The DSP LCS was required to transmit primary sensor data (Link 5) in one direction and satellite command and control information (Link 6) in the opposite. For the primary sensor to image the full field of regard, the DSP satellite exhibits constant rotation, with the axis of rotation pointed toward the center of the earth. Thus, for the cross-link to maintain a constant link to the opposite satellite, a gimballed telescope was mounted on a boom extending from the satellite body (Figure 3). While adding complexity, McDonnell-Douglas developed an elegant solution that featured a counter-rotating gimballed telescope. By necessity, this solution limited cross-link operation to a narrow set of satellite on-orbit stations, which ultimately led to the program's termination.

The LCS was required to be operational 100% of the time that the satellite was on station because of the mission criticality of the cross-linked sensor data. Therefore, the terminal had to operate at full performance over a wide range of thermal conditions (-50 °C to +80 °C) and with the sun pointing down the optical axis of the telescope. Other key performance parameters for the LCS included [6]:

- Link 5 data: 1.28 Mbps at 10^{-7} BER (a 6-dB margin at end of life).
- Link 6 data: 4 kbps at 10^{-6} BER (a >6-dB margin at end of life).
- Link acquisition in <500 s.
- 3-year on-orbit mission life (0.935 reliability).
- No single-point failures (all electronics and electro-optic elements redundant).

The system design that was implemented featured two diode-pumped Nd:YAG lasers, dual sets of acquisition and tracking detectors, and dual sets of electronics. The imaging optical assembly comprised dual optical paths for both fine tracking and point-ahead beam-steering mirrors (Figure 4).

At the time of its development, the LCS was one of the most complex electro-optical systems ever developed. Several demanding component-level requirements were successfully addressed to meet DSP satellite integration requirements regarding size (54 ft^3), weight (300 lbs) and power (200 W) [6].

LCS Laser Technology

Early design trade studies resulted in the selection of a pulsed Nd:YAG laser operating at the fundamental 1.064-μm wavelength. A Pulse-Interval-Modulation (PIM) format was chosen to support the 1.28-Mbps data rate. However, this choice demanded that a convolutional code be developed to minimize burst errors associated with this modulation. Additionally, the link had to exhibit false alarm tolerance because of the radiation environment. The Iwadare-Massey convolutional error correcting code was determined to be optimum. The PIM coding with forward error correction required that the ND:YAG laser operate in cavity-dump mode at a stable 356 kpps. Because

Figure 3: Artist's Concept of an LCS Integrated Onto the DSP Satellite [5].

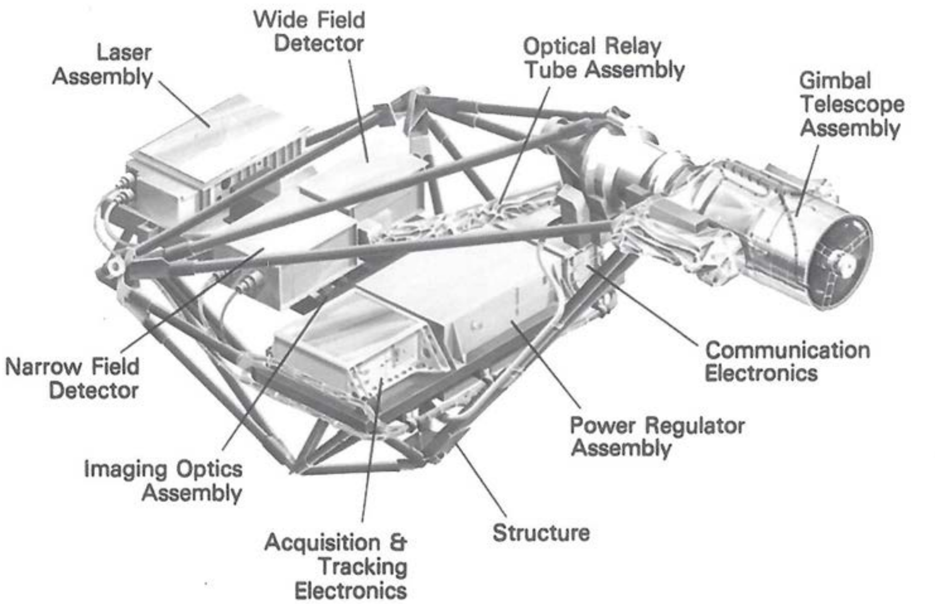


Figure 4: LCS Showing Individual System Configuration [6].

this pulse rate occurs in the middle of the instability region of Nd:YAG lasers, special active internal cavity control techniques were required to maintain <1% pulse amplitude stability for a diffraction-limited laser output pulse energy of 0.2 µJ.

Laser pump diode reliability presented another challenge. LCS represented the first application of diode pumping for an operational program (satellite or airborne). Extensive life testing was required for the mounting and polishing of the laser diode pump arrays to certify adequate lifetime. Thousands of hours of reliability testing for thousands of laser diodes were required to finally validate the allocated reliability for on-orbit operation.

LCS Telescope and Optics

Extremely high antenna gain was required to establish the 84,000-km link with 0.2-µJ pulse energy. The gimballed telescope exhibited an aperture size of 190 mm, CERVIT optics, and an Invar shell. The telescope was designed and qualified to provide a λ/10 wavefront quality after exposure to launch vibrations (80 grms at the secondary mirror) and thermal extremes of -50 °C to 90 °C (with an antenna gain of >112 dB). Unique and complex optical coatings were developed for a solar window to reduce the amount of solar energy entering the telescope to limit both damage to downstream optics and to minimize temperature swings.

LCS Pointing and Tracking

To support the pointing of the high gain antenna, a wideband tracking loop was required that could maintain pointing to better than 3.8 µrad, 3σ (including open-loop point-ahead error). A redesign of the torque-motor-driven, beam-steering mirrors that was first developed for the AFTS program was required to reduce both noise and uncompensated drift over temperature.

LCS Receivers

Quadrant silicon APDs that could meet the sensitivity and noise performance for operation at 1.06 µm had not yet been developed. To implement a null-seeking tracking detector, an arrangement of four silicon APDs was positioned around a four-sided pyramid. The physical spot size was 100 µm at the focal plane, thereby requiring a better than a 10-µm tip on the pyramid. The introduction of diamond-turned optics met this need. The silicon APDs were required to exhibit extremely high quantum efficiency at 1.06 µm as well as extremely low dark noise. Additionally, because of the natural and man-made radiation environments, special changes were required to both the diode physical structure and the transimpedance amplifier to achieve better than 1×10^6 V/W with noise equivalent power (NEP) of less than 1 nW at 1.06 µm.

> With the need for improved targeting accuracy and assured target prosecution, the demand for high-resolution imagery to and from the dismounted soldier is even more pressing now than it was 5 years ago.

The RDT&E program required 4 years to complete. The follow-on production program, including full qualification, ensued after successful RDT&E testing. Production proceeded until 1993, the start of the Gulf War. As part of that conflict, the satellites were repositioned for early warning of SCUD missile launch detection in the Middle East. The new satellite on-orbit stations required operational angles that were outside of the cross-link design limits. By that time, the ground station processing facilities had been dramatically reduced, facilitating the development of mobile ground station terminals that could be placed where the data were required, thereby obviating the need for cross-linking of the data to one centralized processing center. Components for all eight terminals were assembled, and three terminals were fully integrated and passed acceptance and qualification testing. Two terminals were integrated on satellites. Unfortunately, when the program was terminated after the expenditure of nearly $0.5 billion, the USAF decided to remove the terminals from the two satellites, and they were never flown [7].

TRANSFORMATIONAL SATELLITE COMMUNICATIONS SYSTEMS

The DSP-LCS program was the last major lasercom initiative for several decades. There were a number of studies, such as cross-link studies for the Follow-On Early Warning System (FEWS) program, which became the Space Based Infrared Sensor. This study was halted in 1993. MIT Lincoln-Laboratories began an effort to develop key component and system technologies under the program Lasercom Intersatellite Transmission Experiment (LITE), which comprised a number of phases that ultimately resulted in a satellite-based demonstration of capability. The Defense Advanced Research Projects Agency funded Terahertz Optical Reach Back (THOR) in 2002 and the Optical RF Combined Link Experiment (ORCLE) in 2004. Both NASA and the European Space Agency funded demonstration programs at this time [7].

The Transformational Communications Architecture (TCA) initiative, a major lasercom program, with defined program goals, schedule, and (U.S. government) funding, began in 2003. The TCA was started in response to the recognized growing demand for bandwidth on the battlefield. The TCA included a variety of communications systems (Figure 5) intended to satisfy military bandwidth needs through the middle of the 21st century.

The centerpiece of the TCA was a new satellite-based network, the Transformational Communications Satellite (TSAT) Network. The TSAT Network featured a top-down design to promote backward compatibility with existing RF systems. The TSAT architecture consisted of five geosynchronous satellites that could be interconnected in a variety of physical topologies. However, the logical topology was a mesh network. The routers employed in this application exhibited IPv6 protocol. Each satellite consisted of two terminals to support an optical transport network (OTN)/synchronous optical network (SONET) framing of 10-Gbps cross-link or 2.5-Gbps downlink to airborne intelligence, surveillance, and reconnaissance (ISR) terminals [8].

Lasercom terminal designs leveraged the significant advances achieved in commercial fiber-optic technology, including high-power (5 W) erbium-doped fiber lasers and commercial communications link protocols and hardware. The pointing and tracking subsystem designs incorporated the latest advances in InGaAs receiver technologies, fast beam steering,

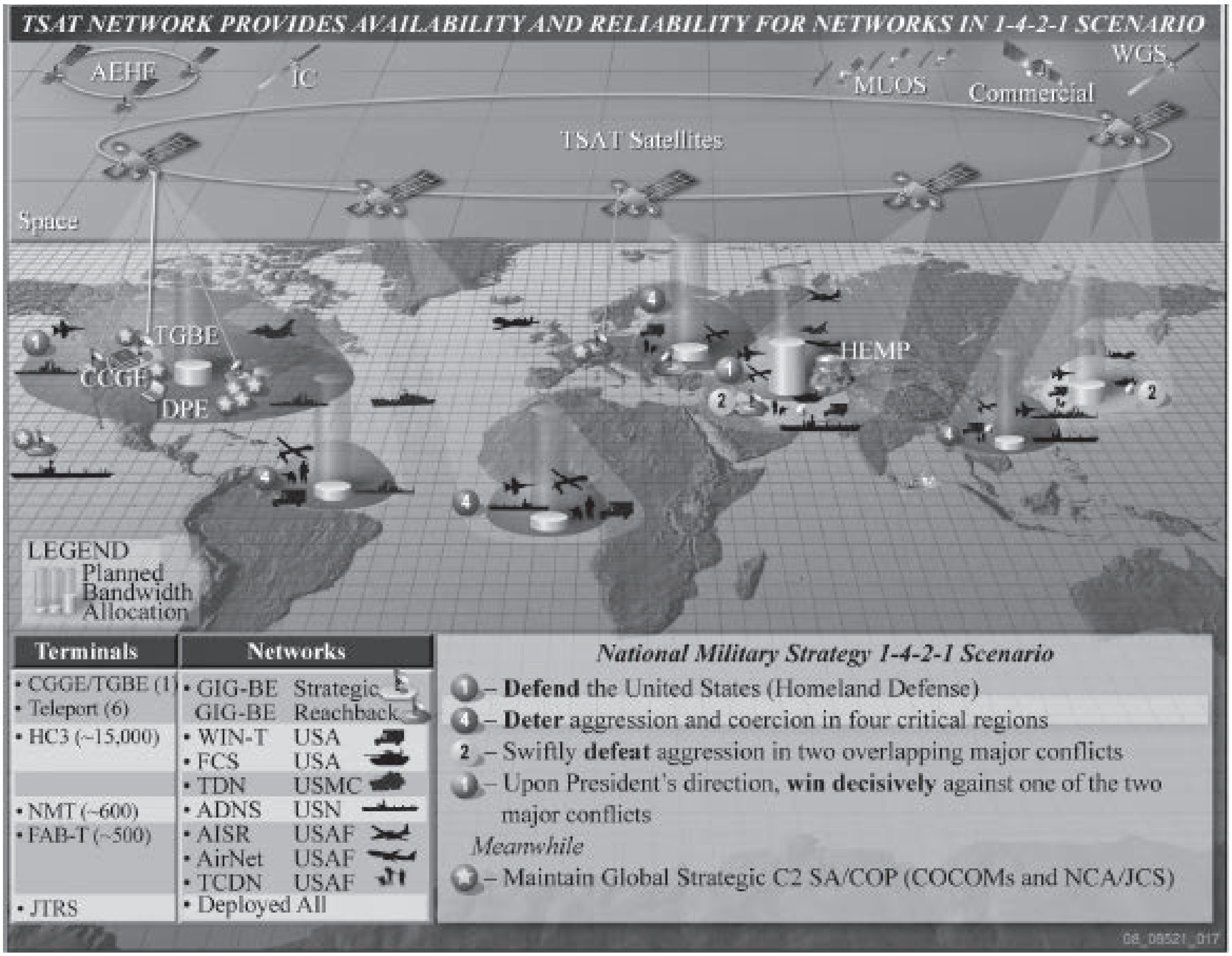


Figure 5: The TCA Integrated Numerous Existing RF Communications Missions With a New Lasercom-Based Network of TSAT Satellites [8].

and carbon fiber lightweight optics. However, a few significant technology issues for both the satellite and airborne terminal segments required resolution. A robust switching capability was necessary to support dynamic bandwidth and resource allocation, and a low-noise modem was needed to accommodate multiple modulation waveforms optimized to support various links. Lockheed-Martin (Sunnyvale) and Boeing Space Systems were each awarded contracts in excess of $500 million for satellite lasercom terminal definition and risk reduction [9].

The Airborne Lasercom Terminal was to be hosted on high-value ISR platforms, including U-2, E-10 (MC2), and the RQ-4 (Global Hawk). Stringent limitations were placed on terminal aperture projection into the windstream because of the aerodynamic characteristics of the U-2 and Global Hawk. Therefore, a significant investment was made in the development of "conformal" beam-steering apertures. The following companies were awarded contracts to define, mature, and demonstrate the critical technologies required for an Airborne Lasercom Terminal that could be integrated onto each of the target aircraft and operate with the TSAT Lasercom terminals: BAE Systems (Nashua, NH), Raytheon (Marlborough, MA), Lockheed-Martin Integrated Systems and Solutions (San Jose, CA), and Northrop-Grumman (Linthicum, MD). Although each of the terminals exhibited slightly different architectures, all of the terminals selected Risley prism technology as the conformal beam-steering aperture.

Unfortunately, amid growing concerns with overall TCA system risk and growing estimated costs (~$26 billion) for system deployment, the Department of Defense cancelled the program in its 2010 budget request. The total spent on the program at that point was $1.5 billion, which primarily addressed lasercom terminal development (both satellite and airborne terminals). The design and qualification of the high-power erbium-glass fiber amplifier for space use was probably the most significant advance provided by the TSAT development program prior to its cancellation [10].

LASERCOM: LOOKING FORWARD

The need for secure bandwidth on the battlefield continues. With the need for improved targeting accuracy and assured target prosecution, the demand for high-resolution imagery to and from the dismounted soldier is even more pressing now than it was 5 years ago. Today, airborne and space assets carrying Lidar, high-resolution imaging systems, and multi-spectral imaging systems generate massive volumes of data that must be exfiltrated, processed, and redistributed to a myriad of users, all of whom are fully networked as an integrated fighting force. However, no major operational program for implementing a wideband, secure data link (lasercom) is even in the planning stages. Fortunately, the same demands for instant connectivity exist in the commercial sector, and the commercial sector may ultimately solve the problem. The Airborne Lasercom Terminal, like the one being developed by General Atomics to operate with the European Data Relay System, may eventually provide the solution [11]. ■

REFERENCES

[1] Barry, J, P. Freedman, C. Kennedy, and J. Heitman. "1000 Megabits per Second Intersatellite Laser Communications System." TR-75-145, Air Force Avionics Laboratory, Wright-Patterson AFB, OH, June 1975.

[2] Elson, B. "Laser Communication Timing Revised." *Aviation Week and Space Technology*, 20 March 1978.

[3] Maynard, J., and M. Ross. "Airborne Flight Test System (AFTS) Final Technical Report." Contract F33615-76-C-1002 HQ AFSC, Los Angeles, CA, October 1981.

[4] Richelson, J. *The Wizards of Langley: Inside the CIA's Directorate of Science and Technology*. Boulder, CO, Westview Press, 2002.

[5] https://en.wikipedia.org/wiki/Defense_Support_Program, accessed August 2016.

[6] Maynard, J. "Production of a Laser Communication Satellite Cross Link System." CLEOS WN-1 New Lasers for Space and Atmospheric Applications, Baltimore, 1989.

[7] Hyde, G., and B. Edelson. "Laser Satellite Communications: Current Status and Directions." *Space Policy*, vol. 13, issue 1, pp. 47–54, February 1997.

[8] Pulliam, J., Y. Zambre, A. Karmarkar, V. Mehta, J. Touch, J. Haines, and M. Everett. "TSAT Network Architecture." IEEE Military Communications Conference, San Diego, CA, 2008.

[9] "Special Report: The USA's Transformational Communications Satellite System." *Defense Industry Daily*, 8 June 2009.

[10] Brinton, T. "Pentagon Cancels T-SAT Program, Trims Missile Defense," *Space News*, 6 April 2009.

[11] http://www.ga-asi.com/Websites/gaasi/images/products/communications/Laser_Comm_Brochure.pdf, accessed August 2016.

BIOGRAPHY

JOHN MAYNARD is currently president of MAYNfocus, LLC. His career in laser communications began in 1975 as the principal system engineer for the McDonnell-Douglas Airborne Lasercom Flight Test System, for which he was responsible for the flight system design and development as well as system test operations. He held a number of positions on the DSP Laser Cross-Link System RDT&E and Production programs, including Chief Scientist. At BAE Systems, Mr. Maynard held the position of Chief Engineer for Laser Communications and was responsible for the design and development of the ALT prototype. He has also served as Chief Engineer for Advanced Electro-Optic systems development for Soldier and Ground Systems at both Northrop-Grumman and Elbit Systems of America. He holds B.S. and M.S. degrees from the Georgia Institute of Technology with areas of specialization in electro-optical systems design and communications engineering.

JAMES "RALPH" TEAGUE is a principal research scientist at the Georgia Tech Research Institute, with more than 45 years of experience in sensor and related technologies, encompassing material science to large-scale sensor system integration. Dr. Teague currently serves as a technology specialist supporting DSIAC, responding to technology inquiries from the military and homeland defense sensing communities. He provides short courses to the sensor community in detection and tracking systems; laser systems; missile seeker design; EO/IR payloads; self-defense systems; chemical, biological and explosion detection systems; as well as sensor-related technologies, such as detectors, image processing, and optics. Dr. Teague is also active as a technology advisor, consultant, and expert witness. Dr. Teague has also been an Associate Editor for the *IEEE Aerospace and Electronic Systems* magazine, responsible for sensors, EO, and radar content. He holds a Ph.D. in experimental physics from the University of Missouri-Rolla, an M.S. from New Mexico Highlands University, and a B.A. from the University of North Carolina.

Table of Contents

(FORT BENNING, Ga.) PICATINNY PALLET: SUSTAINMENT AERIAL MOBILITY VEHICLE (Photo by Patrick A. Albright: MCoE PAO Photographer)

NDIA SCIENCE ENGINEERING AND TECHNOLOGY BRIEFING UPDATE

By Bruce Simon

On 4 August 2016, the National Defense Industrial Association (NDIA) Science and Engineering Technology (S&ET) Division met at The Army and Navy Club, in Washington, DC. The keynote speaker, Mr. Earl Wyatt, Deputy Assistant Secretary of Defense, Emerging Capabilities and Prototyping, in the Office of the Assistant Secretary of Defense for Research and Engineering, briefed attendees on the greater emphasis in the Department of Defense (DoD) on prototyping and experimentation under a constrained defense budget. Mr. Wyatt expounded on the virtues of DoD prototyping as "a set of design and development activities intended to reduce technical uncertainty and to generate information to improve the quality of subsequent decision-making." Mr. Wyatt further explained why his office needs to be aware of the technologies being developed in the private sector, so that he can be in a position to procure such technologies when the need arises—often with little advance notice. He also discussed Better Buying Power 3.0, explaining how the initiative reduces cost; increases innovation; and encourages working with, and selling to, global partners.

Technology focus areas described by Mr. Wyatt included asymmetric force applications, space capability, electromagnetic spectrum, autonomous systems, information operations, and analytics. And the current priorities of his office are Better Buying Power 3.0, the Defense Innovation Initiative, and the National Defense Authorization Act for FY16 and completion for FY17.

DSIAC is actively supporting many of the Better Buying Power 3.0 initiatives described by Mr. Wyatt and is available to support the needs of the DoD defense systems community. Please contact us if you are interested in sharing your defense systems-related technologies with the greater DoD community.

A recent DSIAC success story in the area of prototyping resulted from the pairing of the SURVICE Engineering Company with a British company, Malloy Aeronautics, to develop and market a prototype "Hoverbike," which uses state-of-the-art quadcopter technology. The Hoverbike can be used as an unmanned aerial vehicle (UAV) for a multitude of purposes or possibly even as a manned flight vehicle. This innovative technology was recently featured at the Farnborough Air Show near London, England.

DSIAC looks forward to continuing its participation in the NDIA S&ET briefings. The next briefing is scheduled for 1 September 2016, where the speaker will be Dr. Jason Matheney, Director of the Intelligence Advanced Research Projects Activity (IARPA).

COUNTERING THE UAS THREAT: A JOINT PERSPECTIVE

By Lt. Col. Jeffrey Lamport and Col. (retired) Anthony Scotto

BACKGROUND

As technology advances and the U.S. military touts the advantages of unmanned aircraft systems (UASs) (such as that pictured in Figure 1) for use in combat, a resounding fact is that other countries, terrorist organizations, and criminals are sure to continue to develop and procure low-cost UASs themselves. Often, these small, complex systems are equipped with cameras, laser designators, radio frequency (RF) collection devices, and/or weapons to provide battlefield intelligence and engage friendly forces. The size and composite materials used in UAS production make them inherently difficult to defeat with traditional force protection measures and short-range air defense (SHORAD) systems commonly employed by brigade and below maneuver forces.

One of the most significant uses of unmanned systems on the battlefield today is occurring in Ukraine, where both Ukrainians and Russian-backed separatists are operating UASs in relatively large numbers. These warfighters are reportedly operating more than a dozen variants, including fixed- and rotary-wing configurations, each functioning at different altitudes with various sensor packages designed to complement each other's capabilities.

Figure 1: RQ-7B Shadow Launch During Exercise (U.S. Marine Corps photo by Chief Warrant Officer 2 Jorge Dimmer).

And the battlefield is not the only susceptible area to the effects of nefarious UAS operators. The U.S. capital, nuclear facilities, correctional facilities, borders, and sporting venues are among the localities already infiltrated with this rapidly proliferating technology. Terrorists leverage UASs to interrupt our daily routine, while criminals defeat traditional security (e.g., fences, walls, and "no-fly" zones) to scout low-risk routes for illegal alien and drug transport across the border and contraband delivery to prisoners. While these are not traditional military missions, Department of Defense (DoD) specialized equipment and personnel may be tasked to support civil agencies in the Defense Support to Civil Authorities (DSCA) construct.

For nearly 3 decades, the U.S. Army and unified action partners have had the luxury of conducting ground and air operations in a virtually uncontested airspace environment. As such, development and fielding of dedicated SHORAD systems have declined and passive air defense skills have atrophied across the force. However, continued UAS technology development, UAS fielding acceleration, and the "bad actor" successes around the world clearly demonstrate that we are faced with a viable air threat. Leaders at all levels cannot be lulled into a false sense of security because of the small size of these UASs. They are as effective, if not more effective, than traditional manned aircraft (or even stealth aircraft) in reconnaissance, surveillance, and target acquisition (RSTA); precision attack; and indirect fire support. In short, troops must assume they are being continually watched and targeted and take appropriate action to minimize mission impact.

WHAT LEADERS AND WARFIGHTERS NEED TO KNOW

UASs can create serious problems for maneuvering or static forces. Their size, composite construction, small radar and electromagnetic signatures, and quiet operation make them difficult to detect and track. Their low cost, lethality, and rampant proliferation make them an air threat that we can no longer ignore.

Accordingly, focused counter-unmanned aircraft system (C-UAS) awareness, understanding, and training, (such as the exercise pictured in Figure 2) are needed by today's military planners and leaders.

Factors contributing to the C-UAS challenge include the following:

- Small, slow, and low profiles provide significant challenges to traditional air defenses. Conventional systems often filter out these tracks to avoid confusion with clutter, large birds, and aerostats. Systems optimized for this threat often forfeit effectiveness against other target sets (e.g., manned aircraft, cruise missiles, rockets and mortars, and ballistic missiles).
- Reduction of dedicated SHORAD units to maneuver brigades creates potential gaps in air defense coverage.
- Warfighters are largely indifferent to UASs. Recent combat experience in Iraq and Afghanistan indicates troops may become highly accustomed to friendly UASs and, therefore, less likely to be concerned about them flying overhead and less inclined to actively search for UASs operating in their battlespace.
- Many warfighters lack UAS recognition training. Without training, it is extremely difficult to observe

Figure 2: Target Drone Ready for Launch During a C-UAS Live Fire Exercise (U.S. Navy Photo by Petty Officer 2nd Class Antonio Turretto Ramos).

characteristics visually, which can easily distinguish threat UASs from friendly systems supporting the mission. This issue is compounded by the ever-increasing proliferation of new UAS designs and off-the-shelf systems sold to a number of countries.

- U.S. Army and Joint doctrine have not kept pace with the threat.

Simply put, C-UAS training is not a priority for many units, and thus they have not adequately updated plans to address the hazards that UASs present.

UNDERSTANDING THE THREAT

UASs pose a significant threat to safety and mission accomplishment by providing the enemy critical intelligence, such as a unit's precise location, composition, and activity. UASs may also provide laser designation for indirect fire or direct attacks using missiles; rockets; small guided munitions; or chemical, biological, radiological, and nuclear (CBRN) weapons. Some payload configurations can contain radar and communications jamming or other cyberattack technology. UASs may operate autonomously with little or no RF signature or under pilot control using a ground control station (GCS).

With regard to threat characteristics, UASs:

- Are typically composed of a UAV, a sensor and/or weapons package, a GCS, and communications equipment to support navigation and data transfer.
- Are available on the open market, are often clones of U.S. systems, and are less expensive than stealth technologies.
- Often rely on a global positioning system (GPS) for guidance/targeting and can use multiple RF bands, including frequency modulation (FM), ultrahigh frequency (UHF), satellite communications (SATCOM), and cell phones.
- Often have a limited range and flight duration (especially small UASs), meaning they are frequently operated from within the observed unit's battlespace.

THREAT MITIGATION

To mitigate risks associated with any air threat requires the performance of a comprehensive air threat analysis as part of the Intelligence Preparation of the Battlefield (IPB)/Intelligence Preparations of the Environment (IPE), as well as the leverage of any and all available resources. Furthermore, defeating the UAS threat begins with the following planning process:

- ***Understanding the UAS threat -*** Conducting a deliberate analysis to ascertain the potential UAS type and GCS likely to be employed, understand their capabilities and employment doctrine, predict where and how they will be employed, and identify their most likely targets.
- ***Honoring the threat -*** Ensuring there are adequate/appropriate resources to counter UAS effects in and around a unit's battlespace. If specialized sensors are not available, "air guards" should be established to continuously scan the airspace. Additionally, planners must ensure they understand and are in compliance with the Area Air Defense Plan (AADP).
- ***Maintaining disciplined flight operations -*** Although flight clearances for friendly UASs are sometimes perceived as untimely or overly restrictive, they are critical to ensuring other friendly forces in the area do not engage those UASs. Planners/operators must ensure that flights are in compliance with all local Airspace Coordinating Measures (ACMs) to aid in proper identification (ID).

C-UAS CONSIDERATIONS

UASs are the air threat of the next fight. As mentioned, UAS technology development and employment around the world demonstrate a relevant and viable air threat. And the defense community cannot be lulled into a false sense of security because of the relatively small size of these platforms. Air defense artillery liaison officers should thus consider the following actions when working with/within the Integrated Air Defense System (IADS):

- Take an active role in AADP development to ensure it adequately mitigates threats to the maneuver force.
- Suggest UAS-specific rules of engagement (ROE) when there is a reliable ability to distinguish unmanned platforms to maximize attrition of low-regret targets. ID and engagement authority for low, slow, small UASs should rest at the lowest possible tactical level.
- Ensure that criteria for "hostile act" and "hostile intent" that specifically address UASs are written in terms any warfighter can understand and adequately address ground troop protection.

- Consider requesting liberal "hostile" symbology use and ID forwarding through the Air Defense and Airspace Management (ADAM) Cell to the Common Operational Picture (COP).
- Ensure all Joint data link contributors use a common set of track amplification data (e.g., air type, air platform, and air activity) to categorize the UAS target set.

NATIONAL CAPITAL REGION AND INTERAGENCY SUPPORT

Critical assets within the continental United States have already been "attacked" by nefarious UAS operators. While no deaths have been attributed to these UASs, it is only a matter of time before these systems are directly or indirectly responsible for loss of life or interference with critical infrastructure in the homeland. In some circumstances, Title 10 military personnel and equipment may be required to operate subordinate to civil-military organizations. The following are considerations for personnel working in this environment:

- Per Department of Defense Directive (DoDD) 3025.18 [1], DoD resources may be used in an immediate response to prevent loss of life, mitigate damage to infrastructure, or support mutual aid agreements (Title 42 USC) to address certain precoordinated conditions, or as directed by the President as part of the national response framework.
- All DoD activity within the homeland is conducted to support a primary federal agency to minimize impacts to the American people, infrastructure, and environment.

We must assume localities of vital interest are being watched and targeted.

- It is unlikely that most organic communications systems will be compatible with the civil organization(s) being supported, thereby increasing reliance on knowledgeable liaison officers.
- Missions may include air defense coverage for the National Capital Region (NCR), key power/communications infrastructure, national borders, sporting arenas, political conventions, and Presidential inaugurations.
- Technology countering the UAS threat within U.S. borders must be in compliance with existing Federal Aviation Administration (FAA) and Federal Communications Commission (FCC) regulations. Military planners cannot assume they are exempt from fines or prosecution for violating civil airspace or spectrum management policies in the interest of thwarting a potential hazard.

CONCLUSION

UAS development and fielding are gaining momentum with our adversaries, and with each new innovation, these adversaries are becoming more capable than their previous generation. We must assume localities of vital interest are being watched and targeted. In addition, UAS operations are not limited to the battlefield; they have already been used to disrupt our daily routines at home and violate traditional security measures surrounding our borders, prisons, nuclear facilities, premier sporting venues, etc. Accordingly, leaders across all warfighting functions must take an active role in educating themselves and training their units to defeat this threat. Civil authorities should also be kept aware of the defense industry's ongoing research and analysis in the area and should be encouraged to both leverage the latest military technology and request assistance in defending airspace around sensitive domestic localities. ■

REFERENCES

[1] U.S. Department of Defense. *Defense Support of Civil Authorities (DSCA)*, Change 1, DoDD 3025.18, 21 September 2012.

BIOGRAPHIES

JEFFREY LAMPORT is a Lieutenant Colonel in the U.S. Air Force and a member of the Joint Deployable Analysis Team (JDAT) at Eglin AFB, FL. After graduating from the U.S. Air Force Academy, he served as a C-141 Starlifter and C-5 Galaxy airlift pilot. In 2006, Lt. Col. Lamport joined the RQ-4 Global Hawk program, where he oversaw implementation of the RQ-4 in the U.S. European, Africa, and Central Command areas of operation as the Director of Operations, 69th Reconnaissance Group, Detachment 2. In 2014, he was reassigned to the JDAT, Joint Staff, J6. As project lead for the Black Dart C-UAS Technology Demonstration, he oversaw data collection and analysis efforts leading to decision-quality recommendations in support of combatant command, interagency, and industry C-UAS requirements, capability gaps, and fielding/acquisitions efforts.

ANTHONY SCOTTO is a retired Colonel with more than 30 years of service in the U.S. Army. Currently, he is a senior analyst, serving as the lead contractor for the C-UAS project for the JDAT at Eglin Air Force Base, FL. As a commissioned Army Air Defense Artillery Officer, he served as a Patriot Advanced Capability Project Officer for the Directorate of Combat Developments; the Chief of Air Defense, Chief of Intelligence, and Deputy Commander for the 2nd Battlefield Coordination Detachment; the Army's Time Sensitive Targeting Officer for the Combined Air Operations Center at Al Udeid Airbase in Doha, Qatar; the Chief of Engagements for the Multi-National Division in Baghdad, Iraq; the Commander of the 3rd Battalion 346th Infantry Regiment at Camp Shelby, MS; and the Emergency Preparedness Liaison Officer to the State of Alabama.

REAL-TIME TASKING AND RETASKING OF MULTIPLE COORDINATED UAVs

By Marjorie Darrah, Eric Sorton, Mitch Wathen, and Marcela Mera Trujillo

UAS: RQ-11B Raven®
(Courtesy AeroVironment, Inc.)

INTRODUCTION

Both military missions and civilian applications have led to numerous investigations into using teams of collaborating unmanned aerial vehicles (UAVs) to accomplish a complex mission with strongly coupled tasks [1–26]. Given a team goal, these vehicles coordinate their activities to most efficiently and effectively accomplish an autonomous mission.

For years, teams of UAVs have been proposed for various military applications, such as serving as wide area search munitions [4]; suppressing enemy air defense systems [8–10]; and conducting intelligence, surveillance, and reconnaissance (ISR) [15–18]. Researchers have also been suggesting UAV teams for civilian applications, such as tracking the shape of a contaminant cloud (e.g., to identify radioactive material release into the atmosphere)

[22], monitoring biological threats to agriculture [23], conducting disaster management and civil security [24], and conducting traffic surveillance for sparse road networks [25].

Most current ground stations allow for the upload of waypoints, and by using autonomous controllers on the UAVs, these vehicles can fly a predetermined path without the intervention of a pilot. In most cases, ground stations can determine the correct smooth flight path between the waypoints based on the aircraft's specifications. Thus, no additional flight planning is needed, only the ability to provide the ground station with waypoints.

Reduced reliance on human operators is the goal of autonomy. However, an alternative/complementary goal of autonomy is to allow the human operator to "work the mission" rather than "work the system" [27]. This statement means that autonomy must support, not take over the decision-making. The Intelligent Tasker software was developed to work alongside a ground station to assist an operator in planning a complex mission using multiple vehicles. The user interface and back-end Genetic Algorithm Optimizer make planning and executing an optimized complex coordinated mission straightforward and uncomplicated for the user. The user designs the mission, and the software determines an optimized way to task the assets and provide the ground station with the waypoints needed to direct the UAVs to accomplish the mission. The software allows for the original tasking of multiple assets and then the retasking of assets in real-time if "pop-up" points of interest arise or an asset is lost. This work has been applied to small fixed-wing UAVs but can easily be applied to other types of aerial, terrestrial, or even marine vehicles, as well as heterogeneous teams [18].

MISSION SCENARIO

The mission example considered here is ISR. Conceivably, this mission could be to provide intelligence for securing the surroundings of an Army base or other specific area. This type of mission is also relevant for many civilian applications in which places or points of interest need to be monitored, such as for border patrol or forest fire detection. In this example, a three-plane scenario was chosen since the small AeroVironment Raven RQ-11 UAV (pictured in Figure 1) is currently deployed in sets of three [28]. The Raven is used by the U.S. Army, Air Force, Marine Corps, and Special Operations Command. Additionally, foreign customers include; Australia, Estonia, Italy, Denmark, Spain, and the Czech Republic. To date, more than 19,000 airframes have been delivered to customers worldwide, making the Raven one of the most widely adopted UAV systems in the world. Even though Ravens are widely fielded in sets of three, there do not seem to be any examples in open literature specifically discussing the teaming of Ravens to complete a mission. The ideas in this article extend the usefulness of having three assets teamed to do a coordinated mission without the necessity for adding additional trained personnel.

Intelligent algorithms and autonomy must support, not take over the decision-making.

Figure 1: Raven RQ-11 Field Set.

In this mission scenario, three planes are launched within minutes of each other (as pictured in Figure 2), to return within minutes of each other. The scenario does not require the fastest time to complete the mission but rather requires that the planes observe the area as long as needed to complete the mission and spend the maximum time over the area of interest (while not exceeding the battery life). In the scenario constructed for this exercise, it was assumed that there is a set of points of interest (POIs), $\{p_1, p_2, p_3, ..., p_n\}$, chosen from a map of the area of interest. These POIs would have priorities, {low, medium, high}, assigned to them based on the threat that they may impose or the importance of the site. The priority level dictates how many times during the mission the site will be visited. Also, loiter times are chosen for the POIs that dictate the length of time the UAV should circle, observing the site during each visit.

Figure 2: Soldier Launching Raven UAV.

THE USER INTERFACE

The graphical user interface (GUI) allows a user to easily plan and execute a complex coordinated mission with three UAVs and up to 10 POIs. To begin, an operator chooses a set of POIs and a launch point. The user selects an area of interest from Bing Hybrid Map Provider and indicates how many points of interest in the area are to be visited. Clicking on the map then populates the latitude and longitude of the points and allows the user to specify priority level and loiter time for each (as pictured in Figure 3). From the launch point, the maximum distance a UAV can fly and return within its safe battery life is calculated. Points outside an acceptable range will not be allowed to remain in the list because doing so would result in a mission failure. Points close together (able to be observed at the same time) are clustered for efficiency.

SYSTEM DESIGN

The Intelligent Tasker is designed to work with various ground stations that have autopilot capabilities (e.g., Ardupilot, APM Mission Planner, Corvid) (see Figure 4). The idea is to allow the ground station software to manage multiple autonomous vehicles to complete a coordinated operation. As illustrated in Figure 4, the operator communicates to the Intelligent Tasker to define the mission and runs the simulation to ensure the routes are acceptable. Once the operator determines that the suggested coordinated solution is acceptable, then the plan is made available to the ground station. In the event that retasking is necessary, the ground station will relay information back to the Intelligent Tasker. This information will contain the UAV's current position, the points of interest that have been visited, and each vehicle's remaining battery life.

Ground stations may have multiple channels to communicate with multiple vehicles. In this case, the ground station will be given an ordered list of coordinates to visit for each of the UAVs. For a ground station with multiple channels, it is possible for one pilot to handle all UAVs during the mission, as demonstrated in Darrah et al. [17]. If the ground station only has one channel to communicate with a UAV, then multiple instances of the ground station may need to be running, one for each vehicle, and the Intelligent Tasker will provide the ordered list of points to visit to the appropriate instances of the ground station.

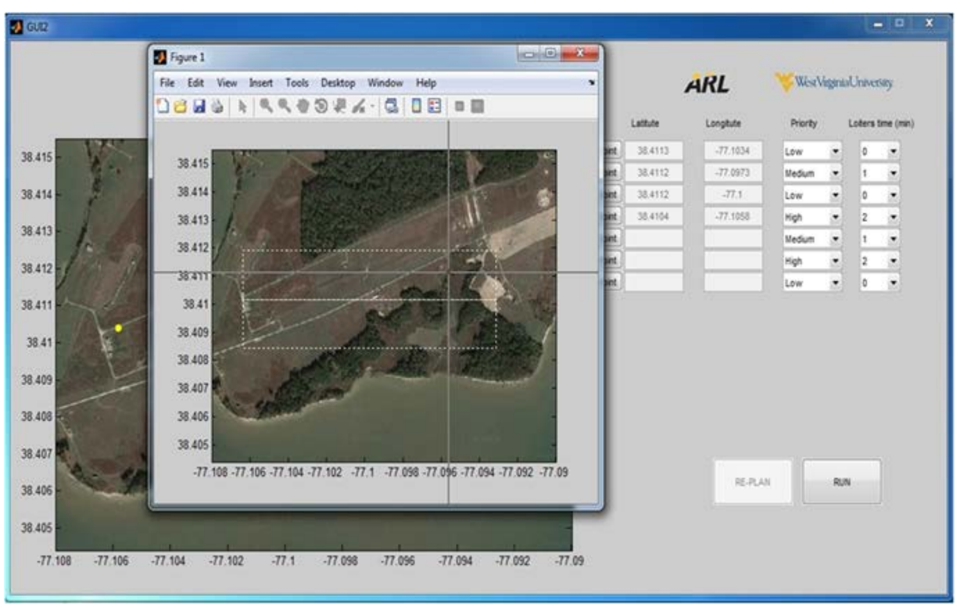


Figure 3: User Interface for Intelligent Tasker Software.

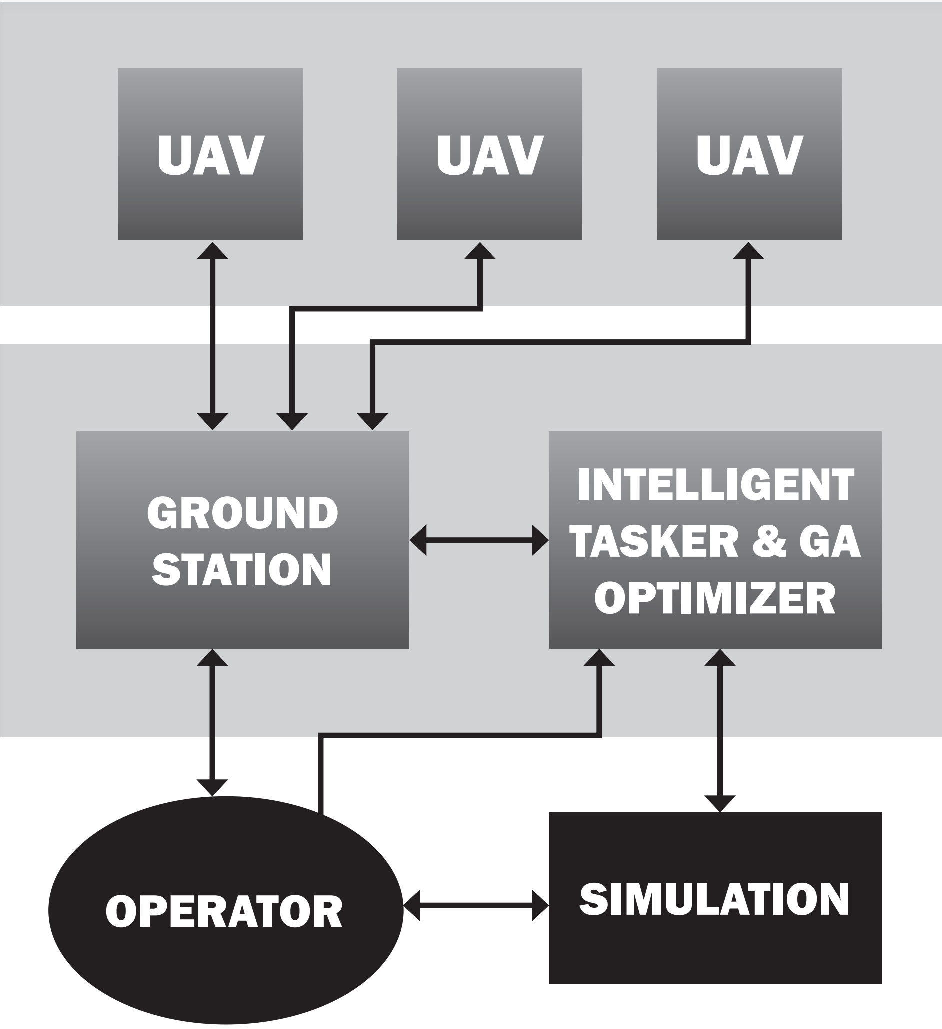


Figure 4: Intelligent Tasker as Part of the UAV System.

The UAVs as part of this system only communicate with the ground station. The UAVs are launched and put in a holding pattern over the launch site until the coordinated tasking received from the Intelligent Tasker is uploaded from the ground station to each UAV. To ensure vehicles do not collide, the planes are flown with a vertical separation. When retasking takes place for the purpose of either adding an additional point of interest or continuing the mission after one asset has been lost, the UAVs are given the command to again enter the holding pattern where they are located, send their position to the ground station, communicate battery life remaining, and indicate waypoints they have left to visit. The new plan will take into account all taskings that still need to be completed, as well as the new positions of the vehicles.

GENETIC ALGORITHM OPTIMIZER

A genetic algorithm (GA) is a search algorithm based on the mechanics of natural selection and natural genetics [29]. In our software, the GA Optimizer is used to look for the optimal task assignment of UAVs during the mission. The GA Optimizer employees the usual components of a GA, such as a fitness function developed for a particular scenario, chromosomes that represent the solutions to the problem, crossover that is used to develop new solutions from existing solutions, mutation to ensure that the GA does not get struck in a local optimum, and elitism to ensure the solution never degrades. These components work together to quickly provide an optimized solution in the form of a task list for each UAV. Other methods have been employed for the tasking problem [5–9]; however, the GA has proven to be the most versatile and scalable type of solution. A fitness function can be developed for individual mission scenario, and the solution space for each individual type of problem can be encoded as a set of chromosomes. For complete details on how the GA works, as well as various examples, see Darrah et al. [16, 17] and Eun and Bang [18].

> The user designs the mission, and the software determines an optimized way to task the assets and provide the ground station with the waypoints needed to direct the UAVs to accomplish the mission.

FLIGHT TESTING

Testing of this technology was performed at the U.S. Army Research Laboratory (ARL) Blossom Point Research Facility, near La Plata, MD. This 1,600-acre site offers a UAV test area that is 2 miles long by ½ mile wide. The facility is classified as a range and as such is closed to the public. The location also maintains a runway and a command-and-control area, which facilitates take-off and landing as well as UAV observation during the experiments.

During the flight demonstration phase, the three planes were launched one at a time using manual control to take them to desired altitude and then switched to autonomous mode, where they began to circle at their home loiter position. The team could not acquire a set of Raven RQ-11 UAVs (which cost approximately $300,000) for testing, so planes of similar size, shape, and payload capability as the Raven were used. Three PROJET RQ-11 model airframes (pictured in Figure 5) were outfitted with the necessary radios, sensors, and control computers to fly autonomously. For command-and-control functions, a FreeWave MM2 900-MHz was installed in each aircraft as well as the ground control station (GCS). Video was captured from each plane by a HackHD camera mounted inside the fuselage with the lens flush with the airframe. Video was transmitted in real-time to the ground using a Stinger Pro 5.8-GHz transmitter. The video was received on the ground via a YellowJacket Pro 5.8-GHz receiver integrated with the GCS. Each aircraft also had a MediaTek GPS module integrated for position sensing.

The GCS employed for testing demonstrated consisted of a Futaba 9C remote controller and a Linux-based laptop. The Futaba was used by the pilot to directly command the UAVs during takeoff, landing, and any contingency operations. Additionally, it acted as the main communication node between the planes and the ground, except for video. The Linux-based laptop was used for telemetry monitoring, situational awareness, and mission status observation. The Linux laptop communicated with the GA laptop used to calculate new mission plans. Once the mission plan was determined by the Intelligent Tasker, this plan was transmitted via Ethernet from the GA-based system laptop to the Linux-based laptop for review, and then transmitted via WiFi to the Futaba 9C communications package for final transmittal to the in-flight UAV team.

As the three planes were being launched, one of the Army personnel assembled to observe the demonstration was chosen to enter a set of POIs and associated priorities into the Intelligent Tasker, and an optimized coordinated mission was devised and communicated to the ground station. Once all three planes were in autonomous mode circling at the home loiter position, they were given their mission assignments from the ground station. At this point, the UAVs all flew off in autonomous mode in different directions to complete their part of the mission. After completion of their task list (visiting specific POIs in a specified order), they returned to the home loiter position to await further tasking or to be taken over and manually landed. The flights were observed on monitors that were used to track the movements of the UAVs and also view the video feeds that were being sent back from the UAVs' onboard cameras. This monitoring verified that the UAVs found the designated POIs.

Figure 5: Model Planes Used as Surrogate for Raven RQ-11.

CONCLUSIONS

Many complex military and civilian applications necessitate the use of teams of unmanned assets to accomplish diverse tasks. The goal for using a team of assets should be to allow the human operator to "work the mission" and not have to be concerned about the details of how to choose an optimal way to accomplish all the tasks. This means that intelligent algorithms and autonomy must support, not take over the decision-making. The Intelligent Tasker user interface makes it easy for a single operator or small group of operators to plan and execute a sophisticated mission with little effort. The GA Optimizer finds an optimal way to assign tasks to assets. The Intelligent Tasker is an add-on, not a replacement, to existing systems that uses existing autonomous controllers and ground stations to allow a complex mission to be carried out by one operator or a few operators in a supervisory capacity. This technology can provide a new way to maximize the use of UAVs in the field and is flexible enough to be applied to many diverse mission scenarios and types of assets (ground, aerial, terrestrial, or even marine vehicles, as well as heterogeneous teams). It can also reduce the number of required trained personnel, thus saving time, money, and possibly lives. ■

ACKNOWLEDGMENTS

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REFERENCES

[1] Richards, A., J. Bellingham, M. Tillerso, and J. P. How. "Coordination and Control of Multiple UAVs." *Proceedings of AIAA Guidance, Navigation and Control Conference,* Washington, DC, 2002.

[2] Chandler, P. R., M. Pachter, S. J. Rasmussen, and C. Schumacher. "Multiple Task Assignment for a UAV Team." *Proceedings of the AIAA Guidance*, Navigation and Control Conference, AIAA 2002-4587, Monterey, CA, 2002.

[3] Flint, M., M. Polycarpou, and E. Fernandez-Gaucherand. "Cooperative Path Planning for Autonomous Vehicles Using Dynamic Programming." *Proceedings of the 15th Triennial IFAC World Congress*, Barcelona, Spain, pp. 481–487, 2002.

[4] Schumacher, C., P. Chandler, and S. Rasmussen. "Task Allocation for Wide Area Search Munitions with Variable Path Lengths." *Proceedings of the American Control Conference*, Denver, CO, June 2003.

[5] Schumacher, C. J., P. R. Chandler, M. Pachter, and L. Pachter. "Constrained Optimization for UAV Task Assignments." *Proceedings of the AIAA Guidance, Navigation and Control Conference,* Washington, DC, 2004.

[6] Shima, T. S., S. J. Rasmussen, and A. G. Sparks. "UAV Cooperative Control Multiple Task Assignments Using Genetic Algorithms." *Proceedings of the American Control Conference*, Portland, OR, 2005.

[7] Shima, T. S., and C. J. Schumacher. "Assignment of Cooperating UAVs to Simultaneous Tasks Using Genetic Algorithms." *Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit*, San Francisco, CA, 2005.

[8] Darrah, M. A., W. Niland, and B. Stolarik. "Multiple UAV Dynamic Task Allocation Using Mixed Integer Linear Programming in a SEAD Mission." *Proceedings of AIAA Infotech@Aerospace Conference*, Alexandria, VA, 2005.

[9] Darrah, M., W. Niland, and B. Stolarik. "Multiple UAV Task Allocation for an Electronic Warfare Mission Comparing Genetic Algorithms and Simulated Annealing." DTIC Online Information for the Defense Community, ADA462016, 2006.

[10] Darrah, M., W. Niland, B. Stolarik and L. Walp. "UAV Cooperative Task Assignments for a SEAD Mission Using Genetic Algorithms." *Proceedings of Guidance, Navigation and Control Conference*, Keystone, CO, August 2006.

[11] Darrah, M., and W. Niland. "Increasing UAV Task Assignment Performance Through Parallelized Genetic Algorithms." *Proceedings of Infotech@Aerospace Conference*, Rohnert Park, CA, 2007.

[12] Shima, T., S. J. Rasmussen, A. G. Sparks, and K. M. Passino. "Multiple Task Assignments for Cooperating Uninhabited Aerial Vehicles Using Genetic Algorithms." *Computers & Operations Research*, vol. 33, pp. 3252–3269, 2006.

[13] Beard, R. W., T. W. McLain, D. B. Nelson, D. Kingston, and D. Johanson. "Decentralized Cooperative Aerial Surveillance Using Fixed-Wing Miniature UAVs." *Proceedings of the IEEE*, vol. 94, issue 7, 2006.

[14] Matlock, A., R. Holsapple, C. Schumacher, J. Hansen, and A. Girard. "Cooperative Defensive Surveillance Using Unmanned Aerial Vehicles." *Proceedings of the American Control Conference*, St. Louis, MO, 2009.

[15] Darrah, M., E. Fuller, T. Munasinghe, K. Duling, M. Gautam, and M. Wathen. "Using Genetic Algorithms for Tasking Teams of Raven UAVs." *Journal of Intelligent & Robotic Systems*, vol. 70, issue 1, pp. 361–371, 2013.

[16] Darrah, M., J. Wilhelm, T. Munasinghe, K. Duling, E. Sorton, S. Yokum, M. Wathen, and J. Rojas. "A Flexible Genetic Algorithm System for Multi UAV Surveillance: Algorithm and Flight Testing." *Unmanned Systems*, vol. 3, no. 1, pp. 1–14, 2015.

[17] Darrah, M., L. Pullum, S. Beck Roth, B. Gilkerson, and E. Taipale. "Using Genetic Algorithms for Robust Tasking of Multiple UAVs with Diverse Sensors." *Proceedings of AIAA Infotech@Aerospace Conference*, Seattle, WA, April 2009.

[18] Eun, Y., and H. Bang. "Cooperative Task Assignment/Path Planning of Multiple Unmanned Aerial Vehicles Using Genetic Algorithms." *Journal of Aircraft*, vol. 46, no. 1, pp. 338–343, 2009.

[19] Karaman, S., T. Shima and E. Frazzoli. "Task Assignment for Complex UAV Operations Using Genetic Algorithms." *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Chicago, IL, 2009.

[20] Zuo, Y., Z. Peng and X. Liu. "Task Allocation of Multiple UAVs and Targets Using Improved Genetic Algorithm." *Proceedings of the 2nd International Conference on Intelligent Control and Information Processing*, pp. 1030–1034, 2011.

[21] Edison, E., and T. Shima. "Integrated Task Assignment and Path Optimization for Cooperating Uninhabited Aerial Vehicles Using Genetic Algorithms." *Computers & Operations Research*, vol. 3, no. 8, pp. 340–356, 2011.

[22] Sinha, A., A. Tsourdow, and B. White. "Multi UAV Coordination for Tracking the Dispersion of a Contaminant Cloud in an Urban Region." *European Journal of Control*, vol. 15, issues 3–4, pp. pp. 441–448, 2009.

[23] Techy, L., C. A. Woolsey, and D. G. Schmale III. "Path Planning for Efficient UAV Coordination in Aerobiological Sampling Missions." *Proceedings of the 47th IEEE Conference on Decision and Control*, Cancun, Mexico, December, 2008.

[24] Maza, I., F. Caballero, J. Capitan, J. R. Martinez-de-Dios, and A. Ollero. "Experimental Results in Multi-UAV Coordination for Disaster Management and Civilian Security Applications." *Journal of Intelligent & Robotic Systems*, vol. 61, issue 1, pp. 563–585, 2011.

[25] Liu, X. F., Y. Q. Song, Z. W. Guang, and L. M. Gao. "A UAV Allocation Method for Traffic Surveillance in Sparse Road Network." *Journal of Highway and Transportation Research and Development*, vol. 7, issue 2, pp. 81–87, 2013.

[26] Girard, A. R., A. S. Howell, and J. K. Hedrick. "Border Patrol and Surveillance Missions Using Multiple Unmanned Air Vehicles." *Proceedings of the 43rd IEEE Conference on Decision and Control*, Paradise Island, Bahamas, 2004.

[27] U.S. Department of Defense. "Unmanned Systems Integrated Roadmap 2011–2036." Reference Number 11-S-3613, http://www.acq.osd.mil/sts/docs/Unmanned%20Systems%20Integrated%20Roadmap%20FY2011-2036.pdf, accessed August 2016.

[28] Airforce-technology.com. "RQ-11B Raven Unmanned Air Vehicle (UAV), United States of America." http://www.airforce-technology.com/projects/rq11braven/, accessed August 2016.

[29] Goldberg, D. E. *Genetic Algorithms in Search, Optimization, and Machine Learning*. Reading, MA: Addison-Wesley, 1989.

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A MODELING FRAMEWORK FOR COAXIAL-ROTOR UAV SYSTEM SWARMS:

Performance Analysis via System ID and Cognitive Physicomimetics Techniques

By Mark Coy

INTRODUCTION

As evidenced by the significant current funding for advanced helicopter technologies [1], as well as the large quantity of technical papers available throughout the news media [2, 3], the Department of Defense (DoD) is placing increased importance on identifying, developing, and fielding advanced helicopter technologies. Of course, these advanced technologies, many of which are still not fully emerged or understood, bring with them both great opportunity and great potential geopolitical risks for decision-makers. Good decisions in these areas could mean great military advantage; bad decisions could be catastrophic, potentially reverberating for years to come. One needs only to recall the fall of the infamous Spanish Armada, which was relatively uber-tech for its era in 1588, wherein Spain did not recover for approximately 400 years after its defeat.

> Friendly UAV swarms could provide an additional, urgently needed, and difficult-to-defeat solution in confounding the specter of A2/AD threats.

At present, the U.S. Army is aggressively pursuing an ambitious, future-leaning modernization effort called the Future Vertical Lift (FVL) program [2, 3]. According to Maj. Gen. Michael Lundy of the U.S. Army Aviation Center of Excellence Command, this program will be one of the largest programs the DoD undertakes in terms of the number of aircraft that will be replaced [3]. In support of this far-reaching effort and the Office of Secretary of Defense's ongoing tri-Service effort called the "Tactical Cloud" (which is a DoD construct for an "Internet of Things" [IOT]), the Army is making a valuable bridging-like contribution between these two initiatives, based on its dedicated mission within its defined "swim lane."

Manned coaxial-rotor helicopters feature prominently in the design proposals provided in the Army's FVL program. Perhaps alternative unmanned aerial vehicle (UAV) versions of these proposed manned helicopter designs might also be provided as design options (e.g., the present Fire Scout helicopter UAV, a version of the manned Scout helicopter). It is also highly likely that present, as well as future, manned coaxial-rotor helicopter designs, particularly used in swarms, will be under intense and serious consideration for the high-performance benefit offered by these types of helicopter designs.

In the near future, the as-yet-built advanced UAV helicopter swarms may be controlled and/or monitored in real-time for system status, maintenance, etc., and/or serve as data-download sources for user decision-making in big data analytics scenarios, and/or supported (in real-time) with UAV payload-customized demand-pull analytics. Thus, all these tasks will be accomplished via the Tactical IOT.

This article focuses on the analytical framework, central characteristics, and system complexities for future advanced coaxial-rotor helicopter UAVs in swarm mission-flight. However, before developing embedded plug-n-play or hosted software in support of the Tactical IOT tasks described previously, an understanding must be made via a modeling framework focused on the performance characteristics of this highly complex and beneficial coaxial-rotor helicopter UAV swarm. The information contained in this brief summary represents the beginning of an investigation series into the highly complex coaxial-rotor helicopter UAV swarm by reporting on a modeling framework for its ideal coaxial-rotor helicopter UAV swarm performance using system identification (ID) and cognitive physicomimetics mathematical techniques.

The advantage in first developing a modeling framework, which is focused on UAV helicopter swarm performance, is that it is highly likely to yield both superlative quality results and a detailed system swarm model that can be easily verified and validated by the UAV swarm community of interest. Also, serendipitous innovation is typically cultivated by a top-down framework "first" methodology (called Best System's Engineering Practices).

A HIGHER PURPOSE FOR THIS ARTICLE

The purpose and accompanying rationale for swarm UAVs are accurately described in a 2016 *DSIAC Journal* article [4], which states "The Joint Forces do not currently have adequate ways to fully plan, integrate, or synchronize the effects delivered by UA [unmanned aircraft] swarms . . . ." This statement is especially insightful concerning adversarial Integrated Air Defense Systems (IADS) dependent on surface-to-air missile batteries. These missile system threats, in turn, importantly serve as weapons to fortify anti-access/area denial (A2/AD) navigation countermeasures (i.e., air, land, and sea navigation) against friendly forces. The article further states that our Joint forces unfortunately have a single-minded legacy of super dependence on standoff weapons and other standoff strike platforms to confront the increasingly looming A2/AD specters. But friendly UAV swarms could provide an additional, urgently needed, and difficult-to-defeat solution in confounding the specter of A2/AD threats. In short, UAV swarms remain both a highly promising and a highly difficult challenge.

FRAMEWORK

For all the subsections contained in this section, the following are common denominator threads or themes that apply:

- System's thinking or holistic system's thinking.
- The use of system ID mathematical techniques.
- The use of cognitive physicomimetics mathematical techniques.

- System's optimization using linear complementarity and other, where applicable.
- Smart platform autonomy, with the capability to learn and appropriately respond to new and beneficial "knowledge" without forgetting what was learned before.
- Link 16 compatible systems architecture.
- Microelectromechanical system (MEMS)/nanoelectromechanical system (NEMS) integrated circuits (IC) subsystems where applicable.

All of the following subtopics can be viewed as application opportunities for both system ID and cognitive physicomimetics, which will be introduced afterwards as subtopics under the general topic of Framework.

Virtual Advanced Swarm System's Configuration Framework (for Each/ Individual Autonomous Swarm Vehicle)

It is helpful to view each of the following bullets or payloads as application opportunities for system ID and/or cognitive physicomimetics:

- On-board Link 16 assisted autonomous global positioning system (GPS) with inertial navigation.
- Smart autonomous on-board Link 16 communication relay.
  - To-From other Link 16 netted assets (e.g., Patriot, JSTARS, E-2C, F-16, F-15, F-18, NATO E-3, Enhanced Position Location Reporting System [EPLRS]/Single Channel Ground and Airborne Radio System [SINCGARS], Army Air Defense Airspace Management [ADAM] Cell, Terminal High-Altitude Air Defense [THAAD], Forward Area Air Defense [FAAD], Rivet Joint, Compass Call, etc.)
- Smart autonomous image processing and coms via Link 16.
- 802.16-mobile standard equipment – autonomous local swarm air-to-air communications.
- Smart autonomous electronic warfare (for force protection).
  - Radar/Lidar, hyperspectral synthetic aperture radar (SAR), ground moving target indicator (GMTI), jammer.
  - Electronic intelligence (ELINT), electronic support measures (ESM).
  - Multi-path mitigation.
  - Precision geolocation.
  - Anti-jam GPS+inertial navigation subsystem.
  - Jam-resistant antenna+receiver subsystem.
- Smart autonomous real-time airborne foreign language translation.
- Smart autonomous altimeter and avionics.
- On-board power based on proton exchange membrane fuel cell. An all-electric propulsion train will be modeled.
- Smart autonomous on-board platform continuous propulsion train and fuselage status data recording and analysis (e.g., mean time between failures forecasting).
- Smart autonomous and secure bi-directional 802.16-mobile and Link 16 coms-data translation.

System ID [5]

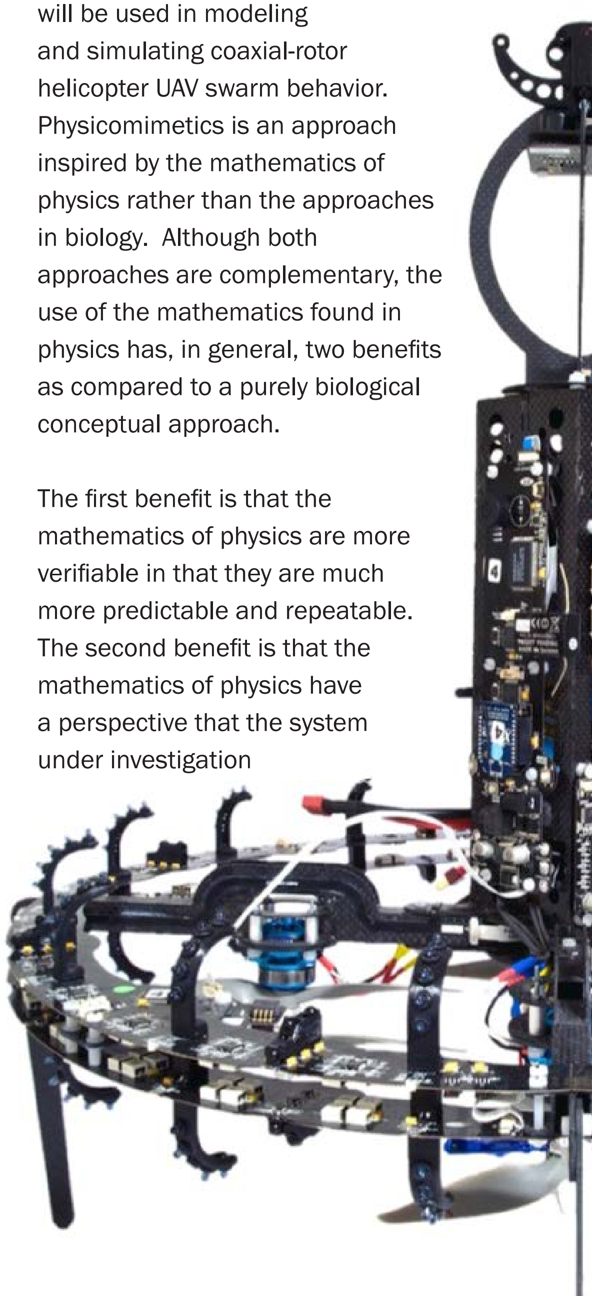
Using a system's measured data as well as external input influences to the system, the system ID uses statistics to construct mathematical models of dynamically changing systems to capture the essential behavior or process (not necessarily the constituent component specification functionality) in either the frequency or time domain.

System ID has the goal of model optimality, efficient but accurate (to the resolution degree possible and desired) model representation, and model reduction or sparsity, especially for highly complex dynamic systems. The system ID approach is that of determining a statistical relation among a measured system's behavioral data and external input influences (as data) to the system.

Physicomimetics [6]

For this Modeling Framework effort, the concepts found in physicomimetics will be used in modeling and simulating coaxial-rotor helicopter UAV swarm behavior. Physicomimetics is an approach inspired by the mathematics of physics rather than the approaches in biology. Although both approaches are complementary, the use of the mathematics found in physics has, in general, two benefits as compared to a purely biological conceptual approach.

The first benefit is that the mathematics of physics are more verifiable in that they are much more predictable and repeatable. The second benefit is that the mathematics of physics have a perspective that the system under investigation



or indeed "nature" is minimally optimal (e.g., the minimal expense of energy to arrive at a system solution in the fastest and shortest way possible). These two concepts can readily capture emergent behavior uniquely found in nature and in artificially made swarms (e.g., the leaderless behavior of ants, birds, or schools of fish). Therefore, these concepts can decidedly aid in the system design with a deeper understanding of the swarms.

Cognitive physicomimetics is the combination of cognition with physicomimetics. For system's thinking, which is an important perspective of this effort, cognition is an attempt at not only making systems "smarter" but decidedly more human-like. For example, it is the ideal system's ability at making decisions and continually learning in a dynamically changing and nonlinear environment with an emergent self-contained system's behavior. It should be noted that emergent behavior simply means that the individual organism or discrete system component (e.g., ants, bees, birds, schools of fish, and UAV swarms) does not individually know and cannot orchestrate the entire group's behavior; the total group's behavior seems as though it was commanded, controlled, or orchestrated.

THE WAY AHEAD

Open-sourced data collection of existing manned and unmanned coaxial-rotor helicopters will be made from reputable organizations, including micro-coaxial-rotor helicopters. The applicable systems characteristics as well as the external input data (i.e., system influences) will be synthesized from the data collection to model and simulate a system under test. In addition, the payloads listed previously in the Framework discussion will be incrementally added to the modeled coaxial-rotor helicopter system. After each incremental payload addition, the results of the modeling and simulation will be reported.

Finally, it is hoped that others in the UAV swarm community of interest will provide constructive criticism to this ongoing effort, whose ultimate purpose is to contribute, even if only in a small way, to DoD decision-making regarding this important technology for U.S. defense. ■

REFERENCES

[1] Defense Industry Daily. "JMR-FVL: Army Casts Dice for Future Helicopter." http://www.defenseindustrydaily.com/jmr-fvl-the-us-militarys-future-helicopter-014035, 17 February 2016.

[2] Tadjdeh, Yasmin. "Future Vertical Lift Could Be Shot in the Arm for Industry." *National Defense Magazine*, http://www.nationaldefensemagazine.org/archive/2015/October/Pages/calLiftCouldBeShotintheArmforIndustry.aspx, October 2015.

[3] Drew, James. "Boeing Upbeat as US Army Moves on Future Vertical Lift." FlightGlobal, http://www.nationaldefensemagazine.org/archive/2015/October/Pages/FutureVerticalLiftCouldBeShotintheArmforIndustry.aspx, October 2015.

[4] Filbert, F. Patrick. "Joint Integration Testing of Swarming Unmanned Aerial Vehicles." *DSIAC Journal*, vol. 3, no. 1, 2016.

[5] NATO Research and Technology Organization. "System Identification for Integrated Aircraft Development and Flight Testing." RTO-MP-11 AC/323 (SCI) TP/7, Neuilly-sur-Seine Cedex, France, March 1999.

[6] Spears, W. M., D. F. Spears, R. Heil, W. Kerr, and S. Hettiarachchi. "An Overview of Physicomimetics." *Lecture Notes in Computer Science*, vol. 3342, pp. 84–87, Springer Berlin Heidelberg, 2004.

BIOGRAPHY

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CONFERENCES AND SYMPOSIA

OCTOBER 2016

33rd Annual International Test and Evaluation Symposium
3–6 October
Hyatt Regency
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21st Annual Expeditionary Warfare Conference
11–13 October
Norfolk Waterfront Hotel
Portsmouth, VA
http://www.ndia.org/meetings/7700/Pages/default.aspx

87th Shock and Vibration Symposium
17–20 October
Sheraton New Orleans
New Orleans, LA
http://www.savecenter.org/index.html

Wargaming II Special Meeting
17–20 October
Hilton Mark Center
Alexandria, VA
http://www.mors.org/Events/Special-Meetings/Wargaming

2nd Annual Cyber Electromagnetic Activity (CEMA)
18–20 October
Aberdeen Proving Ground
Aberdeen MD
http://www.crows.org/event/192-aoc-conferences/2016/10/18/69-cema-2016.html

Unmanned Systems Defense 2016
25–27 October
The Ritz-Carlton, Pentagon City
Arlington, VA
http://www.thedefenseshow.org

Precision Strike Technology Symposium (PSTS-16)
25–27 October
Johns Hopkins U. Applied Physics Lab
Laurel, MD
http://www.precisionstrike.org/events/7PST/7PST.html

Seventeenth Helicopter Military Operations Technology Meeting
26–27 October
Newport News Marriott at City Center
Newport News, VA
http://vtol.org/helmot

MSS Military Sensing Symposium
31 October – 4 November
Gaithersburg, MD
https://www.sensiac.org/external/mss/meetings/list_meetings.jsf

54th Annual SAFE Symposium
31 October – 2 November
Dayton Convention Center
Dayton, Ohio
http://www.safeassociation.com/index.cfm

NOVEMBER 2016

Mirror Technology/SBIR/STTR Workshop
1–3 November
Greenbelt Marriott
Greenbelt, MD
http://www.spie.org/conferences-and-exhibitions/mirror-technology-sbir/sttr-workshop

Additive Manufacturing Consortium (AMC)
2–3 November
Gaithersburg, MD
https://ewi.org/events/247/additive-manufacturing-consortium-amc-fall-meeting/

Aircraft Survivability Symposium
8–10 November
Naval Post Graduate School
Monterey, CA
http://www.ndia.org/meetings/7940/Pages/default.aspx

2016 TARDEC Ground Vehicle Survivability Symposium (GVSS)
16–17 November
Fort Benning's Maneuver Battle Lab
Columbus, GA
http://ausaarsenalofdemocracy.org/event/tardecs-ground-vehicle-survivability-symposium-gvss/

53rd Annual AOC International Symposium and Convention
29 November – 1 December
Marriott Marquis DC and Convention Ctr
Washington, DC
http://crows.org/conventions/2016.html

Interservice/Industry Training, Simulation and Education Conference (I/ITSEC)
28 November – 2 December
Orange County Convention Center
Orlando, FL
http://www.iitsec.org/Pages/default.aspx

DECEMBER 2016

Future Ground Combat Vehicles 2016
5–7 December
Detroit Michigan
http://www.groundcombatvehicles.com

MORS Emerging Techniques Special Meeting (METSM)
6–7 December
Hilton Mark Center
Alexandria, VA
http://www.mors.org/Events/Special-Meetings/Emerging-Techniques

Winter Simulation Conference
11–14 December
Crystal Gateway Marriott
Arlington, VA
http://meetings2.informs.org/wordpress/wintersim2016/

For more events, visit:
dsiac.org/resourses/events

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- Providing referrals to subject-matter experts (SMEs).
- Collecting, electronically cataloging, preserving, and disseminating Defense Systems scientific and technical information (STI) to qualified users.
- Developing and deploying products, tools, and training based on the needs of the Defense Systems community.
- Fostering and supporting the DSIAC technical Communities of Practice.
- Participating in key DoD conferences and forums to engage and network with the S&T community.
- Performing customer-funded Core Analysis Tasks (CATs) under pre-competed IDIQ Delivery Order.

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- Survivability and Vulnerability.
- Weapon Systems.