Technology Visions for APL's Centennial

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ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (APL) will celebrate its centennial in 2042, about 20 years from the time of this writing. As the Lab looks toward this milestone, a team comprising APL staff members who are fellows of several premier technical societies or APL master inventors predicted which innovations and technologies might become global trends by 2042 and, consequently, could be considered as potential elements in APL's science and technology strategy. This article describes their predictions.

INTRODUCTION

Akinwale A. "Wale" Akinpelu

For over 80 years, APL has been making critical contributions to our nation's critical challenges, creating scientific breakthroughs and developing innovative solutions to complex research, engineering, and analytical challenges. Among APL's thousands of contributions to national security and space exploration are a number of defining innovations, game-changing breakthroughs that have created inflection points in history. Examples of defining innovations are the radio proximity fuze, which changed the course of key battles in World War II, and the Transit system, the world's first satellite-based global navigation system.[1]

As the Lab looks toward its centennial, a team of APL staff members considered which technical trends could become global game-changers by 2042. This team, known as the Centennial Task Force, includes two APL master inventors, an honor bestowed on staff members who have been granted 10 or more US patents based on APL intellectual property, and four fellows of premier technical societies. The hope is that their predictions help APL anticipate, leverage, or contribute to realizing advances that might ultimately lead to defining innovations. They briefed their ideas at an event called APL Showcase held at APL on August 2, 2022. This article summarizes their projections.

In the first section, "Faster than the Speed of Thought," master inventor Dave Blodgett describes the concept of humans no longer constrained by the speeds at which our brains can transmit and receive speech and text.

The second section, also by Dave in collaboration with Force Projection Sector chief engineer Glenn Mitzel, describes the concept of coherent distributed networks (CDNs). Such networks could, for example, enable accurate identification of objects in space.

Master inventor Morgan Trexler, in the section titled "Game-Changing Materials on Demand," discusses a robust approach for warfighters in the battlefield, or astronauts on the moon, to fabricate tools, structures, materials, and power sources from the resources around them. This approach would drastically reduce the loads they must carry and mitigate supply chain and logistics issues.

The fourth section, by American Society of Mechanical Engineers (ASME) fellow Kaushik Iyer in collaboration with Rama Venkatasubramanian, Ann Darrin, Ralph McNutt, and Paul Ostdiek, discusses NuX, or "Nuclear Power for Extreme and Space Environments." NuX is a concept to generate abundant nuclear energy in space.

Institute for Electrical and Electronics Engineering (IEEE) fellow Jerry Bath, in the section titled "Shifting Human–Machine Interaction to Symbiosis," considers an approach for human–machine cooperation. In the envisioned future, humans and their machine teammates learn together and increase their levels of cooperation and codependence over time.

The sixth section, by IEEE fellow Ashutosh Dutta and AIAA fellow Nancy Andersen, discusses "Assured Ubiquitous Communications." This concept centers on the development and deployment of a communications network that can be reconfigured instantaneously and with no service disruption in response to outages or cyberattacks.

Why are these centennial predictions important? Because we have observed that technology predictions stimulate creativity and innovation. For example, in 1876, the telephone mode of communication was invented. In 1963, a telephone company manager predicted the development of a smartphone that we would one day carry with us.[2] As we know, by the 2000s, this prediction had become a reality (Figure 1). We hope that the predictions by the Centennial Task Force will similarly stimulate creativity and innovations at APL.

But, as we also realize, many futuristic predictions fall short. In a companion article in this issue, Harry Charles, a master inventor and an IEEE lifetime fellow, describes and assesses the technology projections for the 21st century that APL senior fellows made in 1983, on the occasion of the Lab's 40th anniversary. He notes which projections were realized and which were not.

We acknowledge the possibility that only a few—or even none—of our Centennial Task Force predictions will come to pass by 2042. But then again, one or two of these predictions just might come to fruition.

Figure 1. Technology predictions stimulate creativity and innovation.

FASTER THAN THE SPEED OF THOUGHT

David W. Blodgett

What does it really mean to operate faster than the speed of thought? What problem are we trying to solve when thinking about this concept? What is the capability gap that we are trying to close? Imagine if the brain's transmit or receive bottleneck had been disrupted and information flow was no longer bandwidth limited by either speech or text. What could we accomplish with unlimited data communication rates between the brain and the outside world? The possibilities are endless. So, how could we remove that bottleneck and access all the information in our brains? How could we decrease the time to decision and action? That is the game-changing technological breakthrough we envision (Figure 2).

APL and other research organizations are currently working to develop a brain–computer interface (BCI) that is able to read and write information to the brain. So back to the original question—what could we accomplish with unlimited data communication rates between the brain and the outside world? This brings us right to the "imagine if" scenario.

Imagine a battlefield with a squad of soldiers who want to convey actionable information (Figure 3). If limited by voice, the exchange might go something like this: "There's a building over there, second floor, second window to the right. I think I see a sniper." That is a lot of information both for the observing soldier to give and for the other soldiers to process. But what if they could

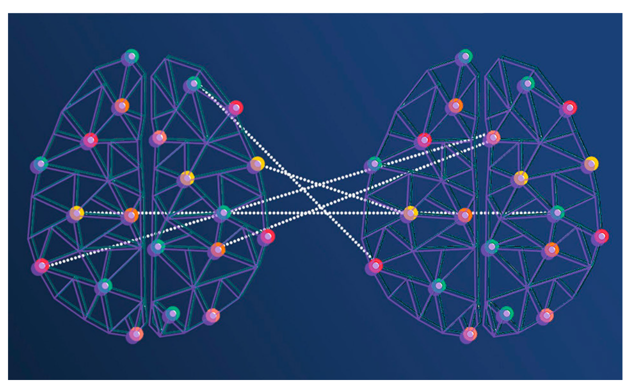

Figure 2. Data flow limited only by the speed of thought.

Figure 3. Real-time thought integration across teams.

simply convey an image of the battlefield highlighted with danger zones? They could provide potentially life-saving information in the time it takes to blink. As the old adage goes, a picture paints a thousand words, and this is just one example of disrupting the information bottleneck.

In many ways, one can think of this as a reimagining of one of APL's defining innovations: the Cooperative Engagement Capability (CEC).[3] At its heart, CEC was motivated by the US Navy's need to combine remote data from dispersed units to provide coverage that no single ship—or even group of ships—could offer. Similarly, situational awareness could be enhanced by cooperative BCI integrating neural information across a squad, a platoon, or even an entire battalion. Think about how that would change the role of the commander.

Another "imagine if" scenario is the seamless integration of external sensor data into the brain (Figure 4). These sensors could provide data as complex as infrared or hyperspectral imagery acquired from uncrewed aerial vehicles (UAVs). Coupled with information from existing senses, these data would augment perception of the environment.

APL started its journey to realize a BCI many years ago at the inception of the Defense Advanced Research Projects Agency (DARPA) Revolutionizing Prosthetics program.[4] The vision of that program is as real today as it was 15 years ago. The Revolutionizing Prosthetics team demonstrated the ability to record and encode neural activity from and to the brain, resulting in actionable events. Examples include control of the Modular Prosthetic Limb to support limb restoration for wounded warriors and the ability to fly an aircraft in a flight simulator. This work continues through DARPA, the National Institutes of Health (NIH), and even private industry.

However, much of this work focuses on development of *invasive* arrays—that is, arrays requiring brain surgery—to provide that high-speed interface to the brain. More recently, there has been a push to develop *noninvasive* neural interfaces. While regulatory and ethical questions will need to be addressed for invasive neural interfaces to be used by people who are not affected by sensorimotor injuries or diseases, the path toward use of noninvasive interfaces with similar capabilities is much clearer. Imagine being able to simply put on a headpiece that seamlessly syncs with your brain.

Figure 4. Persistent 3-D virtual world that coexists with the physical reality.

DARPA shares this vision and has been investing in multiple concepts—including APL's—to explore the realm of possibility in this domain (Figure 5). Even Facebook has invested in this area; its stated goal is to develop a BCI device allowing mobile device and computer users to communicate at a speed of 100 words per minute, far faster than the speed at which anyone can type on a phone.

The question, then, is, What else has to be accomplished over the next 20 years to realize a truly noninvasive neural interface? How would we leverage such a capability? If we were to invest at APL, where would we invest (Figure 5)?

One of the places APL can move the needle is in envisioning how a neural interface could impact and enhance solutions to warfighter challenges. To date, most of the fundamental research in BCI device development has been led by APL's Research and Exploratory Development Department (REDD), but understanding the needs of warfighters will require collaborations across all of APL. What are the known capability gaps that would represent opportunities for a neural interface? What would that neural interface have to achieve in terms of information bandwidth, accuracy, and bit error rate? What kind of information would need to be conveyed?

Extensive work will also be required to both miniaturize and harden the device. How do we fabricate these things? It is one thing to encode or decode neural information in an academic lab setting, but that is a far cry from deploying a technology on the battlefield. Fortunately, APL has a strong background in transitioning technologies from fundamental research to the battlefield; its critical role in operationalizing light detection and ranging (lidar) is one example.

Another key challenge will be effective integration of artificial intelligence (AI), specifically leveraging AI to augment the neural interface's performance. A simple example is the control of a prosthetic limb. It would not be efficient to record every motor control step necessary to pick up an object (e.g., move your elbow, now move your fingers, now grab, now raise your arm . . .)." Instead, the AI should be responsible for these actions so that the person can simply think "pick up the glass" and the limb picks up the glass.

Finally, neural interfaces will require secure communications as they link directly to the brain. This requirement is in addition to exploring and tracking ethical issues involved with their use. Ultimately, the realization of this device will revolutionize both the way our sponsors address their most critical challenges and the way members of society as a whole live their daily lives, making this a prime example of an inflection-point technology.

COHERENT DISTRIBUTED NETWORKS

Glenn E. Mitzel and David W. Blodgett

Large antennas have distinct advantages in sending and receiving electromagnetic signals. Generally, larger antennas emit or collect more of the intended signal energy and in preferred directions, thus increasing sensitivity and resolution. The benefits of larger antennas have driven some extreme engineering, exemplified by China's enormous radio telescope, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) (Figure 6).

However, the quest for larger antennas may be reaching its practical fabrication limits without radical changes in the approach. The size limits could be lifted, ostensibly without bound, if the larger antenna could be built from smaller distributed antennas. But, to realize the greatest benefit from the distributed networks, the antennas ideally need to be operated coherently; that is, the raw constituent signals aimed at or measured from specific distant points must be adjustable so that the signals' cycles can be aligned. Such configurations are known as coherent distributed networks, or CDNs.

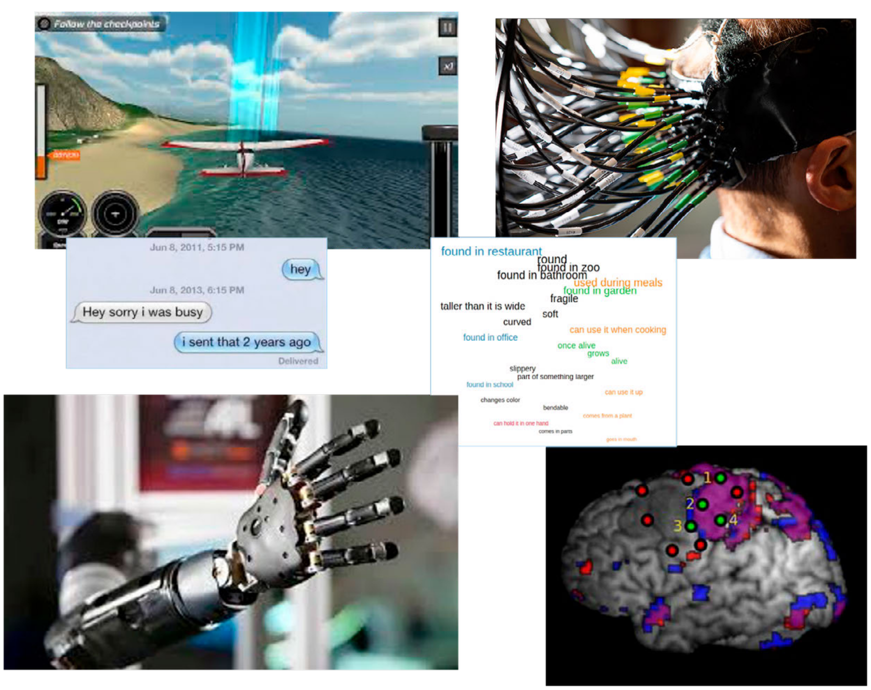

Figure 5. Ongoing work at APL in noninvasive neural stimulation and recording.

Figure 6. China's FAST. (Liu Xu/Xinhua News Agency.)

Since the constituent CDN signal cycles are aligned, the amplitude of the sum is proportional to the number, N, of contributing antennas, assuming common antennas and local signal strengths. Since the power of a signal is proportional to the amplitude of the signal, CDNs boost combined signal power by a factor of N^2, an attractive, frequently cited theoretical improvement in sensitivity over a single CDN element. Also, an antenna's ability to resolve closely spaced distant sources is proportional to the maximum spread of the antenna. Since the maximum spread of a CDN is no longer limited by the largest dimension of a monolithic antenna, the CDN resolution capability can be stretched considerably, theoretically without limit. Of course, these CDN benefits are often mitigated by practical considerations and engineering challenges. But the potential benefits are hard to ignore.

Conceivably, CDNs could enable a number of applications. Among them are unprecedented or even otherwise unachievable capabilities to detect and track faint signals, distinguish closely spaced objects, identify objects with great precision, or extend the range of communication systems. Such capabilities may prove to be game-changers in astronomy, military conflicts with technologically sophisticated adversaries,[5] or cislunar domination.[6]

However, although CDNs may hold promise for enabling remarkable applications by overcoming practical limits on the fabrication of monolithic antennas, coherency itself imposes big, unique challenges. Allowing for imperfections, the constituent signal cycles from distributed antennas must be synchronized to within 5% of the electromagnetic wavelength. As the electromagnetic frequency increases, this requirement can become daunting, as illustrated in Figure 7. In the high-frequency (HF) band, the synchronization requirement is tens of nanoseconds in time or meters in position, both routinely achieved anywhere in world with GPS. But as the frequency increases, for example, to X-band (~10 GHz) where many radars operate, the synchronization requirement tightens by as much as a factor of 1,000, to tens of picoseconds or millimeters. At near-infrared, the synchronization requirements are overwhelmingly small, and other engineering challenges may preclude coherent operation.

Thus, CDNs present formidable challenges, arguably feasibly met, at least for certain portions of the electromagnetic spectrum. APL demonstrated a CDN-enabled radar for deep-space observation, known as Deep Space Advanced Radar Capability (DARC). DARC operates at S-band (~3 GHz) frequencies and is synchronized across multiple transmit antennas and receiving antennas, as illustrated in Figure 8.[7] The demonstration proved that a paper concept inspired by a 2009 NASA study could be realized, thus enabling a highly tailored, scalable, and affordable solution to a challenging surveillance problem. Furthermore, for synchronizing CDNs at even higher frequencies, APL demonstrated femtosecond time synchronization in free space.[8] These and other successes position APL to address the CDN challenges and applications more comprehensively. The potential benefits of scalability for improved sensitivity and resolution, coupled with APL's expertise in this area, make CDNs a goal worth considering in APL's Centennial Vision.

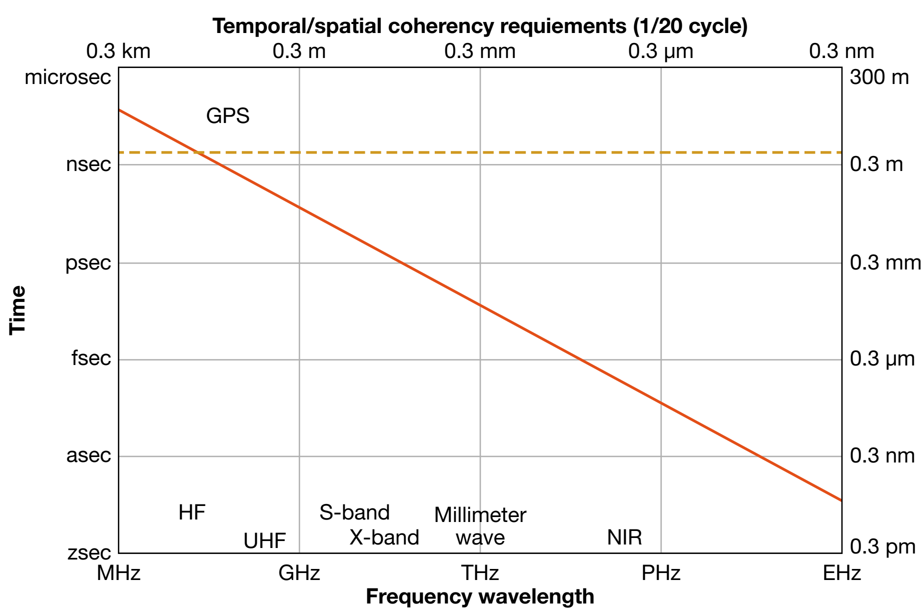

Figure 7. CDN temporal/spatial synchronization requirements.

Figure 8. DARC Technology Demonstrator.

Figure 9. In situ battlefield manufacturing.

GAME-CHANGING MATERIALS ON DEMAND

Morgana M. Trexler

Imagine that missions were not limited by materials' availability, properties, and performance. What if we could quickly conceptualize and make new materials from the resources around us, no matter where we were? Discovery of materials is a driver for industrial innovation, but it is an extremely slow process, usually taking on the order of a decade. And it is largely reliant on trial and error, which is not effective or efficient.

Think about the periodic table. There are endless combinations of materials. How do we find the needle in the haystack? And what if the haystack is as big as the universe? How do we even start? This is the scale of the materials discovery challenge, and because of that, we normally stick close to what we know. We change composition slightly and hope the properties and performance improve and we find something that will enable what we need.

However, approaching materials discovery by using AI integrated with high-throughput material synthesis and high-throughput characterization opens the possibility to explore the unknown more strategically. By leveraging computationally driven discovery, we can potentially determine how to best use resources in austere environments and to make use of them to create new capabilities, regardless of where we are and what we have with us.

In that next frontier, we need the ability to discover the undiscoverable in a targeted and efficient manner in order to make new materials with unprecedented properties on demand. So imagine now a battlefield that our warfighters can set out to with minimal supplies so they are carrying a much lighter load (Figure 9). They can fabricate whatever they need as situations arise; they can make their tools, structures, and power sources from whatever they find around them.

Reducing load is a huge benefit, as is eliminating challenges with the supply chain and logistics. It may seem silly to fabricate a simple widget on the battlefield, but if you think about the cost and time to otherwise ship it to the battlefield, and the downtime and performance impacts in the meantime, it is actually incredibly impactful. Similarly, when an aircraft breaks and a replacement part is needed, ordering, fabricating, and shipping that part significantly impacts performance, preventing pilots from logging flight time and conducting their missions. There are huge trickle-down effects related to

Figure 10. Resilient Arctic operations.

manufacturing and supply chain challenges. So what if we could take the natural materials surrounding the battlefield and fabricate supplies, tools, or whatever is needed, on demand?

The Arctic is becoming operationally important, but there are a lot of technical challenges associated with those cold temperatures. Imagine an efficient and effective Arctic operations setup powered by revolutionary battery materials that can maintain long-duration performance in cold temperatures (Figure 10). Battery chemistry traditionally has a very short lifetime, so we have limited power storage capabilities. Our energy storage capabilities and power for autonomous vehicles, heated textiles, and human-carried devices are limited, and that limits capabilities. So what if we could discover new chemistries for those batteries and revolutionize our capabilities in the Arctic?

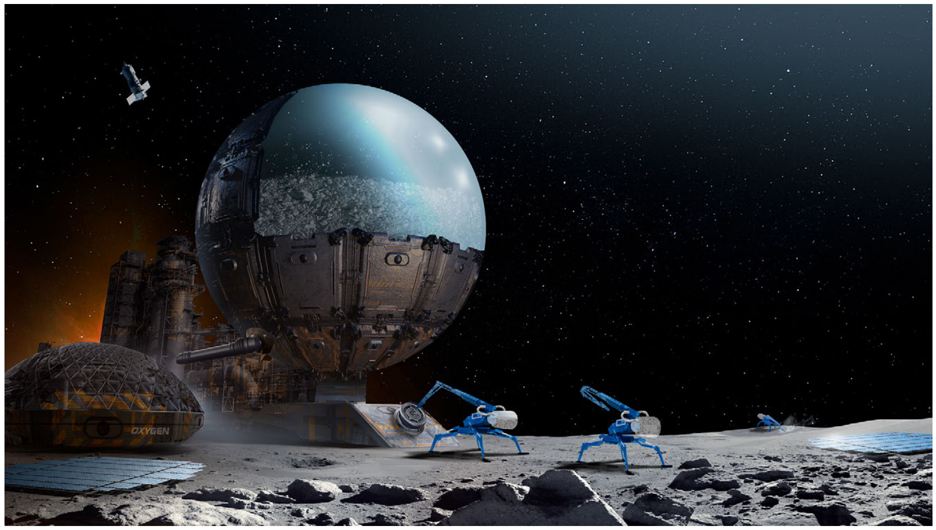

Figure 11. Emergent lunar infrastructure.

Imagine the moon as a thriving cislunar economy based on mining and processing the lunar regolith into structural materials for lunar habitats, solar arrays for energy collection, and fuels for space maneuverability and exploration. Regolith has a variety of compositions that can be separated and processed into functional components. We could create an infrastructure for cislunar operations (Figure 11), fuel for missions to and from geosynchronous orbit, and oxygen for life support, for example. So what can we enable with these lunar resources with a novel discovery platform? Additionally, what if we were to exploit the different atmospheric and gravity conditions on the moon and use those to our advantage during fabrication to make materials that cannot be made here on Earth? And, perhaps, we could also use some of these new materials to solve challenges here on Earth.

APL is already working toward this future of novel materials discovery.[9,10] A multiyear research project has been focusing on disrupting the materials discovery paradigm by accelerating the process and optimizing where to look for novel solutions. We are working to solve critical challenges by discovering new materials and reducing discovery timescales from 10 years to months, weeks, and hopefully even less. There is no way we can make and test all the possible materials, so models are helping us to predict and down-select where in the compositional space we should be looking to even target discovery of new materials. We can then synthesize using high-throughput approaches, characterize the materials, and use the resulting data to retrain the models, closing the "predict-make-measure" loop and teaching the models so that their accuracy improves over time. We have already demonstrated significant increases in throughput accuracy and the rate of discovery.

For proof of concept, we have developed machine learning models to accelerate discovery of superconductors in a targeted fashion. We have predicted, made, and measured many different compositions and closed this loop several times, demonstrating accelerated learning (Figure 12). Additionally, we are developing methods to make better use of the inherently sparse and noisy materials testing data by supplementing those data with computational modeling–generated data. So far, we have rediscovered five materials that were unknown to the training model. We have also discovered, fabricated, and validated a previously unknown superconductor. Though we originally focused on developing models that

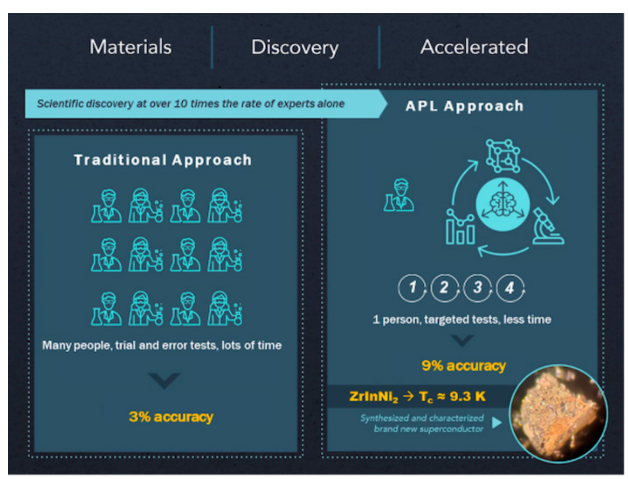

Figure 12. Disrupting the materials discovery paradigm.

can forward-predict properties for superconductors, this framework is extensible to other systems. We are also working to discover low-temperature electrolytes and magnetic materials that do not contain rare earth elements.

Looking forward to APL's centennial, we believe that APL could revolutionize materials discovery and in situ manufacturing. Our grand vision is to integrate AI, accelerate discovery, and overcome the current paradigm of intuition-driven trial-and-error materials discovery (Figure 13). We believe that by integrating AI, machine learning, data management, materials science, and advances in computational innovations—maybe quantum computing in the future—we can begin to discover, design, and fabricate new materials on a much quicker timescale, resulting in unprecedented speed and automation of discovery. And we hope that then, whether we are in Antarctica, on the moon, or even on Mars, we can create new capabilities for our next frontier.

Figure 13. Game-changing materials on demand.

NuX: NUCLEAR FOR EXTREME AND SPACE ENVIRONMENTS

Kaushik A. Iyer

In response to being asked to look 20+ years into the future and prioritize cutting-edge research areas and notional missions, the bidecadal technology disruption we present to you is NuX. NuX stands for Nuclear Power for Extreme and Space Environments.

Imagine a world where we are a spacefaring civilization (Figure 14). What might that world look like? Would it involve expanding sustainable human presence into cislunar space on lunar soil or other planetary bodies, perhaps in some ways that have already been described in science fiction novels and in other ways we cannot possibly foresee today?

This then takes us to a world where we have abundant and replenishable energy, both in space and here on Earth—power that is required for us to truly thrive as a spacefaring civilization. We believe the drive toward pervasive and resilient power sources applicable to both extreme terrestrial and space environments will start to manifest at high technology readiness levels (TRLs) by 2042.

Other nations are believed to have already deployed a miniature radioisotope power system (RPS) on the

Figure 14. Infrastructure for a truly spacefaring civilization takes form.

dark side of the moon or have the capability to do so. The advent of new commercial space entities and investment will drive the development of the radioisotope power and propulsion in space needed to expand the envisioned commercial activities and government operations on the moon in the next 20 years.

The confluence of urgent military competition and commercial capital will cause a shift in government (NASA and Department of Defense) policy to accommodate this technology development at private-sector cost. Government will play a guiding role, owing to numerous potential benefits, will from the private sector, and minimal risk to the government. Twenty years from now, we believe that the institutions that are foundational for a spacefaring civilization will possibly have started to emerge (Figure 15).

Figure 15. In-space power generation technology will drive envisioned futures on the moon, in cislunar space, and in other extreme environments.

One can imagine that we will go from single space-built and -powered satellites to the future that we have just outlined, much in the way that our oceanic shipping industry, born from the craft of building single seafaring vehicles, evolved into building military fleets and then into the present-day massive commercial shipping industry. NuX can do in space in the second half of this century what nuclear-powered aircraft carriers did for the United States in the second half of the previous century.

We expect this world will have its own infrastructure, human presence in space, policy and regulations, and commercial and government activity related to invention, manufacturing, science, defense, and so on, all enabled by pervasive and resilient power sources in space (Figure 16). In this new world, APL can bring the ability to straddle military and commercial space and serve as a trusted head node with a unique ability to demonstrate flagship missions of high technical complexity, define the state of nuclear power technology, and develop a roadmap for safe deployment in space and austere terrestrial environments.

The Space Age began on October 4, 1957, but the Nuclear Space Age began on June 29, 1961, when APL launched the first nuclear power source, Transit 4A.

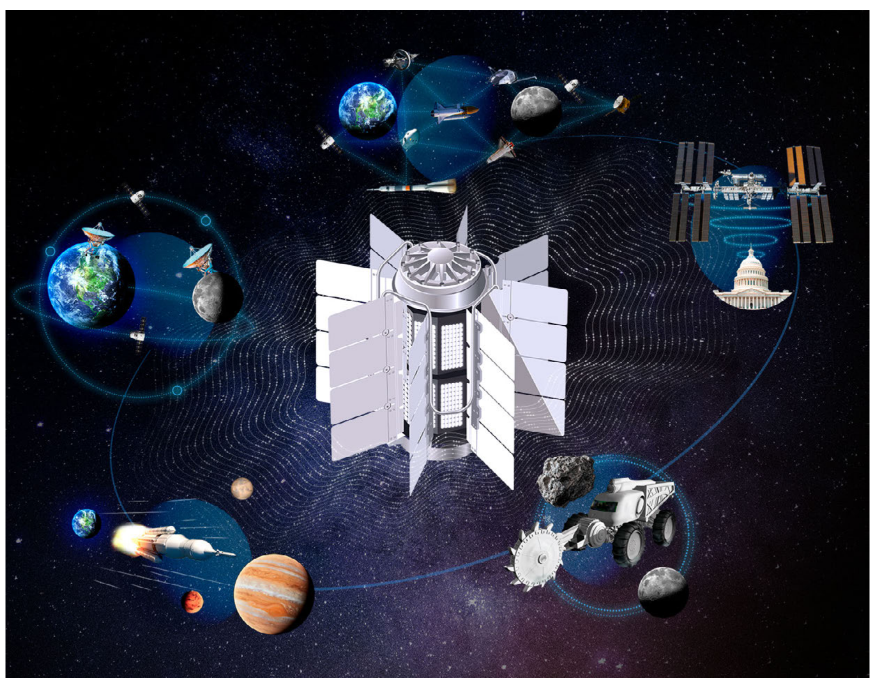

Figure 16. New governance, policies, and institutions will enable human presence, virtual and in person, in extreme environments in ways previously not possible.

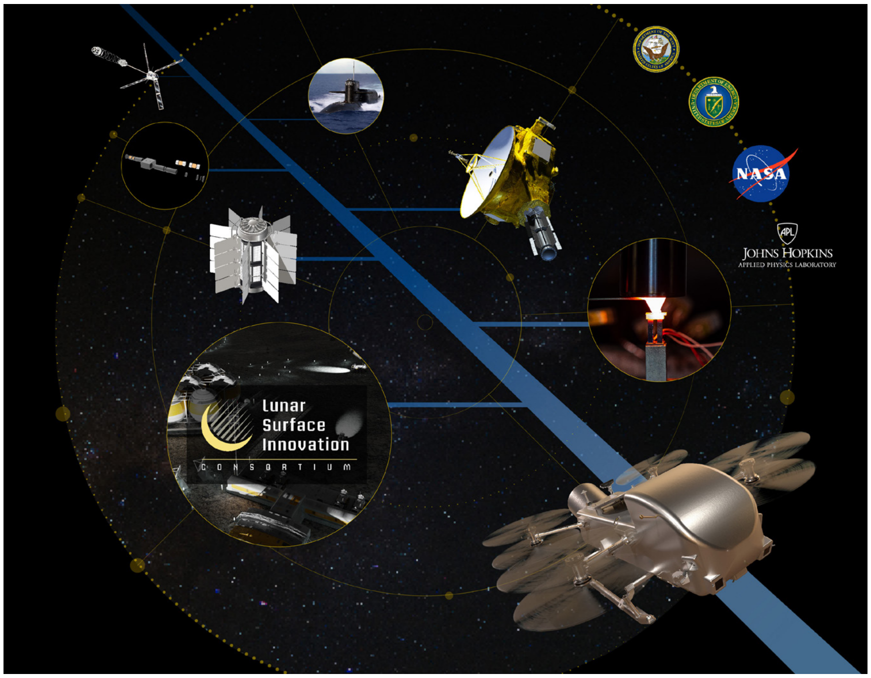

Figure 17. APL's unique legacy in advocacy for, and implementation of, nuclear power technology in extreme environments expands applications into the New Space Age with a focus on national interest.

Think about that—how fast we went from somebody else flying to APL flying a nuclear power source. Four years is all it took. For that launch, APL engineers held that the risk from the radioisotope thermoelectric generator (RTG) was less significant than the risk from the solar cells and the nickel cadmium battery in the power system.

Since that time, APL has continued to contribute to nuclear technology through its work with several sponsors (Figure 17). Transit 4A flew a SNAP-3 RTG, and Triad flew what the Department of Energy (DoE) calls the Transit RTG. APL was also a member of the team that developed the general-purpose heat source (GPHS) RTG that flew on the Ulysses, Galileo, and Cassini NASA missions.

As the 21st century dawned, APL was building the New Horizons spacecraft to go to Pluto and beyond. New Horizons was powered by the GPHS-RTG. A few years after that launch, the core of what became APL's thermoelectric leadership had built the first micro-RTG on a DARPA program called Micro Isotope Power Source. Today this APL team is leading the creation of an advanced version of the energy converter technology[11] at the heart of the GPHS-RTG to enable NASA's outer-planetary missions under design to possibly last past 2050. And consider an example that opens our imaginations even wider: NASA is now trusting APL to build a nuclear-powered quadcopter, Dragonfly, to fly and hop around on Saturn's moon Titan. At APL, the Nuclear Space Age continues.

So imagine all the things we could do as a civilization for humanity, all the critical challenges we could solve, if we could create energy with ease anywhere we want. So how can we do this? Can it be done? The answer is yes, possibly. We start by finding a way to create energy and fuel that creates itself,[12] so to speak, once the process is started (Figure 18). We do this using the sun, and we do it safely. By combining special materials, either sourced from Earth or the moon with a neutron generator, we can generate power in space without fission.

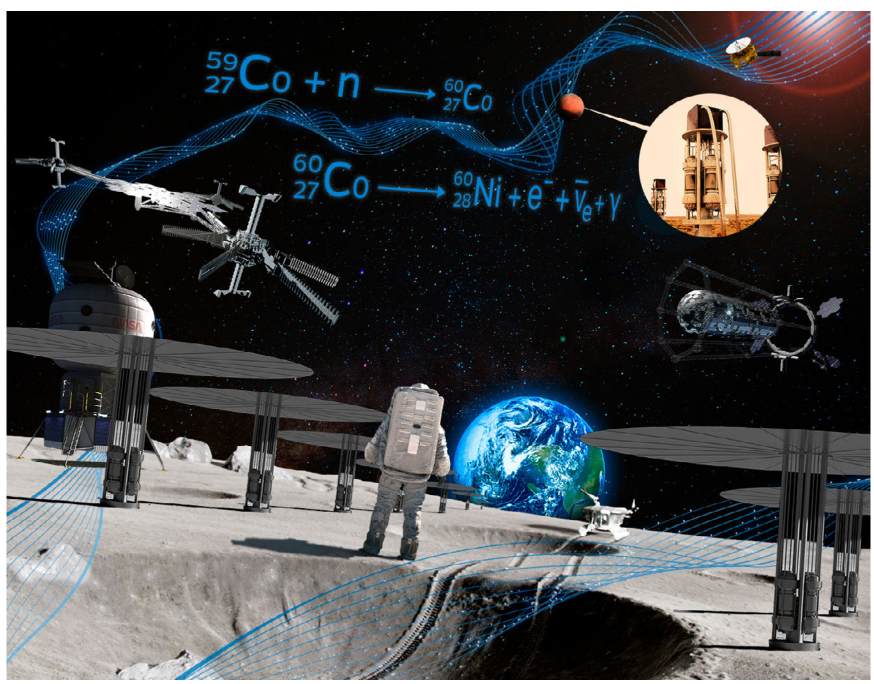

Figure 18. Transforming benign materials into power-generating radioactive isotopes creates opportunities to explore and exploit the New Space Age. (Refer to Lavelle et al.[12])

The core of this technology is in use today in the medical community, in a capability known as the gamma knife, to treat tumors.

SHIFTING HUMAN–MACHINE INTERACTION TO SYMBIOSIS

William G. "Jerry" Bath, Lynn M. Reggia, and David B. Helmer

Figure 19. Humans and machine teammates learning together.

We probably are not quite as far along with this vision as some of the others discussed in this article, but the prediction is that something might happen in the next 20 years that could have a significant impact.

Imagine a world where human and machine teammates sort of grow up together. Today you can talk to your phone, you can talk to your lamp, and you can talk to your car. But imagine that you are now talking to something or communicating with something, or even brain interfacing to something, that is persisting over time and over the thousands of interactions you have when solving problems in your life. It learns what information you need when you are successful and when you are not successful; it learns whether information it provides is what you wanted. And this gradually leads then to an ability to essentially collaborate, for the machine to predict what you need and for you to see things in a context that is provided by the machine.

Figure 19 is a symbolic illustration of this concept. Obviously, the machine is not growing and standing up and walking, but over time, the algorithms and code in the machine are learning about the human, and they are learning enough that the machine can be a true digital teammate.

If we all have these digital teammates, then we can get together to solve a problem. The people in the scenario shown in Figure 20 are trying to solve what is basically a military problem, and everybody is bringing a different perspective. The person on the left is talking about missiles and radars and combat systems. There is another person on the right who is talking about economic sanctions, war crimes, world leaders, and other topics that are equally important. And there could also be someone in the room talking about logistics. These are the kinds of things we do not all understand equally. We are lucky to understand even one of these topic areas.

Figure 20. Human and machines with the same level of understanding.

Figure 21. Distributed collaborative decision-making.

However, each of our digital teammates provides an ability to present that information to us in a way we can understand. And it does that by collaborating with the other digital teammates. The result is that we see the same picture. It will not be perfect, but to some degree we are able to see the same picture.

So now if you can see the same picture, could you work together to solve a problem, not just the *N* humans, but the 2*N* humans plus digital teammates? Imagine a world in which we could do that. And in that world, the 2*N* of us could be superhuman, more powerful than just the humans alone, and super AI, more powerful than just a big computer running AI because we would bring a human perspective to it.

Figure 21 conveys this idea. The left column shows this collaborative decision-making in a nonmilitary setting. For example, when flooding occurred in Kentucky in 2022, we had to bring together first responders, medical personnel, technicians to fix the electrical grid, and people responsible for clearing out the space. All that needed to be coordinated somehow. In another example, Hurricane Katrina, this coordination did not go very well. But the approach of bringing all these people together through their digital teammates and having the teammates collaborate is a way to arrive at a more strategic solution to the problem.

The middle column conveys competition, not yet warfare but competition between states. So now picture the US president and the speaker of the House of Representatives each having a digital teammate, and those teammates can collaborate and present things in their own context. For serious geopolitical considerations, like economic and foreign relations competition, this approach could be hugely beneficial.

On the right is conflict itself, which is what APL mostly works on. In this area, speed is essential. The military has a notion of decision dominance—I can be outnumbered and outgunned but can still win because I have the ability to make better decisions faster. That notion is right in the sweet spot of this digital teammate idea.

So, what are we doing today? Figure 22 shows some examples. As mentioned at the start of this section, we are not quite as far along on this as we are on some of the other predictions discussed in this article. We are just

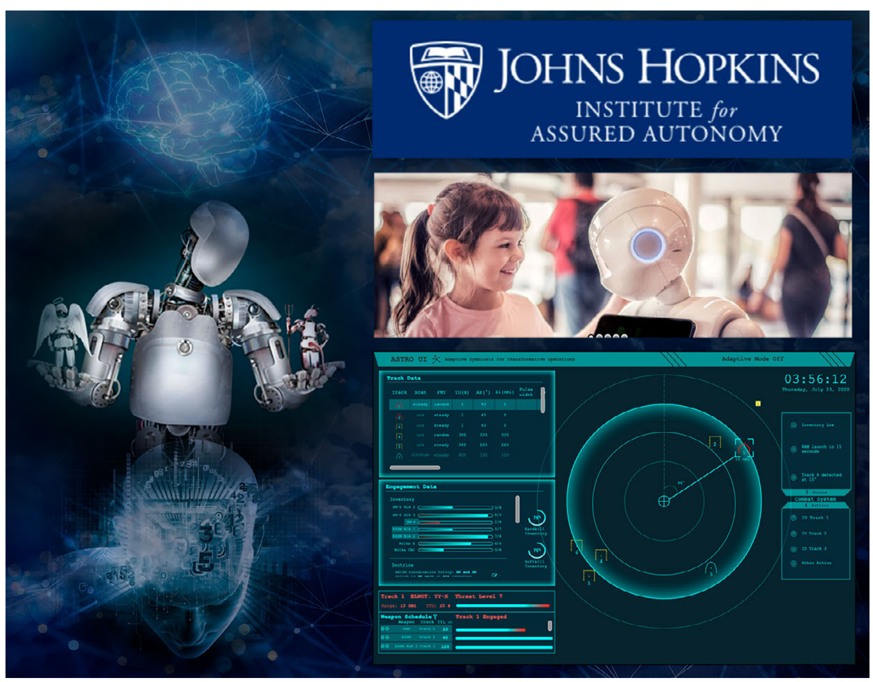

Figure 22. What APL is doing today to shift human–machine interaction to symbiosis.

starting. One of the first things we are doing is trying to get machines to the state where humans can trust them to make decisions. Through the Johns Hopkins Institute for Assured Autonomy (IAA), we are exploring the algorithms in the AI world that could lead to trustworthy interaction. We are also looking at building the facilities and laboratories that will enable us to conduct experiments with warfighters so that we can understand their problems. We are investigating ethics, considering whether we can trust machines to make unbiased decisions. The robotic figure on the left of Figure 22 is holding an angel in one hand and a devil in the other to illustrate the ethics aspect. And, finally, we are building user interfaces. Dave Blodgett talked about a very advanced BCI, but we are also building less-advanced interfaces to facilitate data transfer from humans to machines.

We have made a start, but where could APL go in the long run (Figure 23)? To be frank, I doubt that we will be the place that designs these digital teammates worldwide for everybody. That work will probably come out of the commercial world and be driven by people making money doing it. I think we can assume that someday every 18-year-old who enlists in the military, every astronaut, every medical provider will have grown up with a digital teammate. They will bring that knowledge to the job at hand and to the next job as well. And that will change the whole paradigm of how things operate.

APL's role will be to conduct the critical experiments and development so that those digital teammates are what our soldiers and medical providers and astronauts need for our mission areas. If we can do that, people will be able to evaluate courses of action very quickly, faster than our adversaries, and gain the decision dominance advantage in most of our mission areas. And there are analogies in the nonmilitary cases as well.

Figure 23. APL revolutionizing mission space via human–machine teaming in 20 years.

ASSURED UBIQUITOUS COMMUNICATIONS

Ashutosh Dutta and Nancy F. Andersen

What is going to happen 20 years from now? We are keeping track of what is happening in the world, and we are asking how we can divide communication that can have different verticals—not only military but commercial, agriculture, and health. Communication is the fabric, and we have to develop a fabric that will help evolve this concept.

Three examples are presented here. The first example is communication at a futuristic scale (Figure 24). This example assumes a lot of data, different kinds of networks—low Earth orbit (LEO) and medium Earth orbit (MEO) satellites, different types of cellular networks, and Wi-Fi—and a first responder as the user. The first responder arrives at the scene and starts communicating using cellular communication, perhaps 4G or 5G, and then a hurricane, or some other catastrophic event, affects cellular communication and the tower becomes nonoperational.

At that point, this first responder is communicating with a doctor and is trying to treat a patient. The first responder must be able to seamlessly switch over to Wi-Fi and still maintain priority service for communication. Then the first responder rides with the patient in an ambulance to a helipad and must switch back to cellular when the Wi-Fi network is out of range. Once the helicopter is en route to the hospital, communication switches again, this time to satellite communications. This scenario illustrates handoffs between different types of wireless communication technologies, namely cellular, Wi-Fi, UAVs, and satellite. This communication must be ubiquitous, and secure at the same time, because it may be transmitting patient data and other sensitive information.

How can we make sure the future communication infrastructure is distributed, resilient, and adaptable? There may be a surge of data, so how can we scale the network up and down to support the surge without affecting the quality of service? These are the

Figure 24. Communications at a futuristic scale.

we usually take reactive measures when the attack is happening or after it has happened; we try to determine how quickly we can detect and mitigate or recover from the attack.

We should be focusing on predictive measures—identifying certain predictable traffic behaviors or patterns so that we can anticipate that an attack is coming and prevent it altogether. In what is called a zero-day attack, we have no malware signature or any other knowledge about the attack. We are unaware of the vulnerability the attack will exploit. To mitigate these kinds of attacks, we should be looking at technologies that can predict them. It is important to develop self-learning technologies that can detect attacks proactively, preventing both known and unknown attacks.

interesting questions we need to study, and several APL mission areas are doing just that.

The next example is predictive security (Figure 25). An attack usually targets different parts of the network, not only on the radio network. The 4G-5G network, for example, has different components—radio access networks, the cloud, end devices, and applications. Today

A third example is autoconfiguration (Figure 26). Think back to the example of communication at scale. Consider scenarios like 9/11, Hurricane Katrina, or an active assailant situation. An ad hoc network is set up with perhaps five nodes, and then a lot of people start communicating over that network. High volumes of data need to be transmitted, and the data traffic grows exponentially. The network grows from having one node or 10 nodes to having a thousand or even many thousands of nodes. How quickly can we automate and scale up the network?

Imagine the need for microsecond network auto-scaling and digesting context-free, massive amounts of data—many terabytes of data and many nodes. We need a mechanism that will allow us to scale the network up and down within fractions of seconds; we need automation and orchestration that actually help to scale the network. This is important because mission-critical applications need the support to ensure desired quality of service.

These are just three examples. So, where are we today? What are the enablers? A lot of 5G work is happening at APL in collaboration with others in IEEE and the 3rd

Figure 25. Predictive security.

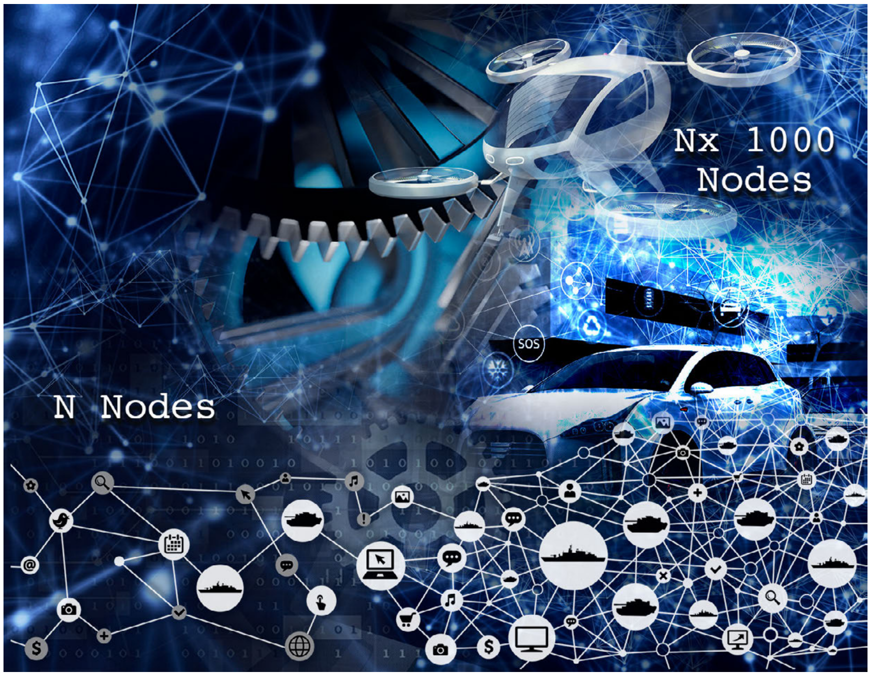

Figure 26. Auto-configuration, big data, and unlimited bandwidth.

Generation Partnership Project (3GPP; www.3gpp.org).[13] This work focuses on converged networks (Figure 27). We mentioned Wi-Fi, cellular, and satellite, but there are also wired networks, like Ethernet (depicted by the RJ45 connector in the figure), or fiber connections. We have the option of using various types of networks based on the availability and application need. Hence, the network has to be ubiquitous and then we can determine how to take advantage of the convergence of wired and wireless networks.

Various next-generation technologies, such as dynamic spectrum sharing, virtualization, and softwarization, do not depend on any proprietary systems or software. Software-defined networking (SDN) can be used to make the network programmable, and mobile edge cloud computing can support ultra-low latency applications, such as remote surgery. We have to take advantage of technologies like network slicing to ensure the quality of service for mission-critical applications.

We have a vision. We know what the state of the art is today. So, as APL, how can we work with the world to explore what we can do 20 years from now? We have seen the evolution of cellular technologies. Every 10 years a new cellular generation has been introduced. We are in the middle of 5G deployment right now, with 5G being deployed in various parts of the world. People have already started looking to 6G, so we should be investing in Next G (Figure 28). APL is a contributing member of the Next G Alliance (www.nextgalliance.org), the third generation partnership program (www.3gpp.org), the Next Generation Mobile Network (www.ngmn.org), and NSF PAWR (Platforms for Advanced Wireless Research) consortium. APL also leads the roadmap efforts within the IEEE Future Networks Technical Community and, hence, is contributing to the evolution of 6G research and standards.

Figure 27. Current state-of-the-art communications technologies.

But to identify and leverage emerging technologies, we need to focus on other areas as well, such as

- quantum communication;
- homomorphic encryption;
- big data;
- predictive security;
- assured autonomy;
- non-terrestrial networks;
- the metaverse;

Figure 28. Opportunities for APL and the world: 20-year horizon.

- terahertz communications;
- AI and machine learning;
- reconfigurable intelligent surface (RIS);
- biologically inspired communications;
- resilient distributed computation;
- distributed smart and programmable networks; and
- Zero Trust.

POSTSCRIPT

Jerry A. Krill

As mentioned, these six visions of the future were presented to interested APL staff at an "APL Showcase" event in August 2022. As also mentioned, several visions could come to fruition commercially without requiring APL to contribute to their development. APL could then leverage these advances in applications as they begin to appear.

For example, as Jerry Bath notes, human–machine synergy (beyond teaming) is likely to emerge from commercial markets, and the best thing APL should do is continue research in conjunction with the IAA to ensure trusted teaming and, eventually if it happens, trusted synergy. Further, as APL develops test bed facilities for studying human–machine partnered combat and command and control systems, we will be in a position to evaluate emerging synergy processes.

Similarly, Kaushik Iyer points out that APL has been a pioneer in using RPSs from the beginning of both the Space and Atomic Ages and will be involved in their use into the foreseeable future, as exemplified by the Dragonfly mission to Titan. Iyer offers that more could be done to transform RPS technology into ubiquitous and safer systems for spacefaring as well as austere environments on Earth. The DoE labs tend to lead such endeavors. In addition to the NuX technologies mentioned above, nuclear fission reactors for space, initially for long-range propulsion, are being jointly developed under DARPA and NASA sponsorship.[14] So, APL may invent some aspects of the emerging RPS technology for our applications and will likely one day be a user, but developing nuclear power systems is not itself a mainline APL mission focus.

Most assured ubiquitous communications technologies and products will be developed by commercial industry as they evolve from 5G to 6G and eventually to 7G in the farther future. Most communications challenges for the extreme distances of space operations as well as the extreme adverse environments, both natural and adversary-induced, in national security domains will continue to require APL contributions. An example is APL's ongoing research to develop a "cognitive communication network" that employs AI to determine the clear channels among a variety of interconnected networks of a military force.[15]

The other three predictions, "Faster than the Speed of Thought," "Coherent Distributed Networks," and "Game-Changing Materials on Demand," are areas that may not find commercial investment. At the time of this writing, discussions are underway for APL to consider investing in aspects of these visions.

How the six visions play out as the future unfolds is anyone's guess. But as Harry Charles points out in his companion article about how the predictions of 1982 unfolded, when APL has been a player in the development of visions, we sometimes tipped the balance in making them become realities. This is an opportunity to see to what extent we can predict, leverage, and even invent the technologies of the future "to benefit our society and improve the lives of people throughout the world" (quoting APL's present Centennial Vision vivid description).

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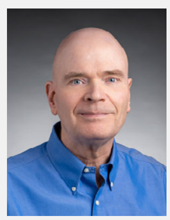

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