Revolutionizing the Art of Strike and Air Combat: Guest Editors' Introduction

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ABSTRACT

The United States' 2018 National Defense Strategy emphasized the nation's need to face the challenge of near-peer adversaries like China and Russia. In the event of hostilities with either nation, US and allied forces will have to fight from ever-increasing range, with high-speed platforms and weapons, and deploy more effective nonkinetic capabilities. The scale of operations will drive us to machine-based intelligence and augmentation to enable human decisions at the speed of tactical relevance. The development of capabilities that address the challenges associated with distant near-peer engagement requires deliberate and strategic investment in technology solutions. The Precision Strike Mission Area (PSMA) of the Johns Hopkins University Applied Physics Laboratory (APL) has focused its internal independent research resources, combined with its direct sponsored tasking, to innovate and mature capabilities associated with four strategic vectors: Continuous Universal Targeting, Control Red Perception, Air Dominance, and Resilient Time-Critical Strike. This article introduces the strategic vectors, and the articles within the issue, organized around these vectors, present selected advancements that PSMA staff members are actively making in these strategic areas.

INTRODUCTION

> "The central challenge to U.S. prosperity and security is the reemergence of long-term, strategic competition by what the National Security Strategy classifies as revisionist powers. It is increasingly clear that China and Russia want to shape a world consistent with their authoritarian model—gaining veto authority over other nations' economic, diplomatic, and security decisions."
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> —Secretary of Defense Jim Mattis, Summary of the 2018 National Defense Strategy of the United States

Following at least two decades of focus on the war on terrorism, and addressing rogue state actors, in 2018 the authors of the National Defense Strategy[1] made a strong and definitive pivot to face the challenge of near-peer adversaries like China and Russia (Figure 1). Not surprisingly, both countries continue to create deep layered defenses of their homelands while investing in offensive capabilities and technologies that stress the best

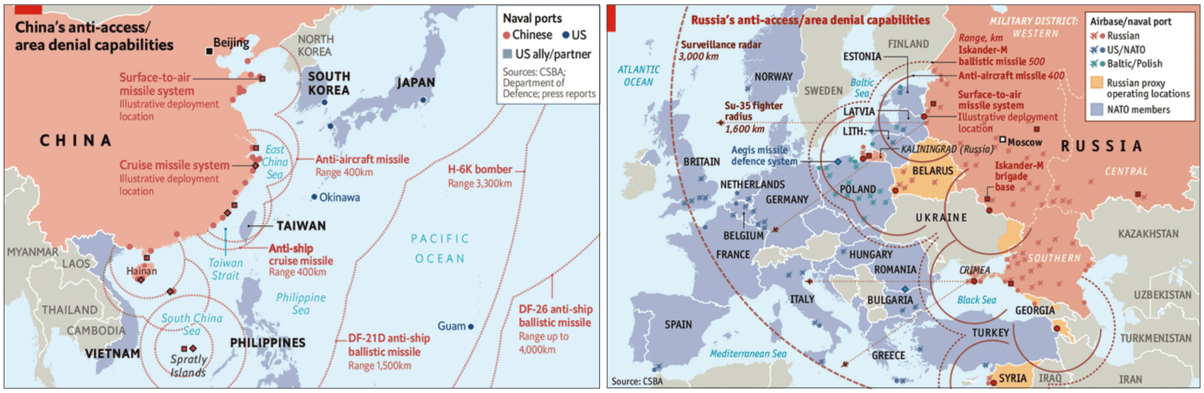

Figure 1. The challenging operational environment. Adversaries, in particular China and Russia, are executing strategies to exploit perceived weaknesses in US capabilities. They are increasing sensor, platform, and weapon inventories, as well as developing long-range effects chains that allow them to extend their combat power over a vast battlespace. (Reproduced with permission from *The Economist*. © The Economist Group Limited, London, 2018.[2,3])

defensive systems the United States and its allies can mount against them. China, especially, has invested in a whole-of-nation approach to field an impressive array of systems to contest perceived US advantages in technology and integrated and coordinated space, land, sea, and airborne operations. In the event of hostilities, US and allied forces will have to fight from ever-increasing range, with high-speed platforms and weapons, and deploy more effective nonkinetic capabilities (as an example, see the inside back cover of this issue). The scale of operations will drive us to machine-based intelligence and augmentation to enable human decisions at the speed of tactical relevance.

To take on the formidable operational challenges presented by near-peer adversaries, APL's Precision Strike Mission Area (PSMA) team developed a strategy built on the foundation of integrated strike operations conducted at daunting speeds and scales. The envisioned future of successful strategy execution includes the ability of US and allied partners to develop, field, and demonstrate sufficient tactical offensive capability to deter adversary aggression and be prepared to win in all phases of conflict. At the core of the PSMA strategy are four strategic vectors that provide the framework for external, sponsor-focused priorities and the Lab's internal investment in the precision strike domain: Continuous Universal Targeting, Control Red Perception, Air Dominance, and Resilient Time-Critical Strike (Figure 2).

The articles in this issue, organized around these vectors, describe selected advancements that PSMA staff members are actively making in these strategic areas.

STRATEGIC VECTORS

Continuous Universal Targeting

Continuous Universal Targeting focuses on long-range intelligence, surveillance, reconnaissance, and targeting (ISRT) systems that can find and identify all enemy targets and hold them at risk. For decades APL has been at the forefront of developing ISRT technologies and capabilities to enable long-range targeting. The most notable recent examples, central to the PSMA approach, are two first-of-breed prototype systems developed by APL experts in space-based and airborne sensor capabilities, data fusion, and operator interactions. These systems leverage national and tactical sensor systems to provide target-quality tracks for follow-on engagements by warfighters. The Dynamic Time Critical Warfighting Capability (DTCWC), in operation with the US Navy and being incorporated in additional Navy, Marine Corps, and Army systems, implements APL's upstream data fusion technology,[4] which accesses and processes data from a variety of sensor systems before the individual sensor processing systems apply a detection threshold. The Minotaur Mission Management System,

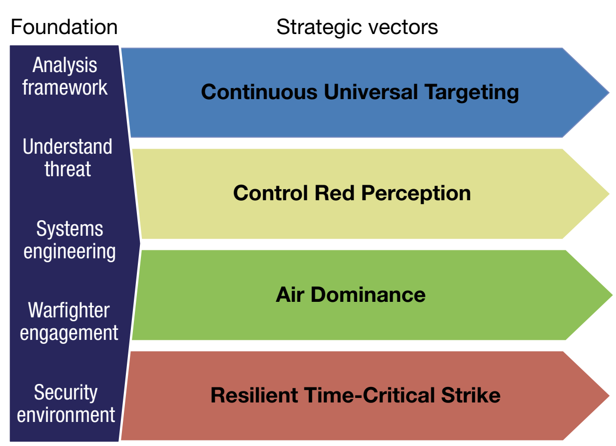

Figure 2. APL's PSMA strategic vectors. These vectors, at the core of the PSMA strategy, provide the framework for external, sponsor-focused priorities and the Lab's internal investment in the precision strike domain.

in operation with the US Navy, US Coast Guard, and US Customs and Border Protection, provides a single common operational picture and interactive user interface, allowing its operators to control and interact with multiple sensors, including video and still cameras.

Building on that hands-on experience and warfighter engagement, the Precision Strike team is leaning into high-speed data processing and dissemination at the tactical edge to enable persistent real-time targeting and timely decisions at scale. The outlined vision for Continuous Universal Targeting responds to both adversary advances in ISRT capabilities and US technology advancements such as hypersonic missiles, on which effective targeting depends on improved ISRT capabilities to achieve the greatest warfighting advantage. Articles in the first section of this issue highlight APL's work toward realizing Continuous Universal Targeting.

The article by Newman et al. presents a vision for a 2030 battlespace where a decisive advantage involves building command, control, communications, computing, cyber, intelligence, surveillance, reconnaissance, and targeting (C5ISRT) systems that provide an operating picture that is more complete, clear, accurate, current, assured, and accessible than the adversary's picture. The proposed new control and analytical framework describes a C5ISRT system that continually and collaboratively orchestrates its resources to optimize the situational awareness available for tactical decision-making. Correspondingly, the authors describe some of the primary related APL projects, as well as an ambitious vision for achieving Continuous Universal Targeting with Impunity (CUTI), where the United States controls perception of the battlespace, such that it has target-quality awareness of every consequential adversary asset at all times (Continuous Universal Targeting), whereas adversaries lack target-quality awareness of any consequential US entity at any time (operating with impunity).

An example use case of Continuous Universal Targeting is the ability to detect "dark" ships (i.e., commercial or military vessels that cease emissions, such as the Automatic Identification System, or AIS, in an attempt to evade detection). Byerly et al. present work from an independent research and development project entitled Neptune that prototyped an integrated multimode solution to detect the presence of dark ships. There are commercial niche solutions that solve portions of this problem under specific conditions, but Neptune is the first integrated, open-ocean-scale, solution. The Neptune team leveraged commercial sensor modalities and data sets, including synthetic aperture radar (SAR), electro-optical/infrared (EO/IR), and AIS and applied deep learning algorithms and the Closed-Loop Collaborative Intelligence, Surveillance, and Reconnaissance Simulation (CLCSim)[5] software platform for developing, testing, and analyzing closed-loop collaborative ISR. The authors demonstrate the ability to automate recognition and pattern of life of target surface vessels from multiple modalities with algorithms suitable to be hosted on a next-generation spaceflight processor to simulate on-orbit detection. Ultimately, the prospect of employing commercial hardware with low size, weight, and power (SWaP) requirements, such as the NVIDIA Jetson TX2i, offers the opportunity to host upgradable algorithms and detection capabilities at the tactical sensing edge.

Finally, the article by William Farrell presents an automated combat identification (CID) estimation process that accommodates imprecise CID evidence and heterogeneous multi-intelligence CID feature spaces to generate an actionable result suitable for targeting decisions. CID is the process of accurately characterizing battlespace entities to enable high-confidence, real-time application of tactical options, such as engagement. Evidence to support CID estimates is often sparse, latent in the battlefield, or both, raising the risk of association ambiguity and potential loss of CID custody. Therefore, an automated CID estimation methodology must properly account for and convey its results' uncertainty, ambiguity, and ignorance to the warfighter to support timely, well-informed decision-making. The automated CID estimation process presented in this article is a computationally scalable approach to achieve robust CID custody in long-range targeting applications.

Control Red Perception

The second strategic vector, Control Red Perception, builds on legacy electronic warfare (EW) capabilities and emerging EW/cyber operations to delay, degrade, deny, and defeat adversary systems with nonkinetic effects in all phases of conflict. One of this vector's ultimate objectives is to create offensive sanctuary to enable access for launch platforms and weapons in and through heavily defended areas when needed. To realize that goal, the APL team seeks to develop concepts for distributed and collaborative EW and cyber effects to present a significant number of real and virtual targets to confuse and overwhelm the enemy's ability to find and target friendly systems. An expected outcome would be that adversaries would make follow-on decisions that hinder, not improve, their opportunity for success on the battlefield based on the tactical picture presented by US forces. Technology areas of interest include EW systems that leverage machine learning and artificial intelligence (AI) to learn dynamically during real-world operations and collaboratively work together to take autonomous action to deal with pop-up threats. Several articles in this issue highlight APL's work in these areas.

Ward et al. broadly describe the technology gaps that must be satisfied to realize the vision of controlling Red perception, as well as some of the recent exciting APL independent research and development projects that are positioned to provide game-changing thought leadership and capability innovations in distributed EW.

Specifically on the topic area of autonomous and adaptive EW, multiple projects have investigated the application of AI and machine learning to operational EW problems. Casterline et al. investigated two particular applications for EW systems that learn. The first is a supervised similarity learning algorithm applied to target communications signals for the purposes of automatic modulation recognition. Results demonstrate that the approach can automatically identify a signal with modulation characteristics different from other signals on which it was trained. This is an important advancement to direct an operator's attention to previously unseen "pop-up" signals or simply to characterize how similar observed signals match the expected signal environment.

Autonomous resource allocation is the second application considered. Generally, an EW system must jam more possible threat emitters across more frequencies than it can simultaneously jam and at high duty cycles that do not allow for sufficient sampling of the threat environment. EW resource allocation decisions must frequently be made quickly during an engagement timeline and based on the available partial information. Frequent sensing intervals allow electronic attack techniques to be refined to better match the threat environment, yet typically at the expense of time not spent jamming. A Bayesian agency approach is applied to the problem of optimized scheduling of sensing periods to autonomously balance EW sensing and jamming resources in a dynamic RF environment. This initial work considers the management of EW resources on a single platform with a growth path to multiple distributed platforms.

While the collaborative use of EW platforms to perform distributed sensing and jamming tasks offers potential relief to single-platform EW resource constraints, the practical control and tasking of distributed EW resources is an open research topic. Practical solutions are limited by fundamental science and technology (S&T) gaps as well as incomplete functional requirements. Stevens et al. describe distributed EW use cases and associated functional requirements to motivate the need for a distributed resource manager architecture. Future work suggests key research areas and enabling technologies required to realize a practical distributed EW resource manager.

Air Dominance

Air Dominance, the third vector, centers on establishing and maintaining supremacy in the air-to-air domain. Peer adversaries are deploying very capable aircraft and long-range air-to-air weapons that challenge the fourth- and fifth-generation capabilities in the US inventory. To address emerging threats, the Precision Strike team works closely with DOD S&T sponsors to develop uncrewed collaborative combat aircraft and complementary mission-focused autonomy to realize a more robust system-of-systems.

The Defense Advanced Research Projects Agency (DARPA) Air Combat Evolution program represents a first step toward effective and resilient crewed–uncrewed teams, starting with the close-in, one-on-one dogfighting of the AlphaDogfight Trials and moving to many-on-many, long-range, beyond-visual-range air combat. Teamed with fourth-, fifth-, and emerging sixth-generation crewed aircraft and more capable air-to-air weapons, US and allied uncrewed systems will challenge and surpass capabilities presented by adversary fighter, bomber, and cruise missile formations. The articles in this section describe important work APL is doing to position the nation to achieve and maintain air dominance, beginning with a discussion of the precursor to the Air Combat Evolution program, the AlphaDogfight Trials program.

DeMay et al. describe the DARPA AlphaDogfight Trials program and APL's role as the trials coordination team. AlphaDogfight Trials sought to explore whether AI agents could effectively learn basic fighter aircraft maneuvers. APL developed a simulation environment, referred to as the Coliseum, where AI agents developed by competitor organizations trained and competed against each other. APL hosted three highly publicized competitor events, of which the finale was a human-versus-AI matchup between the top-performing competitor agent and a human F-16 pilot. Ultimately, the AlphaDogfight Trials program demonstrated the promise of AI agents that can outthink, outmaneuver, and outperform conventional crewed forces alone. Augmenting traditional human systems with AI will allow the tandem systems to operate at machine speeds within compressed timelines and to achieve improved decision-making based on partial information. Indeed, AlphaDogfight Trials was a discrete step toward establishing and demonstrating trust between human and AI operators.

As combat systems grow more complicated, expensive, and interconnected, human operator proficiency must be considered when assessing the performance and survivability. The 2017 collisions of USS *Fitzgerald* (DDG 62) and USS *John S. McCain* (DDG 56) with civilian ships demonstrated the importance of training, as insufficient training was cited as a cause for both accidents. Emanuel et al. describe the Proficiency-Enabled Mission Model (PEMM) that APL developed to characterize the impact of operator training and readiness on mission effectiveness in the context of strike-fighter aircraft in air combat. APL's development of PEMM has advanced the state of the art for air combat modeling and simulation by introducing aircrew proficiency while executing current tactics, techniques, and procedures in the Brawler combat simulation environment. The

F/A-18E/F Super Hornet defensive counter-air mission served as the initial case for proof of concept. The resulting capability informed investment decisions and training enhancements, which have previously lacked quantitative rigor compared with traditional materiel system acquisition activities. PEMM is a novel and powerful method to show the quantitative impacts of operator proficiency to support system acquisition, training, and tactics development decisions.

Finally, the article by Kristofor Gibson presents an algorithm that detects anomalous behavior in the warfare environment and is applied to a tactical airborne scenario. The approach, referred to as sequential sample consensus (SeqSAC), identifies anomalous behavior based on a series of observations of an entity traveling in three-dimensional space over time (e.g., a track history of an aircraft). Detected anomalies may be used as an indicator or discriminator to focus an analyst's attention on a specific entity or to inform the accuracy of future predictive models. A possible extension to this work is the application of SeqSAC to identify coordinated behavior changes among multiple entities.

Resilient Time-Critical Strike

The final strategic vector, Resilient Time-Critical Strike, primarily focuses on the concept exploration and development of next-generation, long-range, high-speed weapon systems to defeat adversary air and missile defenses and strike time-critical targets. Core capabilities for the Precision Strike team leverage the decades-long experience gained as the technical direction agent for the Tomahawk program. Peer adversaries' complex layered defenses and the short windows of vulnerability to find, fix, track, and target mobile and relocatable systems drive weapon requirements to higher speeds and longer ranges. With know-how achieved during the HyFLY I, X-51, and other hypersonic S&T initiatives, the APL team is stepping into trusted agent roles for emerging hypersonic weapon system development programs. Because of the large scale of potential future hostilities, survivability and affordability are critical attributes for next-generation weapon systems. For the past decade, the Precision Strike team has been at the forefront of development of the Hypervelocity Gun Weapon System (HGWS), a long-range, multimission, hypersonic-speed surface-to-surface and surface-to-air artillery capability. HGWS will provide deep magazines at significantly lower cost per shot compared with the exquisite hypersonic and supersonic missile systems in development. Building on the AlphaDogfight Coliseum developed by APL, technical and program leaders in the mission area are working closely with the vanguard Air Force Golden Horde program to achieve networked, collaborative offensive weapon systems that will learn from their environment and autonomously work together to defeat integrated air and missile defenses. The articles in this section highlight some of APL's efforts toward realizing this strategic vector.

The first article, by Nardozzo et al., presents a collection of work that explored a reusable hybrid rocket design to enable low-cost, rapid flight testing. Superiority in the development of hypersonic weapons requires access to test and evaluation facilities to iteratively evaluate and learn from prototyped capabilities. Because there are limited test venues, opportunities, and budgets, accelerated prototyping through system reuse is an attractive option. A vision and design approach for a prototype hybrid rocket motor is outlined within the framework of a "build a little – test a little" prototyping philosophy. Rocket motor reusability requires addressing the unique thermal challenges of the combustion chamber. Specifically, APL focused on addressing an unexpected thermal load on the forward bulkhead that resulted in melted aluminum near the injector. The thermal management design concepts included changes to the forward bulkhead by adding insulation, lengthening the precombustion chamber, and adjusting the spray angle of the injector. The described design choices and decisions illustrate how classic engineering approaches can be successfully applied to an advanced and revolutionary hypersonic testing vision.

One of the fundamental challenges of fielding and maneuvering a hypersonic vehicle is predicting the large changes in heat transfer and aerodynamic performance associated with the transition of the surface boundary-layer flow from laminar to turbulent during flight. The boundary-layer flow can have a dramatic impact on the forces and heat transferred to a vehicle during flight, and thus predicting when it transitions from laminar to turbulent has been the subject of intense academic research over many decades. Legacy methods for analyzing boundary-layer transition are overly simplistic and do not account for the intricate flow patterns of modern vehicles with complex three-dimensional shapes. Araya et al. present work utilizing a novel methodology, known as input/output (I/O) analysis, recently applied to hypersonic flows. This methodology is completely free of geometric constraints and has significant potential to answer many of the open questions in transition analysis. The example results presented use computational tools that were built in collaboration with the University of Minnesota and VirtusAero as part of an APL independent research and development project.

Finally, the article by Wheaton et al. continues the theme of hypersonic weapon prototyping and test and evaluation by describing the Boundary-Layer Transition (BOLT) flight experiment. BOLT was an APL-led collaboration of organizations across academia, government, and industry that sought to obtain flight data on boundary-layer transition behavior for a hypersonic vehicle. The BOLT vehicle geometry was designed to generate a complex hypersonic flow field to challenge existing transition prediction tools. A better understanding of the physics of boundary-layer laminar-turbulent transition on a complex geometry, a process that can significantly increase heating and can affect hypersonic vehicle drag, controllability, and engine performance, will inform development of updated prediction tools and approaches.

APL led a large team of external collaborators to design a sounding rocket flight experiment over an 18-month period, while conducting an extensive campaign of wind-tunnel experiments and computational simulations to predict the flow physics on the BOLT geometry. The final flight experiment was built and instrumented at APL using Laboratory expertise in designing and prototyping hardware for extreme environments. The BOLT experiment was delivered to the US Air Force for the flight experiment, designed to gather critical validation data on BOLT's boundary-layer transition from over 340 sensors in the hypersonic flight regime. The flight test occurred in June 2021. Although unexpected behavior prevented the flight from achieving the desired experiment conditions, the BOLT research resulted in new experimental databases, new computational tool development for complicated hypersonic flows, and significant new workforce development through the inclusion of students in the program. In addition, APL's efforts to develop BOLT led to a follow-on flight experiment focused on turbulence (BOLT2: The Holden Mission), which flew successfully in March 2022.

CONCLUSION

> "We must close the kill chain faster than our rivals with a resilient web of persistent sensors, command and control nodes, platforms, and weapons."
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> —Chief of Naval Operations Admiral M. M. Gilday, CNO NAVPLAN, January 2021[6]

While the vectors provide a useful tool for communicating and prioritizing mission area efforts, it is the ability of the team to coordinate and integrate across the vectors—to generate concepts and explore technology from sensor to seeker—that presents the biggest challenge and opportunity for Lab impact. Integrated capabilities require command and control concepts and algorithms that close a large number of concurrent, distributed fire control loops for high-speed weapon engagements and nonkinetic effects against time-critical targets. Extending Naval Integrated Fire Control concepts, APL's Precision Strike engineers are exploring AI and machine learning algorithms to automatically pair available kinetic and nonkinetic effects from crewed and uncrewed platforms with targets, ensure that the appropriate quality of sensor service and communications will be maintained to consummate the engagements, and provide a recommendation to the operator on when and how to engage (e.g., kinetic effects, nonkinetic effects, or both). Additionally, command and control system concept exploration will include systems that can be used in all phases of conflict from a centralized, deliberately planned capability during preconflict operations to a real-time, dynamic capability for small teams of distributed warfighters to conduct operations at the tactical edge during live engagements. The articles in this issue present just some of the work PSMA staff members are doing to coordinate across the strategic vectors.

It is our pleasure to introduce this issue of the *Johns Hopkins APL Technical Digest*, which provides insight into some of the internal investment and sponsored work driving the execution of the mission area's strategy. This collection of articles demonstrates the progress that PSMA has made in executing internally and externally funded projects to advance our strategic vectors. Yet the articles also provide insight into the magnitude of our ambitious strategic vectors and additional work required to bring new Continuous Universal Targeting, Control Red Perception, Air Dominance, and Resilient Time-Critical Strike capabilities to the warfighter. We hope you will find the articles both interesting and informative and come away with an appreciation of how hard challenges and a team-based approach to solutions lead to critical contributions.

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