Air and Missile Defense: Defining the Future

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ABSTRACT

Since the development of the proximity fuze in 1942, the Johns Hopkins University Applied Physics Laboratory (APL) has been leading the nation in the development of air and missile defense capabilities to defend our military forces, our allies, and the nation. Throughout these 78 years APL has strived to solve many of the most critical challenges in air and missile defense and in doing so has made critical contributions to the nation. As we look toward APL's centennial in 2042, global threats to our nation's military, allies, and homeland are evolving at a pace that will significantly challenge today's air and missile defenses. This article describes the grand challenges in future air and missile defense and how APL, by anticipating these future warfighting environments and leveraging technology innovations, is working to revolutionize air and missile defense to ensure our nation's preeminence in the 21st century.

BACKGROUND

APL has made critical contributions to our nation's air and missile defenses since it was founded in 1942 for the express purpose of developing the proximity fuze for use during the war. These contributions to countering air and missile threats have spanned the spectrum of advanced sensor, weapon, and command and control (C2) technologies and have resulted in the development of four of the innovations that have helped define the Laboratory over its history. These air and missile defense defining innovations include the proximity fuze,[1] which dramatically increased the effectiveness of anti-aircraft artillery during World War II; surface-to-air missiles,[2] which resulted in the Navy's first operational missile defense system and was the foundation of the current Standard Missile program; Advanced Multi-Function Array Radar,[3] which provides near-instantaneous scanning, tracking, and closed-loop guidance needed to defend against simultaneous aircraft and missile raids and was the precursor to the Aegis AN/SPY-1 radar; and the Cooperative Engagement Capability,[4] which was the first networked air defense capability for the Navy, enabling a ship to engage aircraft and missiles using another ship's netted radar data. APL thought leadership and technical contributions to the Aegis and Ship Self-Defense System combat systems, the Standard Missile family, the Evolved Sea Sparrow Missile, the Air and Missile Defense Radar, surface electronic warfare systems, Naval Integrated Fire Control, our nation's Ballistic Missile Defense System and its sea-based Aegis Ballistic Missile Defense element, and numerous other programs have achieved essential air and missile defense capabilities for the Lab's Navy and Missile Defense Agency sponsors.

FUTURE AIR AND MISSILE DEFENSE GRAND CHALLENGES

As we look toward the future, and the centennial of the Laboratory, global threats to our nation's military, allies, and homeland are evolving at a pace that will significantly challenge today's air and missile defenses. Anticipating future warfighting environments and leveraging technology innovations will prepare us to revolutionize air and missile defense to ensure our nation's preeminence in the 21st century.

Highly Contested Anti-Access/Area-Denial Environments

With the reemergence of a strategic, great-power competition, certain nations seek to challenge US military advantage and restrict our freedom of operation across the globe. Strategic competitors are making significant investment in advancing regional anti-access/area-denial (A2/AD) warfighting capabilities to contest US ability to deter adversary aggression. They have developed networked, multidomain battle forces with integrated theater-scale intelligence, surveillance, reconnaissance, and targeting (ISR&T), aimed at applying overwhelming force with large-scale weapon salvos. The capability exists for significant application of nonkinetic and cyber weapons, augmented with the use of artificial intelligence to control these weapons. In this highly dynamic environment, the potential for a rapidly escalating collision of highly networked and lethal forces operating across an entire theater must be considered. Both offensive and defensive operations could occur simultaneously, with all domains heavily contested.

Defending the Homeland

On the home front, the United States has historically benefited from peaceful partners on the northern and southern borders and enjoyed the sanctuary afforded by two oceans buffering the nation from adversaries. The development of long-range ballistic missiles carrying nuclear warheads was a defining characteristic of the Cold War. With no suitable defenses, the United States and the Soviet Union relied on the doctrine of mutually assured destruction (MAD) to provide strategic stability. Today, proliferation of long-range ballistic missile technology into the hands of rogue nations has renewed the urgency for homeland ballistic missile defense. Further, the reemergence of long-range conventional cruise missiles as well as the advent of widely available autonomous systems reveal alarming attack vectors from the air. Ensuring robust air and missile defense of the homeland will be a paramount national priority.

Dominating the Space and Near-Space Domains

New global environments are emerging in the space and near-space domains, with the attendant need to ensure safe and free access to them. In space, the United States has developed capabilities over many decades that are vital to the US economy and are heavily leveraged in most aspects of our national defense. In response, adversaries have matured technologies and operational capabilities to threaten space systems, imperiling US warfighting capabilities and turning space into a contested domain.

Near-space has also emerged as a contested domain with the emergence of hypersonic strike weapons. The domain of near-space (defined as the region between altitudes of 20 and 100 km) favors vehicles designed at the intersection of conventional aeronautical and aerospace systems. Achieving dominance of this domain is of keen interest to adversaries since it is weakly defended with conventional anti-air warfare systems operating below and ballistic missile defense systems operating above this domain.

AIR AND MISSILE DEFENSE STRATEGIC VECTORS AND INNOVATION

Keeping pace with and ultimately leaping ahead of our adversaries will require significant advancement and innovation that may fundamentally redefine our approach to air and missile defense. A framework for contemplating the game-changing capabilities necessary to accomplish this goal across the set of anticipated future grand challenges is depicted in Figure 1. The strategic vectors span the breadth of envisioned capabilities and provide direction toward potential defining innovations. They include ubiquitous ISR&T; novel kinetic weapons; asymmetric nonkinetic defeat; transformational C2; and cognitive communications and networking.

Ubiquitous ISR&T

ISR&T senses the battlespace to establish and maintain an understanding of the operational environment and provide targeting data of sufficient reliability and accuracy to consummate engagements across the spectrum of air and missile threats. Future ISR&T systems must operate in the context of great-power conflict, limiting the effectiveness of systems developed for more permissive environments. Challenges include continual targeting of all potential threats, including missiles (cruise, ballistic, and hypersonic), unmanned vehicles, ISR platforms, and threat delivery platforms. Continual targeting of all potential threats improves the track quality of potential targets by incorporating observations when available or needed and reduces target uncertainties, including threat identification. Additionally, global custody encompasses the timely, continual tracking of potential threats at scale with timeliness to meet engagement orders without the need to fall back and retask sensors. This must be achieved to defend the homeland and protect expeditionary forces during regional conflict.

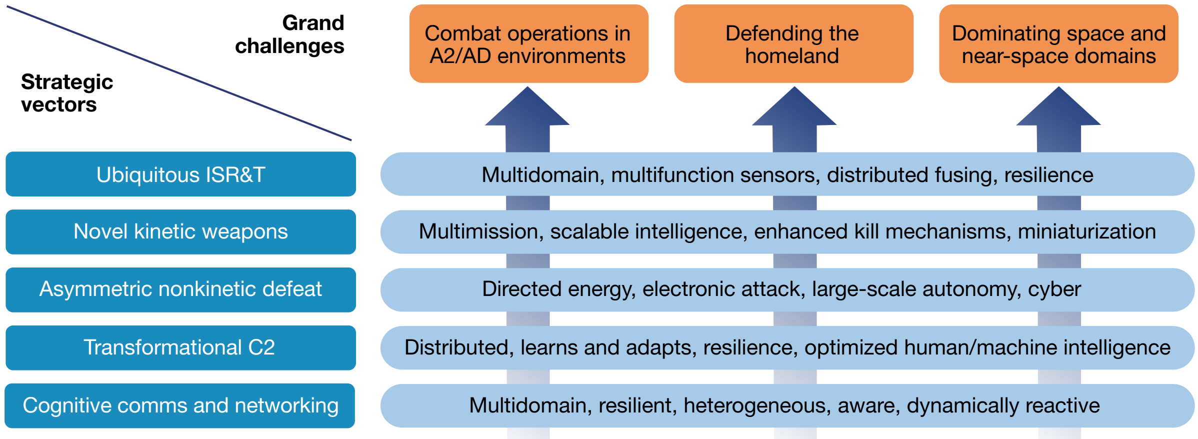

Figure 1. Future air and missile defense capability framework. This framework contemplates the game-changing capabilities necessary to keep pace with and ultimately leap ahead of our adversaries across the set of anticipated future grand challenges. The strategic vectors span the breadth of envisioned capabilities and provide direction toward potential defining innovations.

Overcoming these challenges will require autonomously composable, multidomain ISR&T (Figure 2) that intelligently fuses all available data to enable flexible, effective kill webs in highly contested environments, resulting in the ability to establish and maintain custody of many potential targets and providing cohesive targeting solutions across warfighting domains. Autonomous composability may leverage autonomy and artificial intelligence/machine learning (AI/ML) to concurrently develop multiple viable kill chains, thus realizing kill webs. AI/ML is not a singular solution, but rather it enables key attributes of ISR&T solutions, including timeliness, operating at scale (large numbers of targets), and enabling a human on the loop to manage much more complex systems. This envisioned ISR&T capability requires fusing data agnostic of sensor source; battle management, command, control, and communication to move data between operational areas; and the algorithms to discover, fuse, and task sensors. Achieving this vision will provide multiple viable targeting options to the warfighter while confusing adversary ISR&T. The technology employed to achieve ISR&T capabilities should apply to multiple warfighting domains and should have multilevel security enabling interoperability across domains and handover among modalities.

Figure 2. Envisioned kill webs enabled by ubiquitous ISR&T. Composable networks of space-based sensors (satellites), manned and unmanned surface and airborne sensors, and ground sensors are envisioned to enable adaptable targeting across air, surface, and ground threats.

Novel Kinetic Interceptors

The ability to kinetically defeat adversary threats has been an air defense cornerstone and will be critical for success across all three grand challenges. In highly contested A2/AD environments, adversaries have access to an overwhelming inventory of weapons, so forward-stationed combatants will be required to defend themselves and our allies against massive attacks. So that the nation can be successful in this arena, APL will strive to develop capabilities employing large-scale autonomous, potentially heterogeneous kinetic weapons to overcome inventory disadvantages. In space and near-space environments, we aim to lead development of new multimission interceptors capable of overcoming stressing physical environments and ensuring US dominance in these domains. To support the defense of the homeland, we aim to develop new interceptor technology to allow deployment of cost-effective systems to defend the US population over our more than 3,000,000 square miles of territory, even against weapons from mobile or covert launchers.

To achieve these advances in interceptor and autonomous system capabilities, we envision technology innovations across multiple fronts. Interceptors with the ability to negate more than one threat, or a volume of threats, may be developed, offsetting raid size asymmetry. Weapons capable of operating in and defending near-space and space could be built, overcoming access issues. Persistent propulsion along with cooperative, self-organizing swarms of defensive munitions capable of intra-salvo communication are envisioned to optimize performance as the threat environment evolves mid-flight. Highly advanced seekers capable of containing wide uncertainties while still achieving high precision during terminal homing might be designed, improving mission flexibility, accuracy, and robustness. Kill mechanisms that significantly increase overall effectiveness could be developed, providing a capability for defense and offense. Finally, intelligent multimission interceptors capable of mission selection/reassignment throughout the engagement battlespace could become the norm, allowing robust homeland defense and defense against saturation raids.

Asymmetric Nonkinetic Defeat

Defeating asymmetric air and missile threats, including overwhelming raid sizes and large-cost asymmetries between the adversary threat and our weapons, is a central issue in each of the grand challenges. An example of the former is large raids of aircraft, cruise missiles, small boats, or unmanned platforms in highly contested environments. For the latter, an example is relying on multi-million-dollar interceptors to defeat multi-thousand-dollar unmanned aerial vehicles. In addition to cost, this situation also stresses inventory because of the limited arsenals of kinetic weapons that our forward-deployed platforms can carry. Additionally, each of the grand challenges presents different threats. For combat operations in A2/AD environments, the asymmetry results from our ships and other assets being in close proximity to adversary territory from which large numbers of aircraft, missiles, and other threats can be launched. For defending the homeland, threats include intercontinental ballistic missile raids as well as missiles and unmanned aerial vehicles launched from offshore manned and unmanned platforms threatening a diverse range of targets. Finally, for space and near-space domains, defended assets include our systems in orbit and terrestrial assets that can be attacked from space and near-space. For each of these environments, we must develop new, nontraditional, cost-effective approaches to defeating the asymmetric threats encountered.

There are a number of technology areas through which new defeat mechanisms may be realized. These include high-energy laser and high-power microwave, advanced distributed electronic attack, cyber and electronic warfare techniques, and volume defeat (creating a lethal volume filled with "effects" that would damage/defeat threats flying through that volume). These technologies may yield several potential defining innovations. We could deny or degrade adversary targeting of our assets and forces by action against their sensors and networks in ways that are not readily detectable or attributable. We could create overwhelming confusion for threat missiles or unmanned vehicle swarms via combinations of cyber and electronic warfare driven by advancement in AI/ML. Further, we could deliver cyber payloads that disable incoming weapons and/or targeting sensors, resulting in system malfunction or deception. Additionally, evolution in directed-energy weapons could enable disabling effects at tactically significant ranges. Finally, with advances in electronic warfare and decoy techniques, we could divert incoming threats to a small kill zone, amplifying the effectiveness of defeat mechanisms.

Transformational C2

C2 systems provide the means though which military operations are planned, directed, and coordinated in pursuit of a mission. To be successful in the air and missile defense missions encompassed within the three grand challenges, we must develop a distributed C2 capability that enables our forces to overcome adversaries by making decisions and coordinating actions more accurately and on a shorter timeframe than they can. In highly contested A2/AD environments, we must optimize and schedule the use of kinetic weapons, electronic warfare (EW), directed energy, ISR&T, physical and electromagnetic spectrum maneuver, and unmanned operations to overcome our opponent's

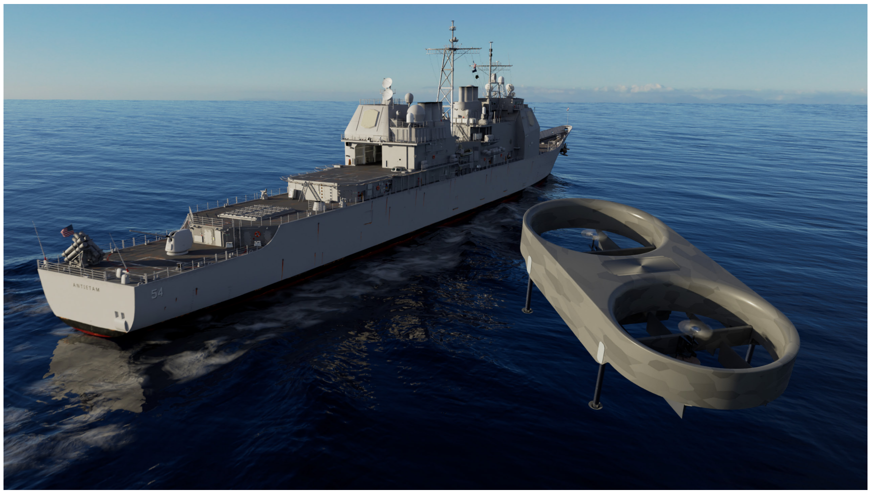

Figure 3. Autonomous netted persistent decoy concept. Employment of distributed manned and unmanned air defense assets will require transformational C2 capabilities that learn, adapt, and optimize human and machine intelligence to counter projected air and missile threats.

"home field advantage" in inventory and other areas. Figure 3 illustrates an APL-conceived autonomous networked persistent decoy concept employing distributed EW techniques to counter anti-ship missiles. In space and near-space, we need to make engagement and fire-control decisions despite profound uncertainty in threat trajectories and countermeasures, and with the full tactical and strategic consequences that our actions will have on adversary response. In defending the homeland, we face many possible avenues of attack and must optimize allocation of our limited surveillance and defense resources to maximize our defense.

To overcome these challenges, we envision transformational C2 systems that learn, adapt, and optimize human and machine intelligence to achieve force-level, superhuman decision-making to outmaneuver our adversaries. These distributed systems will be composed of a combination of manned and unmanned systems in a structured framework compatible with service C2 architectures and operable with a mix of legacy and modernized capabilities. Leveraging academic research and commercial technologies in autonomous systems, optimization, learned behavior, and game theory, we envision predictive capabilities to evaluate multimission courses of action, optimized and coordinated across the theater and resilient to adversary deception and communications denial. The application of artificial intelligence to advanced C2 perception, reasoning, planning, decision-making, and adaptive learning, combined with advancing human and machine teaming, will enhance shared awareness and context between humans and machines to achieve trust in autonomy and order-of-magnitude improvement in decision-making. Finally, technology evolution of state-of-the-art computing and software optimization will enable the speed and resilience required for AI enhancements and robust cyber defenses for these distributed systems.

Cognitive Communications and Networking

Communications and networking provide the underlying interconnectivity between ISR&T, weapons, C2 systems, and platforms. Cognition, resilience, security, and high-capacity communications will be essential enablers for military operations in highly contested environments in the air, space, and near-space domains as well as in defense of the homeland. Future capabilities are envisioned to seamlessly integrate our distributed systems and platforms with heterogeneous communications leveraging all available assets. Communication networks must be flexible to take advantage of new and evolving technologies, while preserving operability with existing systems and capabilities. To enhance warfighting capabilities, better quality of service and higher data rates (potentially 100 times higher) will be needed, as will new algorithms and technologies, including AI, in situ learning, and real-time data fusion. New communications systems should be cognitive and adaptive, sensing the spectrum and reacting to natural and adversarial environments to provide the best available quality of service.

These novel communications capabilities will draw on and extend state-of-the-art technologies in communications networks, particularly 5G and beyond, such as massive multiple-input, multiple-output and modern modulation techniques, full-spectrum usage, and beamforming and directionality, to fully utilize diversity in space, time, and frequency. Anticipated technological breakthroughs include advances in high-efficiency, high-diversity waveforms with diverse media and links, advanced antenna designs, innovative multiplexing techniques, and broad-spectrum utilization methods. Additionally, the capability will achieve flexibility to trade between network capacity and redundancy, as well as resiliency and multilayered encryption with emphasis on the physical layer to achieve security. We envision innovations in encryption techniques, mission-specific algorithms to optimize network capacity, techniques to reduce vulnerability, and smart communication usage that adapts to warfighter mission needs. Further, these capabilities will support heterogeneous traffic (video, C2, text, tactical data) and links (radio frequency, optical, acoustic) that are interchangeable and will seamlessly connect multiple domains. Key enablers in this area are additional non-radio-frequency-based links (such as free-space optical links), quality-of-service-driven network management, real-time data fusion algorithms to merge heterogeneous traffic, and novel scheduling and routing techniques. Finally, innovations will include cognitive capabilities to recognize and mitigate disruptions (physical, cyber, or environmental), optimize throughput, and achieve superior resilience by applying sensing, interpretation, and reasoning algorithms for data validation. Important advancements will include resilient AI-based spectrum sensing and network resource optimization, cognitive sensing, interpretation and reasoning algorithms for data validation, intrusion detection, intruder confusion, vulnerability assessment, and intelligent cyber protection.

CONCLUSION

As we strive to fulfill APL's centennial vision and ensure our nation's preeminence in the 21st century, we foresee a future of intense technological competition pitting emerging adversary offensive capabilities against the defensive system advancements needed to counter them. Meeting the challenges posed by these rapidly advancing threats will require the development and application of defenses far more distributed, flexible, and intelligent than those of today. We are anticipating tomorrow's warfighting landscape to ensure that we remain at the forefront of cutting-edge air and missile defense technology development focused on potential defining innovations. We envision key strategic vectors that can align us toward realizing game-changing defensive capabilities across the range of future grand challenges. Leveraging the deep technical insight we gain through advancing today's state-of-the-art defense systems in the face of current challenges, we focus our technology development and innovation in areas that move us along these strategic vectors toward defining the future of our nation's air and missile defense.

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