Creating Defining Innovations—Great Ideas Overcoming Inertia: Guest Editor's Introduction

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ABSTRACT

The Johns Hopkins University Applied Physics Laboratory (APL) has embarked on a decade-long strategic effort to enhance its level of innovation in an increasingly turbulent world. These initiatives and associated critical contributions reflect a vibrant organization that can look to its future with excitement. Through these pursuits, APL staff members have learned that just having great ideas is not enough. Good ideas are almost never immediately appreciated; persistence is needed to implement those innovative ideas in the face of inertia to maintain the status quo. This article first reviews APL's efforts to overcome inertia in achieving some of its defining innovations. It recalls the persistence and deep expertise that APL has pursued to establish these inflection points in history. It then introduces the variety of articles in this special issue looking toward APL at its centennial in 2042. The expectation is that the breakthroughs these articles describe represent the Lab's future defining innovations.

APL'S FUTURE CONTRIBUTIONS

As APL's 75th anniversary recedes and we look toward the 100th anniversary in 2042, this issue of the *Johns Hopkins APL Technical Digest* is a predictive sequel to the 75th anniversary issue.[1] In that issue, APL director Ralph Semmel describes the nine defining innovations that emerged from APL's critical contributions since its establishment in 1942.[2] That issue also describes a few critical contributions underway today that might be recognized, perhaps by the Lab's centennial, as fundamentally changing the way things are done and, thus, declared APL's defining innovations.[2,3]

Many projects and programs at APL today are exciting, even revolutionary. This issue explores some of these ongoing projects as well as some of the internal investment programs that aim to increase the prospects for creating defining innovations. Of course, many of the truly game-changing developments underway at APL are classified and cannot be written about in the open literature, and APL staff members will create ideas and technologies in the coming decades that are not yet conceived. Therefore, the projects and technologies described in this issue are only examples of current unclassified work that offers a glimpse of exciting accomplishments to come.

NURTURING FUTURE DEFINING INNOVATIONS

What makes a defining innovation? As Dr. Semmel noted in the 75th anniversary *Digest* issue, "The people who make up our past and our present have been responsible for thousands of critical contributions to our nation's most critical challenges, and these include a smaller number of truly defining innovations—game-changing developments that profoundly advance science, engineering, and national security capabilities."[2] Some of our critical contributions are evolutionary, such as a next-generation missile with important new performance attributes. Some are expansionary,[4] such as a deep learning algorithm from one application being retrained for a new application—for example, a machine learning algorithm originally trained to detect and identify threatening objects retrained to read CT scans to identify cancer and dramatically improve the speed of detection. Some of our critical contributions turn out to be game changers—so revolutionary that the practice or operation using the new contribution is fundamentally changed.

APL's strategy for the 2010 decade has been to increase its innovation. Increasing the culture and practice of innovation means increasing the creation and development of revolutionary ideas often beyond the present critical challenges of APL sponsors, anticipating future challenges.

Achieving defining innovations involves not only conception of game-changing ideas but also persistence in implementing those innovative ideas in the face of inertia to maintain the status quo. To paraphrase a 19th-century philosopher, a major new idea goes through three phases: (1) it is first ridiculed; (2) it is then actively resisted; and, after implementation, (3) it is accepted as intuitively obvious.[5] It is important to support truly novel concepts even when there is initial, and sometimes sustained, pushback. Based on descriptions of how impactful APL's nine defining innovations have been, one might be tempted to conclude that these innovations were immediately accepted and their adoption merely a matter of managing the technical risks. That was not generally the case. Some backstories on the difficulties in implementing some of our defining innovations follow.

Acceptance of the Fuze

In 1942 Section T, which had been established in 1940, became APL, part of Johns Hopkins University, to continue development of the proximity fuze, also known as the VT fuze. Installed on the tip of an anti-aircraft gun shell, the fuze would cause the shell to explode when its very small radar sensed the presence of an aircraft. In his book *The Deadly Fuze*,[6] Ralph Baldwin describes the fleet's initial resistance to the fuze, even though it was sorely needed: "They [APL staff] met the usual human attitudes toward a new thing—enthusiastic reception, mild acceptance, skepticism, and even hostility." The book *APL, Fifty Years of Service to the Nation* tells the story of APL's demonstration of the new proximity fuze and a corresponding APL-improved gun director:

> The fleet commander greeted the new weaponry with skepticism. Several previous "improved" gun directors had been sent to his command and failed to live up to expectations, and rather than risk action with another unproven system, he had issued an edict to the Bureau of Ordnance preventing it from placing any new directors on any of his ships. But APL . . . consented to participate in a staged competition against one of the best conventional antiaircraft gunnery crews in the Pacific Fleet to persuade the commander to adopt their system.
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> It was hardly an equal contest. While the Mark 1 guns (on the USS *Wisconsin*) were permitted to fire virtually everything in their arsenal at the targets, the APL-Mark 57 crew (on the USS *Missouri*) firing shells armed with the VT fuzes, was limited to one gun, one director, and four rounds of ammunition per target. Nevertheless, the Mark 57 clearly outperformed its rival, at one point destroying with a single shell a target three miles away. When the commander grudgingly conceded that the Mark 57 had done "pretty good shooting," Elmore Chatham, the leader of the APL target-shooting team, lost his temper. "I was incensed," Chatham recalled. "I said, 'Why Commander, should we knock it down with less than one shot?' But he took it pretty well."[7]

Getting Transit to Operational Service

One might think that invention of satellite navigation would be enthusiastically accepted across the Navy, but that was not the case. "Ironically the concept of a navigational satellite was not greeted with open arms by the Navy hierarchy."[7] According to Ralph Gibson, APL director from 1948 to 1969:

> Most of the Navy at the time thought they could navigate accurately enough, and so they weren't particularly interested in another system. To tell the truth, the rest of the Navy couldn't have cared less . . . Besides, they weren't sure that it would work; lots of people said that it wouldn't.
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> Special Projects, however, knew that its Polaris submarines would require an extremely accurate navigation system. . . .
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> . . . the rest of the Navy refused to accept Transit for a number of years. The Bureau of Navigation (BuNav), in particular, remained hostile to the program because Transit had superseded its own navigation satellite proposal. Unfortunately, the BuNav system involved a large radio telescope with a sizable radar dish and gimbals. BuNav proposed to launch satellites carrying simple radio transmitters that would act as targets for the radio telescope, and since most of this extensive tracking equipment had to be located above decks, the system did not particularly gladden hearts at Special Projects. Although the regular Navy's opposition to Transit did not slow the project in its early stages, largely because of SP's political clout within the service, it did have unfortunate repercussions down the road.[7]

Even engineering and physics seemed to hinder Transit's successful introduction. During the first launch, designated Transit 1A, "the third stage of the rocket

Figure 1. Photo of the front of the AMFAR phased-array antenna. AMFAR was the prototype for the Aegis SPY-1 radar.

failed to ignite sending the satellite plunging into the sea."[7] And "probably the most vexing difficulty arose from an unexpected quarter, when the APL Transit team confirmed that the shape of the earth, especially in the northern hemisphere, was far less regular than previously believed . . . [and] one needed tracking stations pretty much all over the world to get the best out of the system."[7]

Creating the Aegis Fleet

Aegis is presently the backbone of the US Navy cruiser and destroyer fleet. But getting there required persistence in the face of strong pushback. Although APL proved the design of the Aegis SPY-1 phased array-radar with AMFAR (Figure 1), many did not agree with the radical and expensive Aegis design. "Even the Defense Science Board weighed in criticisms: that the system would be too complex, would cost too much, could not be operated by regular sailors, was not focused on the right threats, or could not be done in time were just a few of the complaints."[8] There was a proposal for a new, smaller, less expensive DG-class warship with little room for the radar or missiles.[9] A nuclear strike cruiser concept derived from the nuclear *Virginia* DLG class was determined too expensive for an already expensive combat system. A stretched DD 963 *Spruance* class was finally selected, becoming the CG 47 *Ticonderoga*-class Aegis cruiser. APL's role of providing the technical analysis and test data to dispel repeated political and budgetary misconceptions pulled staff members into these technical debates.

Cooperative Engagement's Long Gestation

What would become the Cooperative Engagement Capability (CEC) began as a "force coordination" concept invented at APL in the early 1970s. For 14 years the Navy funded its concept analysis at a low level, primarily via the Battle Group Anti-Air Warfare Coordination (BGAAWC) program.[10] However, in the mid-1980s it was realized that this radar networking concept could be adapted to solve operational problems that were not anticipated when it was conceived before the advent of the digital age. The Navy then accelerated funding for its development, with much churn and pushback in the process of quickly ramping up. Some of the pushback was the result of needed revisions to established combat system research and development (R&D) and acquisition plans to accommodate the integration and the operational changes that CEC's networking of radars and weapon systems brought to the fleet.

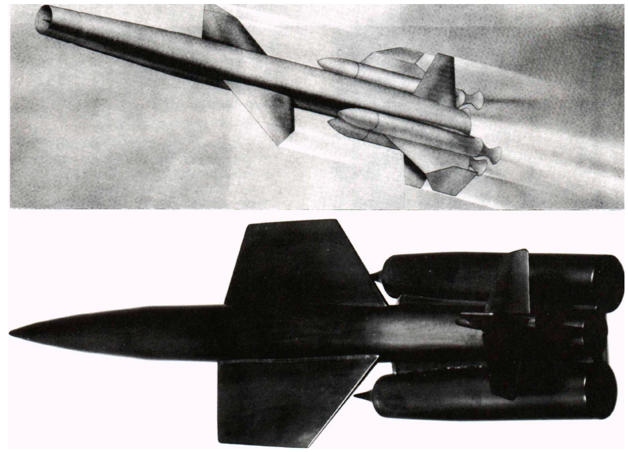

Figure 2. Original Triton concept configurations from the 1950s. The Triton design featured terrain matching that would decades later become a key element of Tomahawk. (Reprinted from Gilreath.[11])

The Long Wait to Make Terrain Matching Guidance Operational

In 1950 an APL team began to work on a ramjet cruise missile called Triton that could fly at high altitude, above Mach 3, for thousands of miles (Figure 2). A special feature of the concept was an approach to follow a terrain map for guidance and control. Despite this feature's revolutionary capability, the project was initially met with resistance:

> The Triton project never made it past the preliminary stage, partly because of competition from the rival Polaris missile, yet a number of significant advances came out of the Triton program. The most notable was the design of an intelligent radar map-matching guidance system—developed in part by the Goodyear Rubber Company—that permitted [the] missile to correct its course in mid-flight by observing the terrain directly below and comparing the data with references and checkpoints on a map stored in [its] computer. Several decades later, a more sophisticated version of this guidance system would be employed in the Tomahawk cruise missile.[7]

The terrain contour matching (TERCOM) subsystem went on to be a major component of the Tomahawk land attack cruise missile. APL's Bill Spohn showed mathematically that the contractor's intended implementation would result in the missile's failure to achieve its target. His analysis, confirmed by testing, led to key design changes that were instrumental to the program's long success.

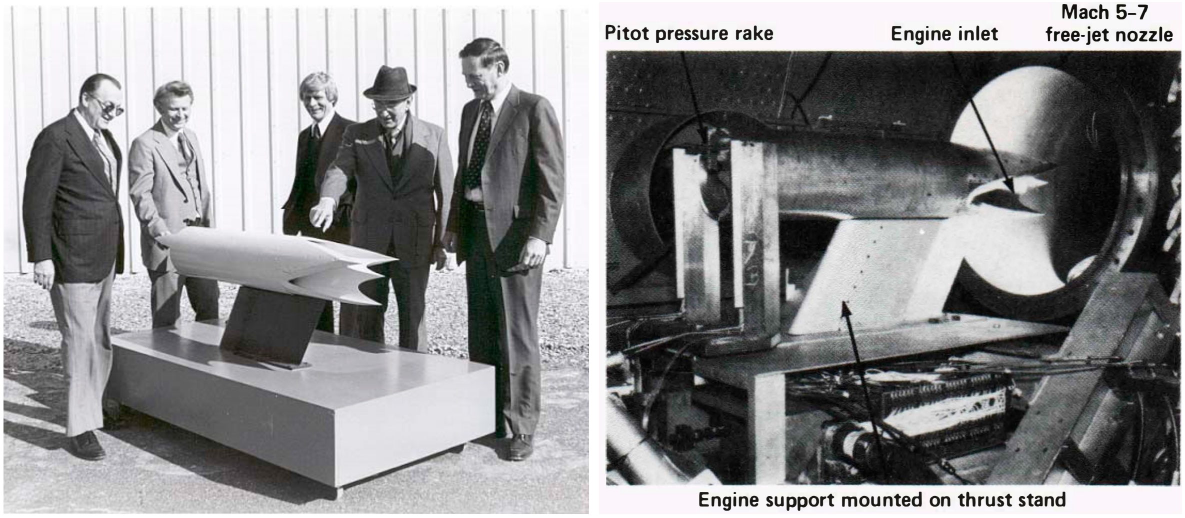

Figure 3. Left, From the APL archives, the APL SCRAM Freejet Engine model; from left to right are Ralph Blevins, Fred Billig, Paul Waltrup, Gordon Dugger, and Jim Kiersey. Right, A scramjet engine model in position for a hypersonic test (reprinted from Keirsey[14]).

Establishing NASA's Discovery Program for More Affordable Solar System Exploration

Today a variety of moderate-cost solar system exploration missions are in development or underway. But three decades ago the cost of each mission was becoming so prohibitive that Congress contemplated a major reduction in scientific exploration. Enter APL's Space Department head and world-renowned planetary investigator Tom Krimigis and his NASA colleague Wes Huntress. Tom believed solar system missions could be much less expensive, and Wes knew that NASA had to try in order to save the future of space exploration.[12,13] Called the Discovery class, missions that are common today were by no means considered feasible back then. Achieving this new mission class required unsettling the status quo at NASA and its key centers responsible for interplanetary missions. It also required APL to step up to win the first proposal for a low-cost mission and then successfully execute the mission far beyond the friendlier near-Earth space region where APL had built and operated its spacecraft for decades.

As described in historical accounts, strong forces pushed back on the approach: bureaucratic inertia, skeptical and even hostile response from the community, and the need to convince people that it could be done. Nonetheless, with clever orbital mechanics to economically reach orbit around an asteroid using a modest launch vehicle, the first Discovery mission, Near-Earth Asteroid Rendezvous (NEAR), was developed and launched rather quickly. Developed and operated by APL, NEAR was bound for the asteroid Eros. However, software glitches prevented the planned rendezvous with Eros, requiring corrections and replanning for NEAR to reach Eros a year later, appropriately on Valentine's Day. The same ingenuity enabled NEAR to land on Eros and operate for some time. This hard-won success changed, in a fundamental and affordable way, how the United States and the world explore space.

Resurgence of Hypersonic Technology

APL began to work on hypersonic technologies in the 1950s with the invention of the supersonic combustion ramjet (scramjet) air-breathing hypersonic engine[11] (Figure 3). It was tested at Ordnance Aerophysics Laboratory, in Daingerfield, Texas, with positive net thrust in 1968.[14] For decades US government funding for hypersonic technology development had been limited despite hypersonics' potential for national security. Today, as the nation steps up to the urgent need to field, and defend against, hypersonic weapons, APL is a leader because, even during this funding lull, it maintained persistent expertise and research capability in this area. APL's critical contributions toward achieving hypersonic flight and hypersonic systems for national defense could result in a future defining innovation (see the article in this issue by Dave Van Wie).

A key lesson from all of these examples is that it is difficult to transition a revolutionary idea into operational use.

Navy Future Vision and APL's Contributions

APL is certainly not the only organization working to spur increased innovation to field revolutionary capabilities. Many of the Lab's sponsors and stakeholders are working toward this goal as well. In 2017 the US Navy published an operational vision looking 30 years into the future, along with requisite science and technology focus areas to achieve the vision.[15] It is an ambitious vision involving artificial intelligence (AI) in nearly

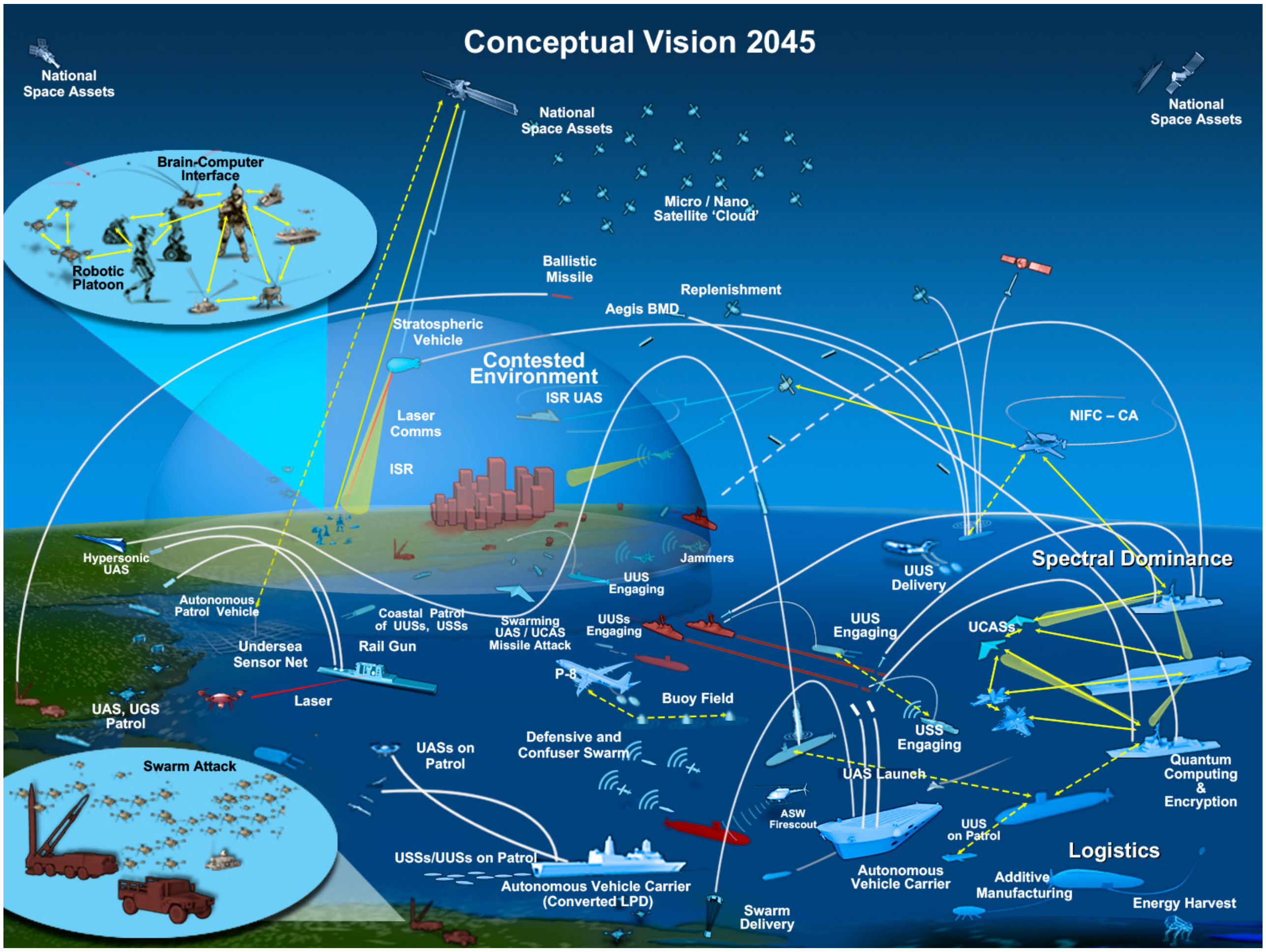

Figure 4. APL collaborated with the US Navy to create a high-level "conceptual view of the battlespace" in the 2045 time frame and a corresponding research agenda. Key features are the prevalence of AI-based systems including a variety of uninhabited vehicles under general guidance of humans in inhabited vehicles and command centers.

every aspect of operations, including a large fleet of uninhabited undersea, surface, and airborne vehicles, in collaboration with inhabited combatants, as well as AI-enabled radio frequency spectrum agility for electronic warfare, sensors, and communications, as illustrated in Figure 4. APL has been instrumental in helping sponsors craft their own visions for the future and worked with the Navy in developing its 30-year vision and research agenda.

THIS ISSUE—IN RECOGNITION OF THE CENTENNIAL VISION

This issue begins with 10 articles about revolutionary concepts and technologies that might one day become defining innovations. These articles cover such advanced topics as the optical noninvasive brain–computer interface (see the article by Clara Scholl et al.), a new capability being developed by APL's National Health Mission Area in collaboration with the Johns Hopkins University (JHU) School of Medicine to apply machine learning to personalized health care (see the article by Alan Ravitz), and an exploratory mission for defending Earth against asteroids (see the article by Elena Adams et al.). Following those articles is a summary, by Ann Kedia and myself, of the innovation initiatives APL has implemented to inspire innovation and creativity.

After these articles is a series of 20 short articles about particularly interesting independent research and development (IRAD) projects that might lead to breakthroughs, led by a perspective on IRAD from Andrew Merkle et al. and followed by articles spanning from neuro-inspired autonomous swarming (Grace Hwang et al.) to Trustworthy Synthetic Biology (Julie Gleason et al.). After this series are articles about strategic pursuits of APL's sectors and departments. Representing the forward-looking pursuits are articles on the future of analysis by Christine Fox and on potential future research explorations by Jim Schatz. APL's Space Exploration Sector is focusing on astrobiology in the coming decades with major missions to Europa and Titan (Kate Craft et al.). Envisioning the future in both combating and leveraging asymmetry is described by Donna Gregg et al., and future challenges to air and missile defense are explored by Vishal Giare and Greg Miller. Challenges and opportunities in communications as they apply to APL are considered by Emelia Probasco, head of the newly formed APL Communications Department.

APL's Centennial Vision goes beyond encouraging revolutionary ideas and strategies; it also ensures a work environment conducive to collaboration and innovation. Several aspects are addressed in special feature articles. Principles for innovation-fostering work spaces, established from global research as well as input from APL staff members, form the basis for concepts for the future buildings and building refurbishments on APL's campus as described by Brian Cornell in the article "APL's New Campus Master Plan."

In keeping with the Lab's Centennial Vision to be a magnet for top talent, Richard Jennings and Luke DeCray anticipate the workforce of the future as APL engages the global innovation ecosystem.

With the increasingly rapid rise—and obsolescence—of technology, our technical staff will need to continually update their education, a process sometimes referred to as "lifelong learning." In partnership with other divisions of JHU, APL is developing a menu of options to support staff members' ability to remain current. Harry Charles describes the options and projected trends, including how the COVID-19 pandemic might alter the future of education.

In addition to partnering with JHU on educational programs, APL increasingly collaborates strategically with other JHU partners on a variety of programs and initiatives. These mutually beneficial collaborations reinforce the university president's One University initiative[16] and one of the elements of APL's Centennial Vision, to be "an integral member of one of the world's finest universities." The two articles that follow Harry Charles's article focus on partnerships with the university. First, Cara LaPointe et al. describe a new institute and related initiatives focused on research and prototyping with the goal of ensuring trust in the increasingly ubiquitous artificial intelligence capabilities. Another key partnership between APL and JHU is in the area of health care. Sezin Palmer et al. describe the long history of collaboration with the JHU School of Medicine leading up to the system described in Alan Ravitz's article, which could revolutionize medicine.

These articles are followed by ideas from APL's Young Professionals Network (YPN)—made up of young and young-at-heart staff members—about what APL will be like a little over two decades from now. The issue ends with a memorial to Ken Moscati, an artist who played an integral part in creating *Digest* issues, this one included, over the last several decades.

As this issue is being written, APL remains in operation during the worldwide COVID-19 pandemic. Heroic critical contributions are underway, both to meet needs resulting from the pandemic as well as to meet the needs of our sponsors under conditions of social distancing and organizational slowdowns. APL is also exploring how to apply new insights from working in hybrid situations, with some staff physically present and others virtually present, in order to create a more flexible, post-pandemic work environment. Through it all, APL staff members showed remarkable resilience in continuing to make critical contributions and in adaptations to further our culture of innovation; some of these stories might be told in a future issue.

FINAL THOUGHTS

As the guest editor for the 75th anniversary issue,[3] I noted that long-time APL leader Al Eaton, a former associate director who came to APL in 1945, had observed that the vibrant culture of APL in the 1940s and 1950s was alive and well in the 2010s. I predict that when the 100th anniversary comes along, a long-time staff member will opine that the APL culture by then is even better than it was in 2021, having achieved the aspirations of the Lab's Centennial Vision.

Our world is rapidly changing in many dimensions. These changes bring emerging challenges with implications to the world, such as climate change; increased individual access to technologies once accessible only by nation states; new states of matter and new phenomena; increased commercially funded research worldwide; commercial space exploration ventures; espionage and cyberattacks with increased sophistication and proliferation; increasingly autonomous health care leading to more medical research breakthroughs; and increasingly AI-driven weapons being developed by nation states. Short of the world war situation that gave rise to the proximity fuze, there has never been a greater need for creative and persistent innovations to maintain this country's preeminence. In the face of these challenges, APL is finding new ways to explore, create, and collaborate to conceive revolutionary concepts and to persistently move these concepts forward. In the coming decades APL will continue to impact the world with its innovations.

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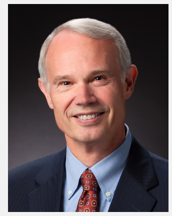

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