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Chairman Cochran, Ranking Member Durbin, and Members of the Subcommittee, thank you for the opportunity to testify before you today about how we innovate at DARPA, the Defense Advanced Research Projects Agency. I am Steve Walker, DARPA's Acting Director, and it is a pleasure to be here with my Department of Defense (DoD) colleagues. Each of us oversees a specific aspect of the Department's innovation ecosystem, and I look forward to sharing with you a snapshot of how we at DARPA contribute to that overall engine of progress.

DARPA's history dates back six decades, when our Cold War adversary, the Soviet Union, launched Sputnik, the first artificial satellite to circle the Earth. The shock of finding ourselves outpaced in space led quickly to the creation of DARPA and its singular mission: to prevent such instances of strategic surprise.

Of course, the best way to prevent surprise is to have a broad vision of what could become possible in the future. And that is exactly what DARPA strives to do every day, as it conceives, develops, and demonstrates breakthrough technologies that push today's limits and help make the improbable real. Through our work at the extreme frontiers of physics, chemistry, biology, mathematics, materials science, electronics, and engineering, DARPA helps ensure that the United States will, for the foreseeable future, be the source—and not the target—of strategic surprise.

That mission differs from the ones overseen by my colleagues in other parts of the Pentagon. Some DoD research teams, including many working in the various Service laboratories, are focused on developing new technologies to fulfill specific goals for programs of record. Others, like my colleagues from the Department's Strategic Capabilities Office, are taking existing technologies, individually and in combination, and finding new, unanticipated applications for them.

DARPA's contribution to this innovation matrix is far to the left of these in terms of developmental staging. DARPA's starting point is more typically along the lines of "That's impossible." Our job is in large part to *change* what's possible—to do the fundamental research, the proof of principle, and the early stages of technology development that take "impossible" ideas to the point of "implausible but, surprisingly, possible." No other agency within the Defense Department has the mission of working on projects with such a high possibility of failure—or such a high possibility of producing truly revolutionary new capabilities. Indeed, a big part of DARPA's particular expertise is *managing* risk in ways that help keep the innovation pipeline flowing.

DARPA's history in this regard is well established, including its seminal role in the development of the internet, stealth technology, and virtually every enabling technology that makes today's mobile phones as smart as they are—from the tiny radio transmitters that connect us to the nation's network of cell towers; to the accelerometers, inertial measurement units, and miniaturized GPS components that tell us where we are and where we are going; to the touch screens that respond to the subtle swipe of a finger; and the ever-responsive voice of Siri.

That's the past. DARPA is also well known for its ambitious imaginings for the future. We are making solid progress, for example, toward our audacious goal of creating a reusable space plane that can take off and land10 times in 10 days—an achievement that would enable the rapid reconstitution of an entire constellation of satellites if that need were ever to arise. We are also aiming to bend some of the most fundamental laws of physics and slice time itself into infinitesimally small snippets to create atomic clocks and navigational devices of almost unimaginable precision. And our emerging focus on neurotechnology points to a possible future in which individuals will be able to enjoy the benefits accelerated learning, enhanced occupational training, strengthened memory, and the ability to interact seamlessly with computers and other digital devices. Later in this testimony I will elaborate on these and other early efforts to change the nature of our technological future.

But what I would like to address first is a portion of DARPA's portfolio that often gets overlooked—neither the Agency's early history nor its exciting future. I am referring to the work that DARPA has been doing in just the past several years and that is right now making its way into the hands of our Nation's warfighters and Defense Department systems, where it is providing new, game-changing capabilities for national security. I want to highlight some of these technologies and resulting capabilities because, as impressive as our historical accomplishments have been and ambitious as our dreams may be, the thing I am perhaps most proud of at DARPA is the constancy of the Agency's creative energy—the steady pipeline of innovations that the DARPA model manages to maintain—and the day-to-day difference that makes for the men and women who work every day to keep our nation safe.

To be sure, not all of DARPA's accomplishments move directly into the military Services. Some of them transition first to private-sector innovators who, inspired by our often-surprising proof that something seemingly impossible is actually possible, then build upon DARPA's fundamental advances to create powerful new commercial products. But by design, directly or indirectly, even DARPA's most basic advances are aimed from the start to fuel advances that have the potential to address national security needs—whether by delivering new capabilities directly to the Services or by breaking open a field, letting the private sector run with it, and then amplifying the resulting off-the-shelf products with additional "secret sauce" for use by the DoD.

The past few years have seen many such success stories in which notable technical advances have found their way into operational settings—far more than I think might reasonably be expected from an agency of just 200 government employees tasked with trying to do the nearly impossible. Among them:

Long Range Anti-Ship Missile (LRASM)

DARPA's LRASM program was created to address a pressing need for longer-range anti-ship missiles able to counter advanced electronic warfare and related defenses. To ensure that transition to the Services would be as fast and smooth as development of the weapon itself, DARPA stood up a rapid deployment office with the U.S. Navy and Air Force, located within the Agency's headquarters, ensuring a seamless and speedy leap to operational capability. Test flights in close collaboration with the Navy have been completed and the missile system is now on track for early operational deployment in FY18. The LRASM program not only bolstered the fleet through its creation of a long-range survivable strike weapon but also demonstrated a rapid acquisition model with potential applicability to other urgently needed capabilities.

High-Performance RF Arrays

DARPA's development of gallium nitride (GaN) semiconductors—with an explicit goal of rapid transition into military systems—catalyzed U.S. development and deployment of the world's most powerful, highest-performing, farthest-sensing, and strongest-jamming radio frequency (RF) arrays. DARPA's foresight to invest in this technology when its future value was still uncertain is paying off today by enabling a new generation of military systems that can scan space for debris, search the distant horizon for incoming missiles, and interrupt adversary communications at ranges not possible with conventional electronics.

Cognitive Electronic Warfare

U.S. military aircraft need protection against new radar frequencies and waveforms not in their onboard jamming profile library. DARPA has developed a completely new way to speed up the process of library updating and the deployment of relevant countermeasures: cognitive electronic warfare, in which the on-board system senses across the radio spectrum, uses artificial intelligence to learn in real time what the adversary's radar is doing, and then immediately generates a specific jamming profile to counter it.

Testing of these systems, developed through DARPA's Adaptive Radar Countermeasures (ARC) program, is underway with U.S. Naval Air Systems Command on F/A-18 combat aircraft and through the F-35 Joint Program Office for Block 4 integration, as well as with the Office of Naval Research (ONR) for inclusion in the Next Generation Jammer upgrade. A related program, Behavioral Learning for Adaptive Electronic Warfare (BLADE), is being leveraged by the U.S. Army's Communications-Electronics Research, Development and Engineering Center (CERDEC) as CERDEC develops requirements for the Army's next-generation Multi-Function Electronic Warfare program.

Communications Through Jamming

Our adversaries are not only deploying new radar frequencies and waveforms that challenge U.S. jamming capabilities; they are also improving their own jammers and their ability to disrupt U.S. military communications. To address that threat, DARPA's Communications Under Extreme RF Spectrum Conditions (CommEx) program has developed innovative technologies that together have resulted in a powerful, modular upgrade to Link 16—the military's primary tactical data-exchange network that among other functions supports air-to-air communication in contested environments. The program's adaptive anti-jam system was recently integrated and tested on Link 16 production radios. Some features have been flight-tested against real jamming systems, and plans are underway for testing of the full system in 2017.

In addition, building upon technologies investigated under the COMMEX program, the Agency's Computational Leverage Against Surveillance Systems (CLASS) program is developing new ways to protect U.S. military signals from increasingly sophisticated adversaries. In collaboration with CERDEC, DARPA in 2016 conducted TRL-6 testing of CLASS in a set of exercises at Ft. Dix, N.J. The technology is also being integrated into a new CERDEC project aimed at securing Army radios against jamming threats.

Finding Nuclear and Radiological Threats

Perhaps no domestic security threat today exceeds that of a nuclear or radiological ("dirty bomb") detonation. Current sensors can detect high-emitting radiological materials that could signal such mass-terror devices, but are too large and expensive to deploy widely to fully protect an urban area or major transportation hub. DARPA's SIGMA program has successfully created high-quality, handheld radiological sensors at a fraction the cost of today's devices. SIGMA developed not only that hardware but also the software to monitor thousands of those mobile detectors in real time—an essential capability to discern the movement of nuclear materials before they can be incorporated into a terrorist's weapon. In collaboration with officials in the Washington, D.C., metropolitan area and the Port Authority of New York and New Jersey, DARPA in 2016 tested the devices and networking system at critical transportation hubs and on a city-wide scale involving 1,000 detectors, and will oversee final testing and transition to appropriate authorities for urban deployments in 2017.

Submarine Detect and Track

Enemy submarines pose a growing asymmetric threat in terms of their low cost and consequential growth in numbers. In addition, these submarines have trended toward lower acoustic signature levels and have grown in lethality. DARPA's Distributed Agile Submarine Hunting (DASH) program is working to defuse this threat through the development of advanced standoff sensing from unmanned systems. The program has already developed two prototype systems that the Navy is supporting through continued field trials of this essential technology with a path to full program deployment.

Highly Autonomous Unmanned Ship

The United States in 2016 took its first step towards long-range, highly autonomous vehicles for maritime operations when DARPA unveiled the technology demonstration vessel it developed and built through the Agency's Anti-Submarine Warfare (ASW) Continuous Trail Unmanned Vessel (ACTUV) program. The 132-foot ship, christened Sea Hunter, is not remotely piloted, but rather is designed to operate over thousands of kilometers of open ocean with only sparse supervisory oversight, all while adhering to international rules for navigation and collision avoidance. These capabilities mean the vessel can patrol large areas at a fraction of the cost of a crewed ship and potentially engage in such dangerous tasks as submarine tracking and mine clearing without posing any risk to Sailors. Sea Hunter began open-water testing off the California coast in 2016, under joint leadership of DARPA and ONR. Transition to the Navy is anticipated in 2017.

PNT Without GPS

GPS has revolutionized the all-important ability to know exact current location and heading, but the Defense Department (DoD)'s growing dependence on it also constitutes a vulnerability in the event of a system breakdown or attack. That's why DARPA developed and is now testing advanced PNT systems that can take advantage of alternative sources to serve as external position fixes, and feature advanced inertial measurement units that require fewer fixes while minimizing navigational drift. This potentially liberating system is undergoing operational testing with the Navy, and DARPA continues to push PNT technologies to new horizons with novel algorithms and reconfigurable architectures that can be customized to particular mission needs.

Protection from Cyberattacks

DARPA's Clean-slate design of Resilient, Adaptive, Secure Hosts (CRASH) program was a basic research effort that designed new computer system components that are highly resistant to cyberattack. The results have quickly made their way into both commercial and military applications. One university performer on the program started a company based on CRASH research, which led to an announcement from HP in 2015 that its new line of printers would feature this security-enhancing software to help prevent those devices from serving as inadvertent system portals for hackers.

Within the Defense Department, the Naval Surface Warfare Center is using CRASH technology to protect shipboard control systems from cyberattack; CRASH software is also being used by the Defense Information Systems Agency and is being incorporated into a number of DoD command and control servers. The Department of Homeland Security and the Air Force Research Laboratory have also been working together to test and evaluate CRASH technology in multiple devices. Each of these transitions is contributing to the Nation's cybersecurity by taking entire classes of threats off the table.

Cyber Operations

Plan X gives cyber operators the tools to understand what is happening in their complex, obscure, and fast-morphing domain, facilitating the planning and execution of their operations as well as assessments of their effects—essential to making the increasingly important cyber domain a tractable one for military operations. Plan X technology is transitioning to U.S. Army Cyber Command and will be used by Cyber Protection Teams to support decision makers and defend networks at the tactical edge.

Assessment of Information Operations

Influence operations in the information domain have already proven integral to campaigns being waged by the Islamic State of Iraq and Syria (ISIS) and Russia and are anticipated to be an increasing part of future conflicts. Yet little is known about the elements that contribute to successful information campaigns, or how best to counter those campaigns. Through its Quantitative Crisis Response (QCR) program, DARPA is delivering to operational partners newly developed tools that provide information operators the first capability to understand on a strategic scale what is happening in the online information environment and to predict the impacts of adversaries' information operations.

Rapid Diagnosis of Infectious Diseases

Today's diagnostic tests for infectious diseases can take a week or more to provide definitive results from the field—far too long when the disease in question is a fast-moving scourge such as Ebola or Zika. DARPA's Mobile Analysis Platform is a simple, rugged, handheld, battery-operated instrument that rapidly identifies a range of infectious diseases and can easily accommodate new modules as needed to address novel or unanticipated pathogens. It enables low-cost and robust molecular diagnostics within 30-45 minutes in locations without traditional laboratories or secure pharmaceutical logistics chains. Instant wireless transmission of test results and location data produces invaluable real-time epidemiological analyses at the pace of outbreaks themselves.

DARPA conducted testing with the U.S. Marine Corps Warfighting Laboratory during the 2016 Rim of the Pacific military exercises and is now testing the device with the U.S. Naval Health Research Center and the U.S. Military HIV Research Program in the United States and in Africa.

Space Situational Awareness

Space is increasingly congested and contested, with valuable satellites and various manmade and natural orbital debris all tracing paths above the Earth. The U.S. Space Surveillance Network, operated by U.S. Air Force Space Command, is tasked with tracking the hundreds of thousands of known objects in Earth orbit to ensure the safety of U.S. assets, and is now enjoying the added assistance of the newest DARPA-developed addition to that network: the Space Surveillance Telescope (SST).

In 2016, SST transitioned from a DARPA-led design and construction program to ownership and operation by the U.S. Air Force, which plans to operate the telescope in Australia jointly with the Australian government. There, SST will provide key space situational awareness from an area of the geosynchronous belt that is currently only sparsely observed. With its numerous breakthroughs in telescope design and camera technology, SST provides unprecedented imaging quality to spot small, faint objects across an extraordinarily wide field of view and the ability to take thousands of pictures per night. It also boasts revolutionary image analysis software that enables much faster discovery and tracking of previously unseen or hard-to-find small space objects.

Looking Ahead

As the examples above attest, groundbreaking DARPA technologies are getting steadily integrated into a wide array of Defense Department systems. I could not be prouder of the positive impact our research and development teams are having on our Nation’s security today, and will continue to have into the foreseeable future.

But those success stories are the result of work initiated by my predecessors. My responsibility today is to make sure that ten or twenty years from now, my successors can testify before you and point to an even more impressive spectrum of technologies and capabilities that are mere dreams for us here today. The seeds of that future are germinating in the DARPA portfolio that I now oversee, and I am more than excited about the possibilities I see in those programs. They vary enormously, spanning in scale from the invisible to the cosmic and in domains from the deepest oceans to the open seas to the skies and the heights of geosynchronous Earth orbit, 22,000 miles above our planet’s surface. Indeed there may be only one thing that can be said to be true about all of them: Each program at DARPA has a specific technological goal that is explicitly not incremental or evolutionary but rather is potentially revolutionary and game changing.

So for the remainder of this testimony I would like to highlight a representative sample of those programs from the DARPA portfolio, to give you a sense of the technological challenges the Agency is tackling, the capabilities those technologies are anticipated to enable, and some potential operational applications for those capabilities. Throughout, you will note two overarching themes that are increasingly relevant to many DARPA programs and that give a strong hint about where the future of technology is going. One theme is the accelerating maturation of artificial intelligence (AI) technologies and, with that, the emergence of increasingly automated or semi-autonomous systems. This is a cross-cutting theme that is manifesting across virtually every tech area and battle domain. The second, related theme is the importance of making the interfaces between these powerful systems and their human operators as seamless as possible—sometimes to the point of developing brain-machine interfaces to facilitate an unprecedented degree of human-machine symbiosis. I will expand on these themes in closing.

At Sea

Untethering the Navy from GPS

The Global Positioning System (GPS) is the predominant means of obtaining positioning, navigation, and timing (PNT) information for both military and civilian systems and applications. However, the radio signals that are the basis for GPS cannot penetrate seawater, thus undersea GPS is effectively denied. Among other drawbacks, that means submarines must approach the surface to get navigational fixes. The Positioning System for Deep Ocean Navigation (POSYDON) program has the very challenging but potentially game-changing goal of developing an undersea system that provides omnipresent, robust positioning across ocean basins. Phases I and II of the program have been focused on accurately modeling the necessary signal propagation channels and developing the signal waveforms. Phase III will aim to demonstrate a complete positioning system.

Collaborative, Cross-Domain Force Projection at Sea

By virtue of their shear enormity, ocean domains are challenging to surveil and control, offering adversaries with closer access to those seas a potentially asymmetric means of projecting power. DARPA's Cross-Domain Maritime Surveillance and Targeting (CDMaST) aims to undermine that advantage by developing novel tactical and strategic architectures that take advantage of recent advances in manned and unmanned systems and of emerging long-range weapon systems. Building upon research across a number of DARPA and external programs, CDMaST will integrate and leverage enabling technologies needed for command, control, and communication between air, ocean surface, and sub-surface domains to create entirely new warfighting capabilities, which in turn will enable a menu of surprising new tactics.

Extending the Advantage of Unmanned Aerial Systems

Options for obtaining airborne intelligence, surveillance, and reconnaissance (ISR) at sea remain frustratingly constrained. Ship- or land-launched helicopters are relatively limited in their distance and flight time. Fixed-wing manned and unmanned aircraft can fly farther and longer but require either aircraft carriers or large, fixed land bases with runways as long as a mile or more. Moreover, establishing these bases or deploying carriers requires substantial financial, diplomatic, and security commitments that are incompatible with today's requirements for rapid response. Tern is a DARPA advanced technology development program that originally designed—and now is about to build—a medium-altitude long-endurance unmanned aircraft system that can be launched from and recovered by small ships, providing unprecedented open-ocean ISR and strike capabilities.

Having quickly matured from an experimental DARPA program to a joint effort with the Office of Naval Research, Tern is now undergoing a detailed design phase, which will be followed by construction of a full-scale demonstrator system. Tests will include initial on-land testing and subsequent at-sea demonstrations of vertical takeoff and landing (involving a test platform with a deck size similar to that of a destroyer or other small surface-combat vessel), as well as transition to and from horizontal flight.

On Land

Bringing High-Resolution Strategic Awareness to the Squad

Airborne and ground-vehicle-assigned forces today have access to astonishingly detailed information about their environs, but dismounted infantry squads often lack such situational awareness because the relevant technologies are too heavy and cumbersome for individual Soldiers and Marines to carry or too difficult to use under demanding field conditions.

DARPA's Squad X Core Technologies (SXCT) program is speeding the development of new, lightweight, easily interfaced systems to help dismounted Soldiers and Marines more intuitively understand and control their complex mission environments. Specific goals include distributed, non-line-of-sight sensing and guided-munitions targeting of threats out to 0.6 mile (1,000 meters) and providing squad members with real-time knowledge of their own and teammates' precise locations in GPS-denied environments through seamless collaboration with embedded unmanned air and ground systems.

Bringing Directed Energy to the Fight

Overcoming a long string of seemingly insurmountable technical challenges, DARPA is driving down the size and weight of high-power fiber laser arrays for multiple Service applications. This new laser technology pioneered by DARPA has demonstrated electrical efficiencies of greater than 40 percent and features ultra-high speed beam corrections to compensate for atmospheric turbulence and maintain precision focus on targets. Through our Endurance program, DARPA is demonstrating the laser kill chain for aircraft self-defense applications in live-fire testing at ranges in the western United States. Later this year the system will be tested for its ability to provide automated, high-confidence detection, tracking, and kill of incoming missile targets.

In the Air

Rewriting the Rules for Fixed-Wing Flight

DARPA is making rapid progress toward achieving one of aviation's most coveted prizes: a vertical take-off and landing (VTOL) aircraft able to fly significantly faster than today's longstanding VTOL limit of 150 knots to 170 knots. Rather than simply tweaking past designs and technologies, DARPA's VTOL X-Plane program—which just last month transitioned from sub-scale demonstrator stage to initial production of a full-scale 12,000-pound aircraft—integrates entirely novel energy distribution and propulsion systems to achieve an anticipated top sustained flight speed of 300 knots to 400 knots while retaining 75 percent hover efficiency and doubling today's cruise lift-to-drag ratio.

Breaking the Mach 5 Technology Barrier

Systems that operate at hypersonic speeds—five times the speed of sound (Mach 5) and beyond—offer the potential for military operations from longer ranges with shorter response times and significantly enhanced effectiveness compared to current military systems. The Hypersonic Air-breathing Weapon Concept (HAWC) program is a joint DARPA/U.S. Air Force (USAF) effort that is developing and demonstrating critical technologies to enable an affordable air-launched hypersonic cruise missile effective against even heavily defended targets. At the same time, DARPA's Tactical Boost Glide (TBG) program—also a joint DARPA/USAF effort—is developing technologies to enable air-launched, tactical-range hypersonic boost glide systems. The program is exploiting the technical knowledge and lessons derived from development and flight testing of previous boost glide systems, including the Hypersonic Technology Vehicle 2 (HTV-2).

Investigating Small Spaces Autonomously

DARPA launched its Fast, Lightweight Autonomy (FLA) program in response to an anticipated need for small (quadcopter-sized), fast, unmanned aerial vehicles able to navigate autonomously through cluttered urban environments. The program is developing a new class of algorithms for minimalistic high-speed navigation and has been testing the software and integrated sensors in small UAVs that fly at speeds up to 20 meters/second with no communication to an operator and without GPS waypoints.

In Space

Enabling Rapid Access to Space

Space launch systems today are exceedingly expensive and typically must be procured years in advance of launch. In an era of proliferating foreign threats to U.S. air and space assets, routine, affordable and responsive access to space is essential to enabling new military space capabilities and rapid reconstitution of space systems during crisis. To close this critical capabilities gap, DARPA's Experimental Spaceplane XS-1 program is developing the technologies needed to fabricate and fly a business-jet-sized, reusable aircraft to the edge of space. The program recently entered a final design and development stage to create a craft that can launch a spacecraft to low Earth orbit at a cost one-tenth the cost of today's equivalent launch systems—and be able to do so ten times in ten days, demonstrating aircraft-like operability, cost efficiency and reliability.

Achieving Robotic Repairs on Orbit

Hundreds of military, government and commercial satellites reside today in geosynchronous Earth orbit (GEO) some 22,000 miles (36,000 kilometers) above the Earth—a perch ideal for providing communications, and meteorology services, but one so remote as to preclude inspection and diagnosis of malfunctioning components, much less the provision of upgrades or repairs. With no prospects for assistance once in orbit, satellites destined for GEO today are loaded with backup systems and as much fuel as can be accommodated, adding to their complexity, weight and cost. DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) program is developing technologies to enable cooperative inspection and servicing in GEO and intends to demonstrate those technologies—many of which have been created in a previous DARPA program and are effectively flight-ready—on orbit. The system is to include a DARPA-developed modular toolkit, including hardware and software, joined to a privately developed spacecraft to create a commercially owned and operated robotic servicing vehicle (RSV) that could make house calls in space.

The Digital Domain

Letting Sleeping Sensors Lie

State-of-the-art military sensors rely on "active electronics" to detect vibration, light, sound or other signals for situational awareness and to inform tactical planning and action. That means the sensors constantly consume power, with much of that power spent processing what often turns out to be irrelevant data. This power consumption limits sensors' useful lifetimes to a few weeks or months with even the best batteries and has slowed the development of new sensor technologies and capabilities. Moreover, the chronic need to service or redeploy power-depleted sensors is costly and time-consuming and increases warfighter exposure to danger. DARPA's Near Zero Power RF and Sensor Operations (N-ZERO) program is developing the technological foundation for persistent, event-driven sensing capabilities in which the sensor can remain dormant, with near-zero power consumption, until awakened by a relevant external trigger or stimulus, such as the acoustic signature of a particular vehicle type or radio signatures of specific communications protocols. The program could extend the lifetime of remotely deployed communications and environmental sensors—also known as unattended ground sensors (UGS)—from weeks or months to years.

Making the Most of a Crowded Spectrum

Across the Nation and around the world, the wireless revolution is fueling a voracious demand for access to the radio frequency (RF) spectrum. In the civilian sector, consumer devices from smartphones to wearable fitness recorders to smart kitchen appliances are competing for bandwidth. In the military there is growing reliance on unmanned platforms, from underwater sensors to satellites, and a push for broadband connectivity for every member of every Service. Managing this increasing demand, while combating what appears to be a looming scarcity of RF spectrum is a serious challenge.

Today's approach of rationing access to exclusively licensed bands is not adaptive to the dynamics of supply and demand and unnecessarily creates conditions of scarcity. DARPA's Spectrum Collaboration Challenge (SC2), which will culminate in a final event in 2019, asks competing innovators to reimagine spectrum access strategies and develop a new wireless paradigm in which radio networks endowed with artificial intelligence will autonomously collaborate and reason about how to share the RF spectrum, thereby avoiding interference and jointly exploiting opportunities to achieve the most efficient use of the available spectrum.

Getting Smart Machines to Tell Not Just What, But Why

Dramatic recent successes in artificial intelligence and machine learning promise to produce autonomous systems that will perceive, learn, decide, and act largely on their own. The usefulness of these systems is limited, however, by their current inability to explain their sometimes surprising or even flat-out counterproductive decisions to human users—a shortcoming that undermines human efforts to program essential correctives. DARPA's Explainable AI program is developing a suite of machine learning techniques to help human users understand, effectively manage, and appropriately trust the emerging generation of artificially intelligent partners, with which the Department of Defense in particular hopes to increasingly collaborate. The program's anticipated final product will be a toolkit library consisting of machine learning and human-computer interface software modules that could be used to develop future explainable AI systems and would be made available for further refinement and transition into defense or commercial applications.

Aiming for the Unhackable

Today's world is a network of interconnected, embedded computer systems with components ranging in size and complexity from large supervisory control and data acquisition systems that manage physical infrastructure such as electrical grids and dams, to smaller but still critical systems inside airplanes, satellites, medical devices, computer printers and routers, and handheld devices such as cell phones and radios. Researchers and hackers have shown that these kinds of networked embedded systems are vulnerable to remote attack, and such attacks can cause not just data loss or but significant physical, economic, and strategic damage. DARPA's HACMS program is creating technology for the construction of safe and secure cyber-physical systems. Taking a fundamentally different approach from the inadequate methods used today by the software community, the program has adopted a clean-slate, formal methods-based approach to enable semi-automated code synthesis from executable specifications. HACMS has already transitioned some of its technology to both the defense and commercial communities.

Speeding the Search for Cyber Threats

Recognizing that no cyber protective system will ever be completely effective, and that the Defense Department in particular demands the highest level of cyber assurance, DARPA is heavily focused on the need to develop data-driven cyber-hunting tools to detect and characterize cyber threats. The challenge for the DoD is great in part because the Department generates orders of magnitude more cyber-relevant data than the total storage available for cyber scanning and security purposes, only a fraction of which is actually threat related. DARPA's Cyber-Hunting at Scale (CHASE) program is developing novel algorithms to dynamically collect data from mission-critical parts of the DoD network, hunt for threats, and disseminate protective measures.

Harnessing Math to Unify Composable Systems

DARPA in recent years has focused heavily on the need to disaggregate complex military systems and to evolve a portfolio of "system-of-systems" architectures to better manage national security applications and improve the survivability and mission success of military platforms. A core remaining challenge, however, has been the lack of sophisticated tools to model and systematically design complex systems of systems. DARPA's Complex Adaptive System Composition And Design Environment (CASCADE) program is addressing this shortcoming by developing novel mathematical foundations that can provide a unified view of system behavior and, ultimately, a formal language and tool kit for complex adaptive-system composition and design.

Making Antenna Arrays More Modular

Today's radio frequency systems use antenna arrays to provide unique capabilities, such as multiple beam forming and electronic steering, which are important for a wide variety of applications such as communications, signal intelligence (SIGINT), radar, and electronic warfare. However, wider use of arrays has been limited by lengthy system development times and the inability to upgrade already-fielded capabilities—problems exacerbated by the fact that military electronics have evolved at a slower cadence than those in the commercial sector. In particular, the performance gap is widening between the radio frequency capabilities of fielded military systems and the continuously improving digital electronics surrounding those systems. DARPA's Arrays at Commercial Timescales (ACT) program aims to shorten design cycles and in-field updates and push past the traditional barriers that lead to 10-year array development cycles, 20- to 30-year static life cycles and costly service-life extension programs. Specifically, as an alternative to traditional undertakings focused on the development of large, monolithic array systems, ACT is developing a digitally interconnectable building block.

The Biological Frontier

Cultivating Complex Microbial Communities

Synthetic biology—in which biological components are engineered into systems with applications ranging from pharmaceutical and fuel production to chemical decontamination to the organic "growth" of new materials with novel structural, electronic, or optical properties—is hobbled today by the need to pamper relevant microorganisms in highly protected laboratory environments. DARPA's Biological Robustness in Complex Settings (BRICS) program is developing the fundamental understanding and component technologies needed to engineer biosystems that can function reliably in less constrained environmental conditions. In a related effort, DARPA's Engineered Living Materials (ELM) program is developing biologically based materials that combine the structural properties of traditional building materials with attributes of living systems, including the ability to rapidly grow, self-repair, and adapt to the environment. Such "living materials" represent a new opportunity to leverage engineered biology to solve problems associated with the construction and maintenance of the built environment, as well as new capabilities to craft smart infrastructure that dynamically responds to its surroundings. Initial program objectives are to develop design tools and methods that enable the production of structural materials that can reproduce, self-organize, and self-heal.

Building Trust with Biological Brakes

DARPA recognizes that efforts to develop synthetic biological systems able to serve the field's large potential spectrum of commercial and national security applications will not bear fruit without concomitant assurances that such systems are safe. Its Safe Genes program aims to deliver novel biological control capabilities that can mitigate the risk of unintentional consequences or even intentional misuse of these technologies, and thereby facilitate the pursuit of positive advanced genome editing applications.

Outpacing Infectious Disease

Vaccine production today is a slow and arduous process, with even the fastest production modes for fast-evolving threats such as influenza taking a full year to implement. Indeed, the primary reason that pandemic threats in recent years have not evolved into even larger global disasters is because the world was fortunate enough for those strains to have burned out naturally, with vaccines arriving only after mortality had peaked. Recognizing that such good fortune is not likely to last, and that large-scale infectious disease or toxin-related disasters—whether natural or human-produced—can quickly lead to global destabilization and a threat to U.S. national security, DARPA launched its ADEPT program. ADEPT has already produced a "diagnostics on demand" system that provides rapid, specific, distributed diagnostics for medical decision-making and accurate disease-tracking, a key to properly focusing limited resources at the critical early stages of a pandemic and a potential game-changer for battlefield medics. The program is also developing new methods for manufacturing vaccines that can decrease production time from years to weeks while increasing potency, and new methods to impart immediate, temporary immunity to a population via fast-acting, genetically programmed antibodies.

Probing the Potential of Human-Machine Interfaces

Inspired in part by the specific healthcare needs of injured warfighters and veterans, DARPA is pioneering the nascent but fast-moving field of neurotechnology, with goals as diverse as the creation of advanced prosthetic limbs to the restoration of an injured brain's ability to create and retrieve memories. Over a period of just a handful of years, DARPA's Revolutionizing Prosthetics program created and helped bring to market a Food and Drug Administration-approved modular prosthetic arm that weighs no more than a standard adult arm and offers users an unprecedented range of motion. Recent advances through that program have added a capacity for users to "feel" what their mechanical hand is touching—a capacity now being furthered under DARPA's Hand Proprioception and Touch Interfaces (HAPTIX) program—and are fueling further improvements, to culminate in complete control of the arm via thought alone. Under the Agency's Systems-Based Neurotechnology for Emerging Therapies (SUBNETS) and Restoring Active Memory (RAM) programs, DARPA researchers are learning how electrophysiological firing patterns in the brain can be translated into digital ones and zeros and then interpreted by computer systems to diagnose and potentially correct neuropsychiatric or memory deficit problems, and perhaps even enhance normal memory and accelerate skills training.

Cross-Cutting Technologies and the Longer-Term Future

As the above highlights reveal, two powerful, overarching technology trends are fueling many of DARPA's fastest-advancing programs. First, artificial intelligence and machine-learning technologies are serving as an accelerator and force multiplier in diverse areas of research, from information processing to electronics to neuroscience. These technologies are helping researchers overcome a problem few anticipated ever having to worry about: an overabundance of data. Sensor data and other intelligence streams from space, airborne surveillance, and ground and maritime systems have flooded analysts with more information than they can properly parse—as has enormous volumes of data collected from probes of the human brain—raising a risk of perceiving statistical associations that are not meaningful and potentially misleading. Ever more advanced AI and machine learning algorithms are helping researchers sort through and make sense of this embarrassment of riches. And over the next few years, it is reasonable to expect that AI-enabled data-processing and modeling capabilities will harness this unruly data glut and give rise to stunning new capabilities in a range of domains, including that of automated and semi-autonomous systems. These advances can be expected to provide new tactical and strategic options for national security but also new challenges—both in terms of defending against adversaries who use these powers to create sophisticated threats, and in terms of our own responsibility to retain adequate technical and policy controls over how these technologies will be used.

At the same time, a second set of technologies is having an outsized impact across multiple research disciplines: a blend of biocompatible electrode arrays and sophisticated software that is making the human-machine interface ever more seamless. This increasingly intuitive linkage between operators and their devices is introducing to the national security matrix a mix of novel opportunities, ranging from therapies for veterans with brain injuries, to regimens for accelerated memory formation, learning, and training for warfighters, to an array of digital systems that can be accessed and controlled at the speed of thought. DARPA has been clear in its views of this opportunity space for some time, recognizing that the future is not going ot be about the advanced technologies we create but about interaction with, and integration of, those technologies with their human operators.

Building in part upon these powerful, cross-cutting technologies—as well as upon insights into where the next major breakthroughs in science and technology are likely to emerge, and what kinds of national security challenges the United States is likely to face in the decades ahead—DARPA periodically sketches out longer-term initiatives that the Agency may choose to pursue. Because these ideas focus on distant time horizons, they are by definition extremely ambitious, but they also have the potential to radically bend the arc of technology development for the military Services and, in doing so, provide a range of tactical and strategic options hardly imaginable today. To complete my overview here of the kinds of work DARPA is doing or is considering, I would like to highlight four of the current crop of such initiatives. None of these four has been fully mapped out, approved, or funded internally as yet, but they give a taste of the kinds of futures we are envisioning—and how we imagine addressing those futures by applying DARPA's most creative energies.

Enabling kinetic ground ops via air-space integration

Recent advances in the development of small satellites, low-cost launch capabilities, novel space-based tactical ISR sensors, and weapons systems that can detect, track, and strike large numbers of targets with short lead times are enabling a new degree of air-space integration in support of ground operations. DARPA is studying approaches to catalyze the operationalization of such a large-scale, cross-domain system of systems by developing the technology needed to fill key remaining gaps, such as architectures and algorithms for seamless integration of communication, data fusion, and command and control. The Agency is already accelerating the development of relevant launch systems and satellite architectures.

Into the megacity gray zone

U.S. assault training and equipment decisions have for years focused on counter-insurgency wars in open, desert terrain. The ability to win battles in the decades ahead, however, will increasingly depend on high-quality ISR, targeting, maneuverability, and strike capabilities in densely populated urban centers, and will be complicated by adversaries' use of gray zone tactics that propagate ambiguity about the identify of those adversaries and their actual objectives. DARPA is studying possibilities for a system of manned and unmanned systems that together could provide a tenfold improvement in the ability of U.S. small military units to move, shoot, communicate, and survive in megacities while pursuing gray zone objectives.

Win at cyber

U.S. warfighters and national security generally depend more than ever on cyber information advantage, but cyber security has not kept up with cyber dependence. Building on recent significant advances within the Agency in the domains of both hardware and software security, DARPA is radically rethinking current security approaches in order to harden systems against cyber attack, operate through cyber attacks, and, when necessary, act and win in the cyber domain.

Eliminate the threat of weapons of mass terror

Chemical and bio-production facilities are now common in many countries that were incapable of supporting such technologies just 10 years ago. Concomitantly, the barrier to entry for weapons fabrication—from homemade explosives to do-it-yourself biotechnology—continues to decrease with the proliferation of instructions and designs on the internet. These trends, combined with the potential of terrorist access to radiologic materials for use in dirty bombs or even to nuclear weapons, present a diverse and challenging array of threats against which to defend military and civilian populations. The most promising approach to eliminating the threat of weapons of mass terror is to create networked sensor and information systems that signal the presence of such threats or, better still, that alert authorities to the transport or aggregation of relevant components. DARPA is studying the possibility of creating a fully networked, continuous monitoring system that functions for the full range of chemical, radiological, and biological weapons of mass terror. Challenges include the development of miniaturized, networked, multi-functional sensors able to detect parts-per-million levels of chemical warfare agents or precursors and extremely low numbers of relevant biological organisms, with automated sample preparation and with false negative and false positive rates equal to or better than those recently achieved by DARPA for city-scale, dynamic radiological sensing.

Maintaining the DARPA Culture

DARPA office leaders and program managers come to work every day inspired and visibly eager to explore the scores of exciting frontiers that my testimony today has only touched upon. I see this enthusiasm every day in these individuals' offices, in the hallways, and in the elevators. The DARPA model for maintaining this remarkable degree of energy and reach has been the focus of many analyses, and many of the key elements are well understood. Some are structural: by design, for example, program managers come to DARPA with an open-ended invitation to move their field of expertise to an entirely new level of achievement, but they are invited to DARPA for well-defined stints of just three to four years, creating a powerfully paired sense of opportunity and urgency. Some of the Agency's keys to success are more cultural than structural, such as the common understanding that risk is not our enemy but our friend. It is not that DARPA is attracted to risk, it is that risk is going to be part and parcel of any effort that seeks to truly break radically new ground. So we take risks, and we manage those risks, and when risk appears not to be nearby we ask ourselves why not, and whether we need to be grasping for something higher and harder. Last but by no means least, DARPA's success is in large part the result of trusting leaders in Congress and across all of Government who have agreed to give the Agency the freedom to pursue DARPA-worthy goals.

Conclusion

From DARPA's perspective, the technological future is enormously attractive, bright with opportunities and if also fraught with unanticipated risks. For nearly 60 years, the men and women of DARPA have taken very seriously their unique mission to serve the Nation by preventing—and when necessary fomenting—technological surprise. I can assure you that from my perspective in the Director's office, DARPA is stronger and more committed to that mission than ever.

I look forward to working with the members of this subcommittee and others in the Legislative and Executive branches to ensure that the United States maintains its historic lead in the development and application of powerful technologies, and to their safe and responsible application in support of a more stable, secure, and sustainable world.