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THE OFFICE OF
NAVAL RESEARCH

MAKING AVIATION
READINESS MORE
PREDICTABLE

FLIP STOOD TALL

REIMAGINE NAVAL POWER:
READINESS
AND THE
FUTURE
FLEET

OFFICE OF NAVAL RESEARCH
75th ANNIVERSARY
1946 — 2021

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SPEAKING
OF S&T ▶▶ By Dr. Douglas Blake

It sounds paradoxical, but in order for the US Navy and Marines to maintain their dominance in the future, they must begin laying the groundwork today. This involves maximizing the talent pool in their uniformed and civilian ranks, enhancing the effectiveness of their technology and warfighting capabilities, and fostering innovation in their scientific and technological research.

In the recent issue of the prestigious US Naval Institute *Proceedings*, Chief of Naval Research Rear Adm. Lorin C. Selby penned an article (included in this issue of *Future Force*) about the significance of the history of the Office of Naval Research (ONR), which is in the midst of commemorating 75 years of service to the Navy and Marines. In tandem with this look at the past, this issue also includes Rear Adm. Selby's call for reimagining naval power for the future. He states the Department of the Navy (DoN) is operating under an 80-year-old force structure that has not been tested against a great power competitor since World War II. Moreover, technology has changed dramatically in the last two decades, thanks to the digital revolution—and the sea services must keep up to maintain their superiority.

Selby writes, "These technological changes profoundly altered the principles on which organizations must operate to be successful in the digital paradigm. As the United States finds itself engaged in a great power competition with Russia and China, we must ensure that we possess the naval capabilities to deter our adversaries and, if necessary, defeat them."

To accomplish this, Selby highlights the need to bring capabilities together in novel ways and change the way we solve operational problems. For decades, the DoN focused on building large, complex systems that are too expensive to generate in mass. In the future, Selby says we must create a Strategic Hedge, or backup plan, that focuses on "the Small, the Agile and the Many." Selby calls for dozens, hundreds or even thousands of unmanned systems to augment warfighting capabilities. These systems can be constructed, tested and adapted quickly; can be built in large numbers; and are less expensive than larger platforms. They also can be outfitted with a variety of sensors and payloads for diverse missions.

Both of Rear Adm. Selby's articles tie in perfectly with the overarching theme of this *Future Force* issue—Readiness and the Future Fleet. Topics range from ONR's 75-year history of contributing to DoN and the nation, to the importance of training and maintenance in keeping the fleet and force in good working order, now and in the future.

Meet experts from Naval Surface Warfare Center Dahlgren Division who are engaged in projects as wide-ranging as anti-drone lasers and workflow methodologies that have been compared to a pizza delivery tracker. Learn how data scientists at Naval Information Warfare Center Pacific are improving air readiness. Read about how the Marine Corps is strengthening its additive manufacturing capabilities.

These are just some of the compelling stories spotlighting the efforts of ONR, the Naval Research Enterprise as a whole, and their partners in industry and academia to ensure US warfighters can respond to future challenges with characteristic agility and resiliency. I hope you enjoy reading them and are inspired to discover that next breakthrough innovation to equip our Sailors and Marines.

Dr. Blake is the acting executive director as well as the head of the Aviation, Force Projection, and Integrated Defense Department of the Office of Naval Research.

READINESS AND THE FUTURE FLEET

Readiness—defined by the Department of Defense as efforts that "train qualified people and prepare working equipment to be deployed, operate, and ultimately recovered"—and innovation are sometimes seen as, if not opposites, at least decidedly different endeavors. Maintenance signifies stability and predictability; change conjures images of chaos and movement. The Navy and Marine Corps require the judicious and thoughtful implementation of both imperatives. Even as the fleet and force are changing as never before, the needs of readiness—to train, to fix, to maintain—remain as essential as ever.
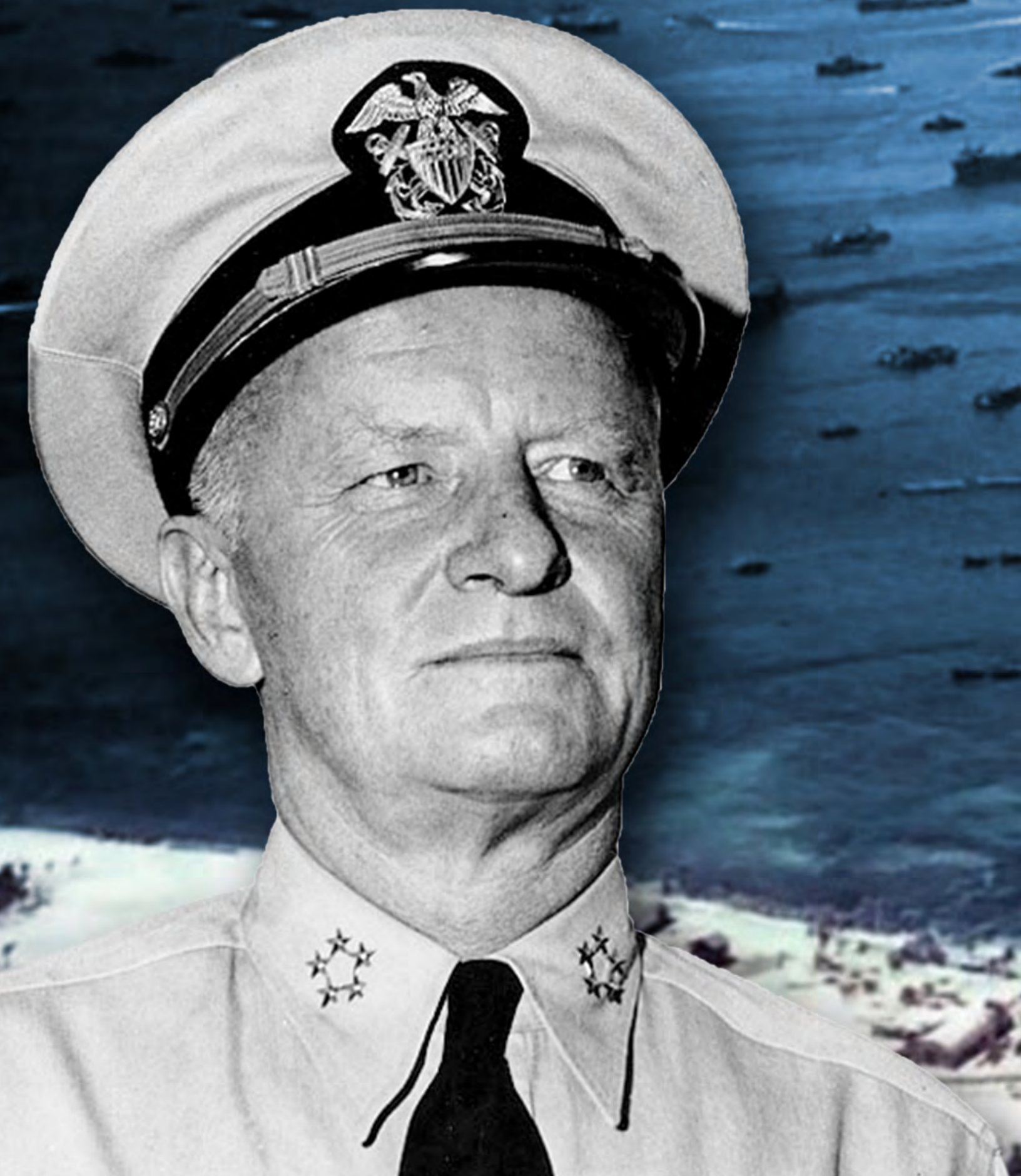
OFFICE OF NAVAL RESEARCH:

75+

YEARS

OF

TECHNOLOGICAL ADVANTAGE

FOUNDED JUST AFTER WORLD WAR II, THE OFFICE OF NAVAL RESEARCH HAS CONSISTENTLY ADVANCED KEY TECHNOLOGIES THAT LED TO WAR-WINNING CAPABILITIES FOR THE DEPARTMENT OF THE NAVY. ITS ONGOING EFFORTS WILL BE KEY TO US SUCCESS IN 21ST-CENTURY STRATEGIC COMPETITION.

As the long conflicts of World War II at last came to an end in 1945, Fleet Adm. Chester Nimitz—one of the greatest naval strategists this nation has ever known—commanded the largest naval armada the world had ever seen. With the United States now the unquestioned leader of the free world (actually coming out of the war with far greater strength than going in), it would have been reasonable for Nimitz, and the rest of the world, to believe the United States was holding all the right cards to ensure continued dominance.

Yet Adm. Nimitz knew resting on laurels would not win tomorrow's battles. The United States had seen dark days during the war—times when the enemy's technological capabilities had surprised the Allies and led to significant losses in battle. Those surprises started with the attack on Pearl Harbor, when not only the attack itself was a surprise, but the accuracy and power of Japanese torpedoes caught the US Navy off guard. (It would take us a year to catch up on that front alone, an amount of time we will likely never have again in modern conflict.)

Tech surprise came into play also in the Atlantic, where early on German U-boats operated with near impunity until allied anti-submarine capabilities came of age. Even toward the end of the war, the adversary in Europe was working furiously to develop new capabilities for revolutionary V-2 rockets—the world's first long-range, guided ballistic missiles.

Thankfully, the United States had made dramatic technology advances through new partnerships with industry, academia, and allies which proved crucial to victory. Radar played a critical role in success in the battle for the Atlantic and beyond. The Manhattan Project assembled some of the world's greatest minds and developed the atomic bomb. US industry and government paired up as never before to create multiple new platforms to dominate land, air, and sea, and manufactured them at a scale never seen before. Crucial new materials, such as synthetic rubber, while lacking the star-power of new carriers or bombers, nonetheless played key roles—as did new medical technologies, advances in computers, and even duct tape.

Adm. Nimitz and other key leaders knew that the recent past underscored the importance of imagining the future. And that would extend to the Navy itself. "There will always be a Navy," he said, "Not necessarily a Navy of battleships, or submarines, or carriers, but a Navy in the sense of what the word Navy truly means . . . what the future Navy will be like, we cannot say as yet."

Against this backdrop, in 1946, Congress created the Office of Naval Research (ONR). President Harry Truman signed the bill into law in August 1946—a little over 75 years ago. The bill's instruction for the new organization: "to plan, foster and encourage scientific research in recognition of its paramount importance as related to the maintenance of future naval power, and the preservation of national security."

Since its founding, ONR has produced incredible results. ONR sponsored-research has played a key role in the development of GPS, radar, computers, new uses for gallium nitride, new autonomous surface, sub-surface, and airborne platforms, virtual training, tropical cyclone prediction, directed-energy weapons, stealth capabilities, and so much more. The raw knowledge coming out of ONR over the years has been astounding: More than 70 Nobel Prize winners have been sponsored by ONR; in many cases, they have thanked ONR directly for pivotal guidance and partnership.

Impressive as its history is, and as exciting as today's technologies are, the people of ONR cannot be satisfied with what we have already accomplished. We must continue to forge ahead with an ongoing call to intellectual arms. Today, the Department of the Navy and the nation require us to reimagine naval power, and recognize that, across the Navy and Marine Corps, we must change to maintain naval dominance. Monumental efforts are needed, in the spirit of people like Adm. Hyman Rickover, whose singular focus brought about the nuclear-powered Navy, despite entrenched bureaucracy seemingly designed to slow down dramatic change. I recently introduced the concept of a new "hedge strategy" for the Navy, where newly developed, autonomous platforms and sensors on thousands of unmanned vehicles—the small, the agile, and the many—will complement the Navy's powerful carriers, aircraft, and submarines. Noted entrepreneur Steve Blank wrote about this strategy in Proceedings earlier this year.

Our nation and the Navy are the better for ONR's first 75 years of research and development. We must act just as boldly today because what happens in the next 10 years in science and technology may well determine the next 100 years of history. We are at a
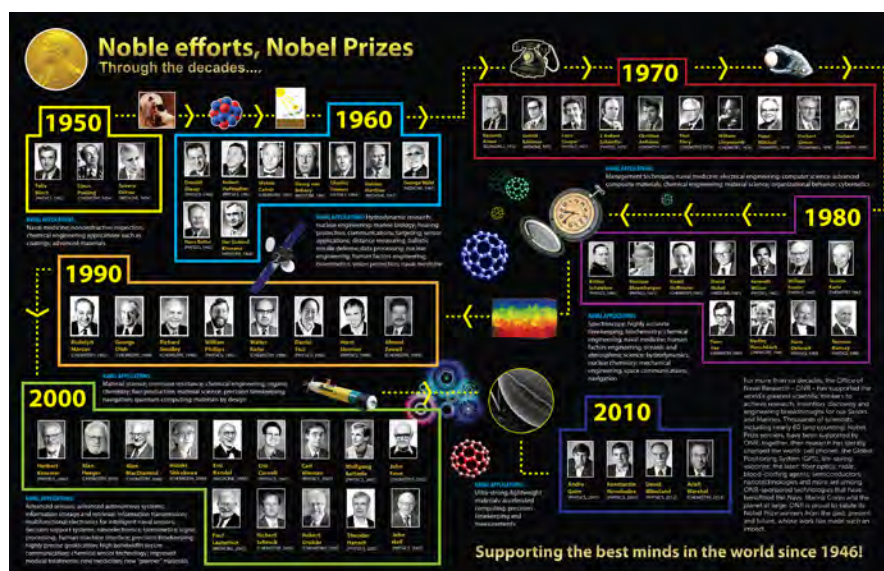
From advanced computing to precision navigation and timing to materials science, the Office of Naval Research has supported the efforts of dozens of Nobel laureates through the past eight decades.

pivotal moment—and technologies being developed now are going to be akin to James Watt's steam engine and the subsequent Industrial Revolution that changed the world. Artificial intelligence; autonomous and unmanned capabilities; quantum computing; directed energy; materials science; and biotechnology are today's equivalents. And, too often-overlooked, the workforce development and STEM educational efforts that drive those advances are what will ensure the US Navy and Marine Corps maintain their edge and ensure a safe and secure nation and global commons.

1946-2021

Eight months before Winston Churchill declared at Westminster College in Missouri that an "iron curtain has descended across" Europe, US naval officers ensured that the postwar Navy would have the services of the first military organization dedicated to advancing civilian science and technology for future readiness. Originally founded on a temporary basis in July 1945 as the Office of Research and Invention on the authority of the Secretary of the Navy and the War Powers Act, the new organization was the product of what had been learned from the national mobilization of science for the war.

Soon renamed the Office of Naval Research, the command had a revolutionary mission: to support science in the interest of national security, in peacetime as well as wartime. As had Nimitz, Vice Adm. Harold Bowen, the first Chief of Naval Research, championed the argument that readiness was no longer something that could happen after a conflict had begun. Enduring technological advantage was a national security imperative.

As the Naval STEM Executive, I believe that maxim has never been truer. To maintain that technical advantage, we need to view our naval STEM workforce as a matter of national security. Our edge will continue to come from great ideas; the great ideas will come from a unique, diverse workforce; but that STEM-inspired workforce will not just magically appear—it must be supported and nurtured. Holistically,
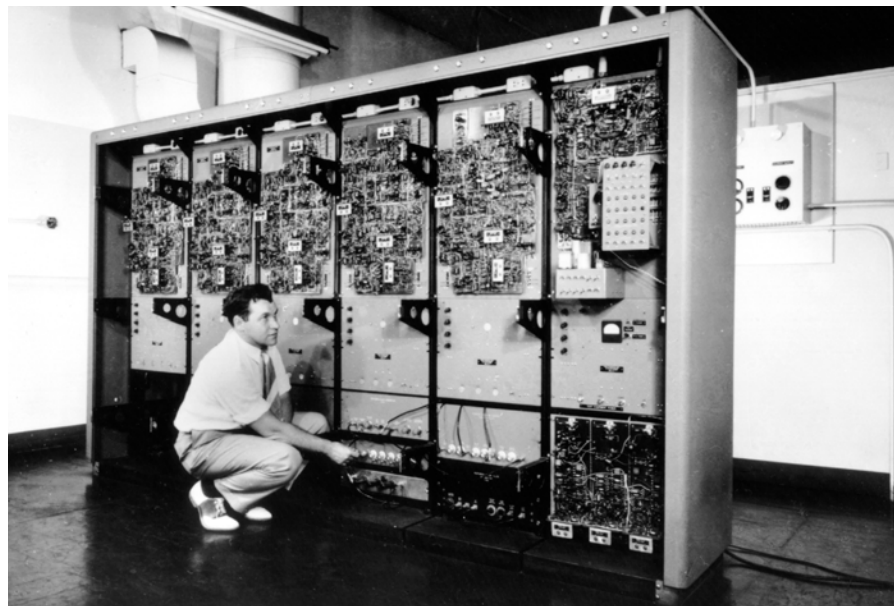
One of the early advanced computing efforts supported by ONR was Project Whirlwind. Photo courtesy of Computer History Museum

if we are to succeed in a rapidly-changing technological landscape, our brightest young minds in general—and formal educational organizations, including university STEM programs and historically black colleges and universities and minority-serving institutions in particular—must be viewed as national assets. Within the Naval Research Enterprise—which includes ONR, ONR Global, the Naval Research Laboratory and PMR-51—we are prioritizing support to these programs as foundations of the future.

Across the globe, determined adversaries are rapidly developing advanced weapon systems, shrinking (or in some cases overcoming) the capability advantage U.S. forces have long enjoyed. To maintain or regain our edge, ONR is engaged in scientific and engineering efforts from the ocean floor to space.

Let's start with the oceans. It is here that ONR made some of its most well-known impacts. Indeed, the field of oceanography itself likely would not exist as it does today without ONR's early and persistent investments after World War II. Early efforts in wave prediction and acoustics, many headed by the late "Einstein of the Sea," Walter Munk, contributed to our understanding of the oceans and expertise in undersea warfare. Marie Tharp and Bruce Heezen developed the

first comprehensive three-dimensional map of the seafloor, which was essential to the later formulation of the theory of plate tectonics. Sponsored research in deep-submergence technology resulted in the record-breaking dive to the bottom of the world's ocean in 1960, when Navy Lt. Don Walsh and explorer Jacques Piccard went to the bottom of Challenger Deep in the Mariana's Trench on board the bathyscaphe Trieste.

It didn't stop there. ONR's support for basic research in the 1970s resulted in the discovery of undersea hydrothermal vents, and an entirely new form of life sustained by chemosynthesis—work led by Robert Ballard. And the latest generation of networked sensor platforms, such as floats, gliders, and remote vehicles, originally developed with ONR support to study ocean dynamics and climate change, provides the means for real-time maritime domain awareness today.

In addition to discoveries in the oceans, ONR continues to lead in developing the vehicles, sensors, platforms, and ships that make all these discoveries possible. These efforts include everything from building submersibles such as Alvin, launched in 1964, and unique vessels such as the Floating Instrument Platform (FLIP), to providing many of the nation's largest ocean-going research ships such as the venerable

R/V *Melville* (AGOR 14) and R/V *Knorr* (AGOR 15), each of which provided more than 40 years of service, and the current R/V *Sally Ride* (AGOR 28) and R/V *Neil Armstrong* (AGOR 27).

ONR's impact goes beyond marine sciences. One of its earliest projects in the 1940s, Project Whirlwind, resulted in the first digital computer capable of real-time computing. Originally intended to control a next-generation flight simulator, Whirlwind would eventually be incorporated as the heart of the first strategic air defense early-warning system. Today, nearly every device that contains a real-time computing device—from the computer in your car to the servers that monitor daily shipping traffic—owes something to ONR's early work in digital computing.

ONR-sponsored research aided in the development and enhancement of the atomic clock, an essential and necessary component to the satellite navigation systems upon which so much of modern life depends. Early investments in directed energy supported the research of Charles Townes, who invented the microwave amplification by simulated emission of radiation (maser) in the 1950s and contributed to later development of the light amplification by simulated emission of radiation (laser). Those investments came full circle in 2014, as ONR deployed the first laser weapon system on a warship, the USS *Ponce*

(AFSB(I) 15)—and today has put a far more powerful laser aboard USS *Portland* (LPD 27). ONR-sponsored research in railguns over the past decade resulted in a series of record-breaking kinetic milestones with this next-generation technology. And, ONR has long been at the forefront of new materials for nearly every environment, from explosive-resistant coatings for vehicles and ships, to highly conductive materials such as gallium nitride—found in nearly anything with full-color LED lighting and, more significantly, in high-power radars and electronics.

Warfighter protection efforts have been front and center as well, with significant military and societal significance. Medical research sponsored by ONR has included everything from the SeaLab underwater habitats that helped us understand human interactions underwater, to more recent automated trauma monitoring systems, virtual reality PTSD treatments, and QuikClot, a wound dressing that accelerates blood clotting. Indeed over the years, ONR has supported an array of technologies that have directly benefited Marines, from wearable tactical energy systems, mobile power and logistics systems, to next-generation tactical ground vehicles.

Our work in unmanned systems has led to enormous success and even greater promise ahead—but it is

worth noting it took decades to get to the point of such groundbreaking autonomy exercises as the Integrated Battle Problem 21 (IBP21), where over 30 autonomous platforms were successfully tested in blue water operations. Beginning with some of the earliest investments in artificial intelligence that resulted in the first autonomous robot, Shakey, at Stanford University in the 1960s, ONR has been a leader in building and improving autonomous vehicles, automated decision-making, and human-robotic teaming and interactions. This year, our new SCOUT initiative—a novel partnership with the Joint Interagency Task Force-South—will provide impressive new autonomous capabilities to support narcotics interdiction efforts.

ONR's importance to American science and technology extends beyond research and new capabilities—indeed, the organizational infrastructure that ONR uses to support research and innovation has been replicated across the Department of Defense and beyond. The first deputy chief of ONR, Alan T. Waterman, had served as the director of field operations for the Office of Scientific Research and Development during World War II, and would become the first director of the National Science Foundation when it was founded in 1950. Our peer organizations—the Army Research Office, the Air Force Office of Scientific Research, and the Defense Advanced Research Projects Agency—were founded during the Cold War using the same S&T management principles pioneered by ONR.

Over the decades, a wide range of warfare centers, laboratories, and university-affiliated research centers, have been established and grown into a diverse S&T network, dedicated to advancing innovation. Of all ONR's many legacies, collaboration between institutions and organizations—military, industrial, and academic—is perhaps the most profound and longest-lasting. Fostering an environment of partnership, from the Naval Research Laboratory and ONR Global, to our sister organizations throughout DoD and beyond, has proven time and again to be essential to advancing modern science and technology.

ONR funded the deep ocean research accomplished with the bathyscaphe Trieste in the 1950s and 1960s. Here Don Walsh speaks at the 60th anniversary of the Challenger Deep dive in January 2020. Photo by John F. Williams

The Floating Instrumentation Platform (FLIP) is owned by ONR and operated by the Scripps Institution of Oceanography. Photo by John F. Williams

Moving Forward

As impressive as the organization's history is, we will not rest on our laurels. The challenges facing our Nation today are grave. To ensure continued deterrent-level dominance over increasingly sophisticated state and non-state actors, we must in this decade overcome our own well-intentioned bureaucratic hurdles, which may have once been useful but are no longer. As happens periodically, there come tipping points where what has worked well in the past—how we operate both internally as well as externally with our partners—is no longer effective.

In that spirit, ONR has expanded its paradigms and vision. In the early decades, ONR was optimized as a basic research organization focused on discovery in universities and basic research institutions. In the 1980s and early 1990s, though, as the Cold War was ending, ONR took on more applied research and advanced technology development. In the past 30 years, we have added new ways to approach innovation. Examples include: TechSolutions, which takes ideas from Sailors and Marines to swiftly produce working prototypes; Future Naval Capabilities, which accelerate cutting-edge technologies into the fleet and force; and Innovative Naval Prototypes, which take seemingly "over the top" ideas, technologically, and explores finding the next game-changing capability.

Innovation is not only about platforms or technologies. We must also rethink how we do business. For some programs, it will take decades to "get there." But for others, our research is so close to maturity that we simply cannot accept slow contracting processes, constrained funding lines, and inability to get on ship modernization schedules. Our sailors and Marines need capabilities now. We can better utilize tools that already exist to get things done—including newer forms of funding, such as Partnership Intermediary Agreements (PIAs), Other Transactional Authorities (OTAs), hackathons and prize challenges, new internships, and creative academic programs such as multidisciplinary university research initiatives (MURIs), and more, all of which can accelerate innovation deliveries.

One of the key ways we're doing this is through our Naval X program, with its associated Tech Bridges. At its essence, Naval X is a new way of inspiring collaboration and fostering new paths for new ideas. The Tech Bridges, envisioned as a new kind of collaborative workspace and uninhibited idea factory, have taken off around the country and now, around the world, with new ones in London, U.K., and Yokosuka, Japan.

Too often, projects fail to move from advanced technology development to component development and prototyping. Bureaucracy and complacency are powerful and omnipresent, poised to grab onto promising projects and stymy them. We must overcome these obstacles—go around them, over them, and do whatever it takes to defeat them. I do not have all the answers on how to do that, but we are making progress and eagerly looking to new ways of doing business. If you have a great idea, the Naval Research Enterprise wants to talk with you.

As I meet with thought leaders around the country, including author and entrepreneur Safi Bachall, MIT lecturer and author Steven Spear, process guru Steve Blank at Stanford, and other brilliant folks from government, industry and academia, I am hearing excitement about what ONR is trying to do and agreement that the time to act is now.

As it has for 75 years, ONR is pursuing the future with a sense of determination, and optimism. Yes, our adversaries are moving quickly, fielding new technologies and weapons faster than they have ever been. But ONR is answering the challenge with a sense of optimism. Working with civilian universities, industry large and small, other government labs, and our allies, we will continue to provide the technological edge that allows the U.S. Navy and Marine Corps to adapt, survive, and win.

About the author:

Admiral Selby is a career submarine officer and the 26th Chief of Naval Research.

THE SMALL,
THE AGILE,
AND THE MANY:

REIMAGINE NAVAL POWER

By Rear Admiral Lorin Selby, USN

A MODERN NAVY DESERVES A MODERN FORCE STRUCTURE. GENERATIONS HAVE PASSED SINCE THE DAYS OF WORLD WAR II, BUT THE NAVY STILL LIVES IN THE WAR'S SHADOW. WE MUST REIMAGINE SOMETHING NEW.

Our Navy operates using an 80-year-old force structure that has not been tested against a great power competitor since World War II. Technology has changed significantly over the past 80 years, however, particularly with the advent of the digital revolution. These technological changes profoundly altered the principles on which organizations must operate to be successful in the digital paradigm. As the United States finds itself engaged in a great power competition with Russia and China, we must ensure that we possess the naval capabilities to deter our adversaries and, if necessary, defeat them.

If carrier strike groups composed of the large and the complex do not turn out to be the dominant naval formation of the 21st century, we must have an alternative—a strategic hedge. Therefore, the Office of Naval Research (ONR) is going to build out a novel naval formation made of the small, the agile, and the many. This means going beyond mere experiments and war games; it means building out new formations composed of dozens, hundreds, or even thousands of unmanned vehicles above, below, and on the ocean surface using digital principles. ONR will not do this alone, instead tapping existing sources of innovation through partnerships with our allies and American industry. Ultimately, ONR will demonstrate a viable naval formation that can be fielded in conjunction with existing formations or, if necessary, independently.

Naval Power Today

ONR has a congressional mandate to conduct "specialized and imaginative research" to ensure "the maintenance of future naval power, and the preservation of national security." To fulfill this duty, ONR takes a wide range of factors under consideration to execute research programs that don't just follow the current trajectory of naval power, but steer that trajectory in directions beneficial to the United States.

Over the past 80 years, humanity has seen the most rapid period of technological change since the industrial revolution with the introduction and exponential growth of digital technological paradigms such as mobile computing and the internet—an era branded as "the digital revolution." Over that same time period, US naval power has been and continues to be centered

2021 PORTFOLIO
PRIMARY ASSET

Our primary naval formation is based around carrier strike groups—a core concept that has changed little since World War II. Photo by MCSN Larissa T. Dougherty
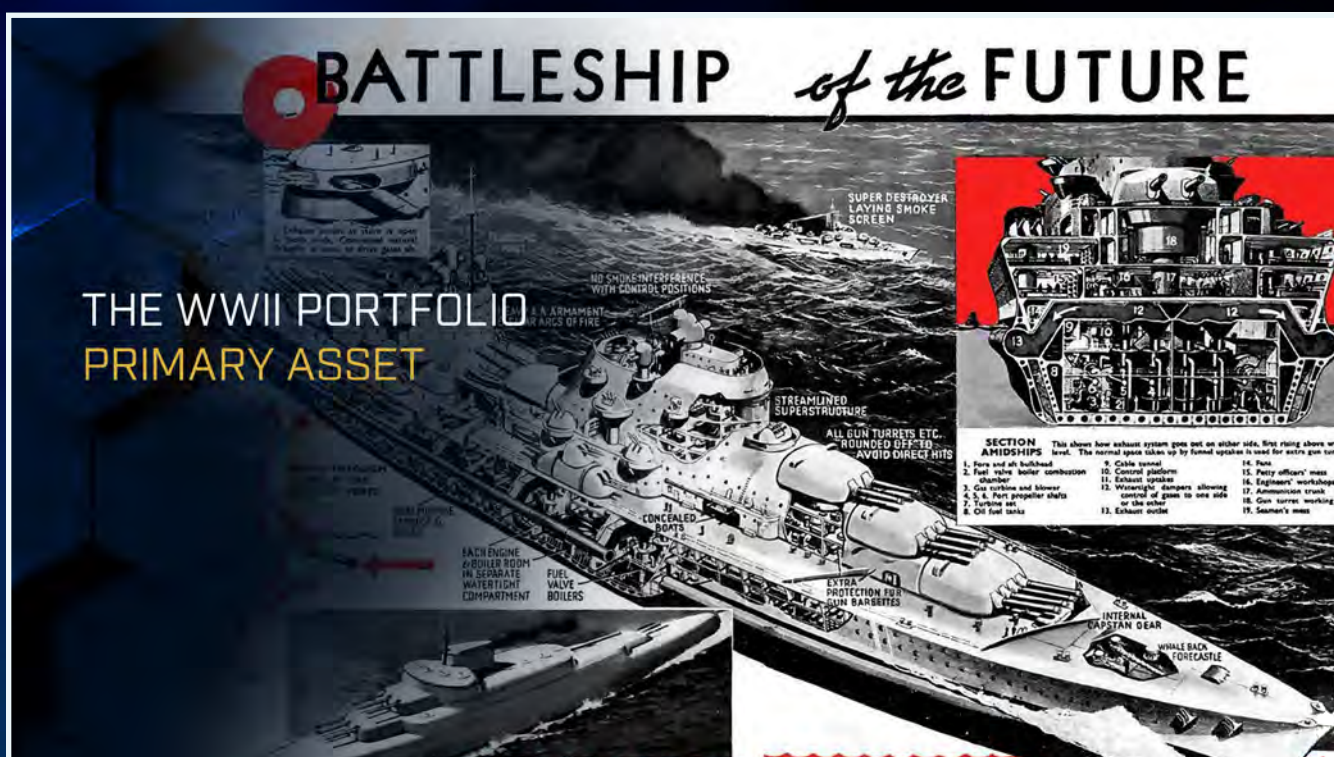
This illustration from the September 1940 issue of *Popular Mechanics* touted a British engineer's drawing of the "battleship of the future." At the time, the battleship was the dominant naval asset and conventional wisdom suggested this would continue long into the future.

on carrier strike groups supported by submarines. Moreover, this force structure has not been tested in a conflict with a great power adversary since World War II. Simply put, the core concept behind US naval power has remained unchanged and untested through the most profound period of technological change in human history. The advent of digital systems has brought fundamental changes in design, capabilities, economics, and logistics—in the digital age, data is the new oil, and software is the new steel. Trends in the private sector indicate that successful organizations in the 21st century operate using a different set of principles than those of the 20th century. It is certain that naval warfare also has been changed by digital technologies, and it is unclear whether carrier strike groups will continue to be the dominant naval formation in the face of those changes.

At the same time, the United States has found itself engaged in a growing great power competition with Russia and China. Recognizing the important role United States naval power plays in national security and foreign policy, these adversaries have spent decades closely studying our naval formations and investing significant resources to develop effective counters. China, for example, has been building a series of artificial islands in the South China Sea, complete with military barracks and airstrips, to create what is effectively an unsinkable fleet of permanent aircraft carriers. Other developments such as hypersonic antiship missiles that have been specially designed to counter our current air defense systems indicate that our adversaries see rendering our carrier strike groups ineffective as a key part of their naval strategy.

A Strategic Hedge

The combination of rapid technological change, determined naval competitors, and a primary fleet composition that has not seen a major conflict in several generations necessitates the creation of a viable alternative naval formation. From a portfolio management perspective, we need a hedge strategy in case our primary investments in carrier strike groups composed of large, complex assets are not ideally suited for future warfighting requirements.

The idea of a strategic hedge is not new, and our own naval history emphasizes the importance of such a hedge. In 1940, war planners in the United States were preparing for a potential conflict with the Empire of Japan. The resultant "War Plan Orange" centered on the idea that powerful battleships would form the backbone of the allied fleet and ultimately determine the outcome of the war. Japanese war planners shared that view and orchestrated the surprise attack that left a significant portion of the United States' battleship fleet at the bottom of Pearl Harbor. But as it turned out, the war in the Pacific was dictated not by battleships but by aircraft carriers; war planners for both the United States

THE SMALL
THE AGILE
AND THE MANY

ONR will build out a novel naval formation composed of the small, the agile, and the many, to serve as a strategic hedge against our current fleet structure. Photo by John Williams

and Japan had been wrong. Thankfully, the United States had begun operating aircraft carriers decades earlier and quickly adapted to field a fleet centered on aircraft carriers and submarines rather than battleships. The United States had invested early in a strategic hedge to create a viable alternative to battleships, and that hedge turned out to be the future of naval warfare.

To be successful, a strategic hedge must be sufficiently differentiated from our current force structure. Though our fleet is composed of a diverse range of different assets, including aircraft carriers, submarines, surface combatants, and many types of aircraft, each of these assets share many of the same characteristics:

- They are large compared to their forbearers
- They are expensive—to the point where the United States cannot afford the number of platforms our force structure assessments suggest we need
- They are multimission and therefore complex—these platforms do many missions, and the system-of-system interactions to create these complex integrations drive up costs and manufacturing lead times if we critically need force structure surge capacity
- They are acquired on a requirements model that lags behind operational identification of need by years, sometimes decades, when construction span times for some of these complex capabilities are included
- They are difficult to modernize—the ability to update the systems aboard these platforms, even the software systems, still takes years to accomplish.

The large and complex may well be what is needed to fight and win a future naval war. If technological change and/or the efforts of our adversaries render our primary fleet assets ineffective, however, we must have a viable fleet formation that emphasizes specialization, modularity, agility, and affordability.

Reimagining Naval Power

At present, we have no viable alternative to the large and complex. Despite many experiments, demonstrations, and war games showcasing possible alternatives, we have yet to field a novel naval formation that we can fall back on if our current formations are rendered ineffective.

Therefore, ONR is going to reimagine naval power by building out a novel naval formation made of the small, the agile, and the many that can fight alongside our primary assets or independently if required. This means going beyond experiments and war games to create a viable formation composed of dozens, hundreds, or even thousands of unmanned vehicles above, below, and on the ocean surface. These unmanned assets won't just be a collection of heterogeneous platforms, but a collaborative and autonomous formation. It is critical that this formation be built around digital-age principles, not just for the individual systems themselves, but also in the processes we use to design, procure, and ultimately operate them.

Build to Operational Needs

Unlike physical systems made of steel, digital systems made of software are extremely malleable—they can literally be redesigned at the press of a button. At the same time, the design space for software is virtually limitless, unbounded by the laws of physics that dictate the form and function of physical systems. As a result, the systems design process we have spent the past 150 years perfecting for physical systems is less than optimal for the design of software-based digital systems. A digitally native design process is iterative rather than linear, taking advantage of the malleability of software to quickly explore the solution space and converge on the optimal solution over multiple iterations.

This novel naval formation must be created using a digitally native design process that builds to operational needs rather than requirements checklists. This means starting the design process with "what is your problem?" instead of "what is your requirement?" and using design thinking and other techniques to hear and understand the problems. Starting with this information, an initial prototype is built and tested first digitally and then physically, feedback is collected, and another design iteration begins. Critically, this design iteration will take place over the course of a few months, not years. This is how the most successful digital organizations in the world design and release products that meet customer needs on time and on budget, and ONR is employing these principles to do the same for a novel naval formation.

Build a Virtuous Loop

Of course, the physical aspect of the design process is important as well—software is an integral part of the small, the agile, and the many, but the core platforms are still physical systems. Models and simulations provide an excellent sandbox for experimenting and selecting down from a collection of potential solutions, but ultimately performance must be measured in the water. Our digital design process must incorporate a physical component, with deliberately built physical testing infrastructure tightly integrated into each design iteration to quickly measure the real-world performance of these systems.

Therefore, ONR will build out the formation of the small, the agile, and the many by using digital design and experimentation informed by in-water tests. This process has already started with events such as HACKtheMACHINE and the SCOUT series, which take digitally generated ideas and models and put them to the test using real systems in the water. This is the start of a virtuous loop that leverages the speed and malleability of software-based systems to quickly and cheaply explore new ideas virtually and validate them in the water.

Partnership with American Industry

American industry has always been home to the foremost innovators in the world. In the 20th century, military and government entities leveraged the principles and ideas introduced by these innovators to bolster national defense and lead the world in military technology and output capacity. In the early 1900s, Henry Ford perfected the assembly line and Frederick Winslow Taylor laid down the early principles of industrial engineering. Three decades later, the United States produced almost two-thirds of all allied military equipment in World War II. A few decades after that, NASA teamed with American industry to put a man on the moon.

American industry continues to be a world-leading source of innovation today—the digital revolution that has been unfolding over the past few decades has been spearheaded by American companies such as Intel, Amazon, Google, Apple, Microsoft, and Tesla. But tech giants are just part of the picture; thousands of small businesses across the United States have been and continue to be a critical source of specialized knowledge and disruptive new ideas. ONR is going to draw on American innovation by creating new partnerships with industry players both big and small that are simple, effective, and still accountable. Ultimately, these partnerships will contribute to an innovation ecosystem that draws upon partners at all levels of government, academia, and industry.

Conclusion

As the United States enters a new age of great power competition with Russia and China, it is more critical than ever to ensure the United States maintains the ability to project naval power around the globe. History indicates that it is difficult to predict what the future of naval power will be during periods of rapid technological change, and it is not certain that the dominant naval formation today will remain dominant into the future. To ensure the United States has an effective hedge to carrier strike groups made up of the large and complex, ONR is reimagining naval power to build out a novel naval formation composed of the small, the agile, and the many. Drawing on digitally native design principles and partnering with innovators in industry and academia, ONR will go beyond experiments and war games to establish the small, the agile, and the many as a viable operational alternative to our current naval formations.

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DARTE: MAKING AVIATION READINESS MORE PREDICTABLE

By Dr. Benjamin Michlin, Dean Lee, Phu Thoi, Josh Duclos,
Dr. Jamal Rorie, Gary Williams, Jazlynn Wied, Dr. Andrew Sabater

A TEAM AT NAVAL INFORMATION WARFARE CENTER PACIFIC IS MAKING THE JOB OF AVIATION READINESS JUST A LITTLE BIT EASIER.

In early 2018, Rear Adm. Jeffrey Czerewko, then chief of staff at Commander, Naval Air Forces, sought to take a data-driven approach to increase air readiness. As manning, training, and equipment are the traditional pillars of readiness, this meant deriving actionable insights directly from these data sets. The data scientists at Naval Information Warfare Center (NIWC) Pacific were asked to take on this difficult task and build the Digital Aviation Readiness Technology Engine (DARTE) for the naval F/A-18 fleet.

The initial phase of DARTE was marked by rapid iteration of data exploration, prototype algorithm development, and subject-matter-expert engagement for analyses of insights. Throughout these iterations, NIWC Pacific and naval aviators collaborated to refine the scope of DARTE as well as to incorporate expert points of view. Working directly with warfighters was a key component of the success of DARTE.

"Readiness" is an abstract concept and not necessarily a well-defined metric. This required NIWC Pacific to work with naval aviators to find metrics that constitute readiness. Ultimately, it was determined that quarterly flight-hour execution and the number of mission-capable aircraft are the key metrics by which aviation readiness is judged.

Through the rapid iteration cycles, it was also determined that actionable insights through "levers," data attributes which can be influenced to affect readiness, and "drivers," data attributes that are driven by policy but nevertheless have an impact on readiness, are crucial to leadership.

Together with the predictions of future flight-hour and mission-capable values, the identification of levers and drivers that influence readiness form the core capabilities of the DARTE algorithm.

In addition, by using lessons learned throughout the development and deployment of DARTE, NIWC Pacific has developed a general data analytics "pipeline." This pipeline, or playbook, focuses on working with stakeholders and warfighters to derive impactful metrics, using machine learning to predict those metrics, implementing explainable artificial intelligence techniques in order to explain the black-box models in a human-understandable way to develop intuition, iterating with subject matter experts to derive actionable insights, and using these insights to improve the target metrics. Following this methodology yields a high probability of success and model utilization.

DARTE

The goal of DARTE is to predict F/A-18 squadron readiness as measured by monthly mission-capable aircraft and quarterly flight-hour execution. Moreover, DARTE provides the ability to monitor readiness as a squadron moves through a quarter. This is accomplished in two steps. First, a deep learning model is created to predict the mean number of mission-capable aircraft for each squadron three months in advance. This model is then extended and used as an input for a second machine learning model that predicts the flight-hour execution of a squadron over a quarter, up to three months in advance.

The availability of future readiness predictions from DARTE leads naturally to an additional question: what changes can be made to improve the readiness of under-performing squadrons? To this end, an explainable artificial intelligence engine is implemented to provide human-interpretable results, and suggest areas of focus to improve a squadron's outcome. Further, NIWC Pacific implemented the Resource Optimization and Allocation Model (ROAM), which takes a statistical approach to improve squadron readiness by recommending changes to the distribution of maintainers throughout the enterprise.[1] ROAM also may be used to influence recruitment and professional development of maintenance personnel.

Deep/Machine Learning Models and Performance

The DARTE Mission Capable Model uses cutting-edge machine learning techniques in the form of a hyper-deep ensemble of deep neural networks with several attention mechanism-enhanced long short-term memory layers in order to make a mission capable forecast.[2] After training and hyperparameter tuning, the model achieves excellent predictive power up to three months into the future. Furthermore, the ensemble model produces prediction intervals, which provide individual prediction uncertainties. A prediction interval is incredibly useful, as it provides a way to estimate the likelihood of future observations falling into the specified interval. Decision makers may use these prediction intervals to decide how much to trust an individual prediction and if action should be taken.

The results of the model for predicting the number of mission-capable aircraft that a squadron will have three months into the future is shown in Figure 2. The actual values have about a 68-percent chance of falling in the green $\pm 1\sigma$ shaded prediction area and about a 95-percent chance of falling in the yellow $\pm 1\sigma$ shaded area. This figure shows both the accuracy of the predictions and the utility of prediction uncertainty intervals.
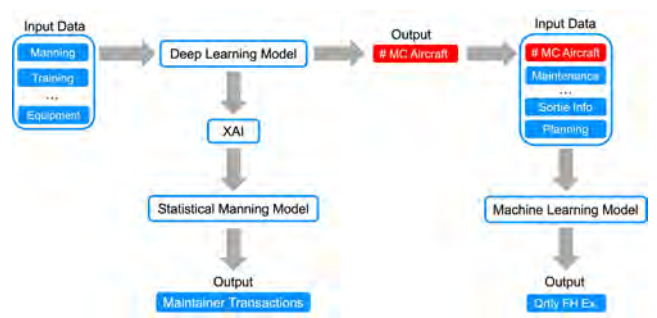

Figure 1. DARTE architecture showing how each model is connected. This shows an overview of the DARTE architecture and how each model is connected. It is important to note that although DARTE is a highly specialized model, this generic approach may be applied to any number of problem domains. The general pipeline process of predicting an important metric or value, explaining the prediction, deriving actionable insights, and then acting on those insights to improve the target metric has widespread applicability.
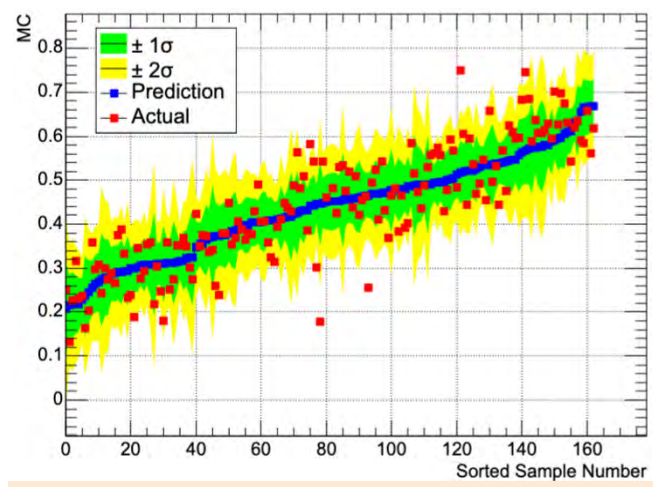

Figure 2. Normalized number of mission-capable aircraft by the sorted sample number for the three-month model. The blue points show the predicted mission-capable value and the samples are ordered for increasing predicted value. Red points show the actual mission capability. The green and yellow shaded areas show the $\pm 1\sigma$ and $\pm 2\sigma$ prediction intervals, respectively.

The mission capable models are then used as an input to create an ensemble Flight Hour Model. This model predicts the flight hours executed as a fraction of the flight-hour entitlement, or goal, for an individual squadron (FHEx/FHEnt). The distribution of the quarterly flight-hour ratio is shown in Figure 3. The goal is to predict whether a squadron will meet 98 percent of its hour entitlement (green), less than 85 percent of its entitlement (red), or in-between (yellow). These classes are shown in Figure 3. As with the Mission Capable Model, a Flight Hour Model is created for each month in the quarter so that predictions for the squadrons' flight-hour ratios at the end of the quarter can be made on the first day of each month in the quarter.

As expected, the Flight Hour Model performance improves as the quarter progresses. This is because each successive model is predicting a shorter distance into the future. Even for the month 1 Mission Capable/Flight Hour Model, however, predicting the flight-hour ratio 90 days in advance with an average accuracy (recall) of 70 percent is an extremely powerful result. Further, since this is a multiclass classifier, an accuracy of 70 percent is exceedingly good.

Explainable Artificial Intelligence

With these models in hand, there are several new challenges. First, it is often difficult to explain how and why deep learning and ensemble models make certain predictions. This difficulty is compounded because people tend to dismiss or distrust a model prediction that they do not understand—particularly if it conflicts with intuition. Second, even if a prediction is accepted, it does not necessarily suggest courses of action that can be taken to improve an outcome. Both of these problems are addressed using the SHAP (Shapley additive explanations) method.[3] SHAP is an additive feature attribution method established in game theory that creates explanations for individual predictions. This explainable artificial intelligence method is applied to the mission capable model to determine the
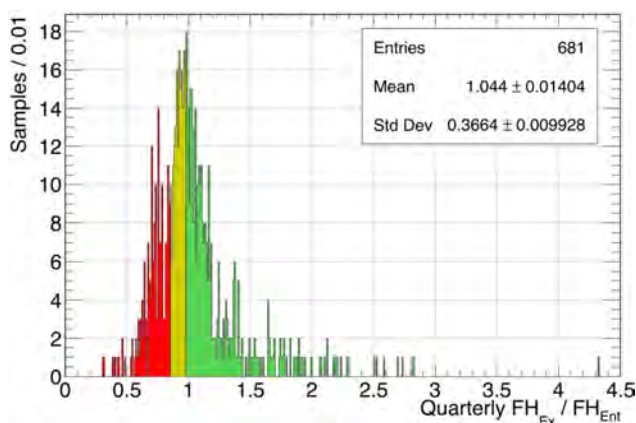
Figure 3. Histogram of the quarterly flight hour ratio is shown. Delineations for 98 percent of squadron's flight hour entitlement (green), less than 85 percent of their entitlement (red), or in-between (yellow) is shown.

"drivers" and "levers" of mission capability. In this context, drivers are features and attributes that influence a mission capable prediction which cannot be changed, and levers are those that can be changed. For example, the manning level of a squadron could be a lever, while the age of the aircraft or flight hours on the airframe might be a driver.

Figure 4 shows one of the results from implementing the explainable artificial intelligence engine on an individual prediction. The current mission capable prediction is shown to be six aircraft, and the red features are those that cause the prediction to increase while the blue features are those that cause the prediction to decrease. The magnitude of the blue and red arrows show how much the prediction is influenced by each feature category. In this case, this squadron is performing well in the categories of training and maintenance; to improve their outcome they need more manpower, funding, or newer equipment. This explanation is unique to this individual squadron and prediction. Thus, this method allows for completely custom results, explanations, and suggested courses of action for each squadron and prediction.

This methodology of producing a machine learning model leading into explainable artificial intelligence is extremely general and may be applied to any machine learning pipeline.
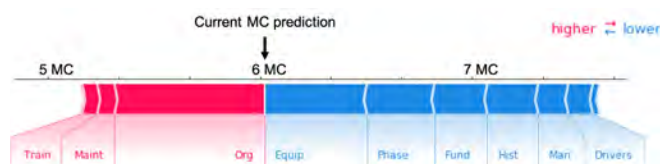

Figure 4. SHAP force plot explanation of a single mission-capable model prediction.

The Resource Optimization and Allocation Model

In response to the manning lever identified by the explainable artificial intelligence engine, the ROAM engine takes a statistical approach to improve squadron readiness by optimizing the distribution of aviation maintainers throughout the enterprise. ROAM provides high-quality courses of action to improve the readiness of the Naval Aviation Enterprise. Furthermore, ROAM provides insights on the overall manning surpluses and shortfalls throughout the enterprise and may be used to influence training and hiring practices.

Statistical methods are used to model squadrons that are capable of meeting or exceeding their mission-capable goals and targets. Specifically, the distribution of maintainer "fit" and "fill" percentages for each Optimized Fleet Response Plan phase are studied. Here, "fit" refers to the qualification of the maintainer and "fill" refers to the raw number of maintainers. ROAM focuses on the aviation maintainers that are responsible for creating mission-capable aircraft. The idea is then simple: once the statistical model has been created using all of the historical data,
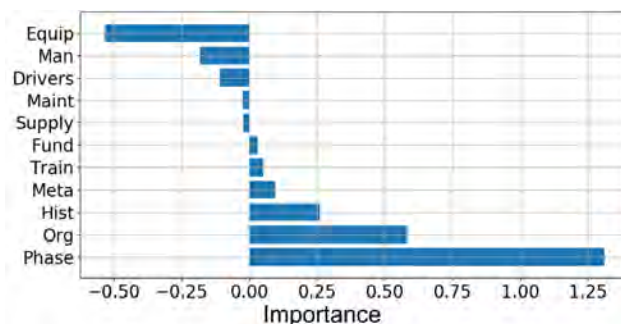
Figure 5. Aggregated mission-capable model feature importance. This shows the aggregated feature importance from all mission-capable model predictions. The magnitude of each bar indicates how important that feature is to the model, and the direction of the bar indicates whether or not that feature tends to increase or decrease the predicted value. For example, it is clear that phase, a driver, is the largest factor influencing predictions. This makes sense since the squadron's activity phase (deployment, maintenance, etc.) dictates their overarching goals which in turn impacts mission capability. Likewise, the largest factor reducing mission capability is an aging fleet. However, the second most important feature reducing the number of mission-capable aircraft throughout the enterprise is manning, which is a lever that may be addressed and improved.

squadrons are compared against the model and maintainers are taken from over-manned squadrons and given to under-manned squadrons.

For implementation, the results from the statistical model are then combined with a complex set of business rules to produce suggested courses of action to give the entire F/A-18 enterprise a better chance of meeting its aggregate goals. Crafted in collaboration with experts, these business

Figure 6. ROAM transactions displayed as a network graph. The blue circles represent squadrons. The red lines indicate a maintainer trans- action. The maintainers being transacted are written on the line in the form of *Quantity Rate (Experience)*.

rules are designed to integrate and enforce existing rules that decision makers and experts are required to follow so that no suggested course of action would conflict with the actions of an expert.

The courses of action produced by ROAM are a set of maintainer transactions, which may be represented in the form of a network graph as shown in Figure 6. Here, the blue circles repr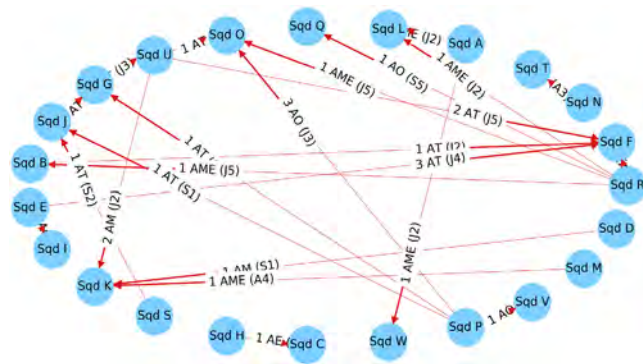esent squadrons, the red lines indicate a maintainer transaction, and the maintainers being transferred are written on the line showing the quantity, rate, and experience information for the maintainer. The rate shows the maintainer specialty and job function (e.g., AM, AT, AO), and the maintainer experience information corresponds to experience levels (e.g., supervisor, journeyman, apprentice) and specific trainings and qualifications for a maintainer (e.g., S2, J3, A4).

ROAM shows decision makers an aggregate representation of squadron behavior. For example, in Figure 6, squadron R is a big donor squadron and may be over manned. Conversely, squadron F is a big receiving squadron and may require assistance, while squadron B has an imbalance— donating maintainers of one rate and receiving another. ROAM does not move large numbers of maintainers but rather makes extremely targeted transactions. In addition, ROAM may find that after all possible transactions are made, there is a shortfall or surplus of a specific type of maintainer or training certification. These insights may then be used to influence enterprise-level hiring and training practices.

ROAM shows an example of how a lever, identified by the explainable artificial intelligence engine, may be optimized to improve readiness. This completes the final step in the analytics pipeline wherein a model has been created to predict an important metric or quantity, the model was then explained, and actionable insights were produced to

Future Work

The DARTE model follows a specific application of a general methodology: predict, explain, derive actionable insights,

and improve. Using manning, training, and equipment datasets, deep learning models have been created to predict the monthly number of mission-capable aircraft that a naval F/A-18 squadron will have up to three months into the future. The mission capable deep-learning models were combined into a machine-learning ensemble to predict the quarterly flight-hour execution of a squadron up to three months in advance. An explainable artificial intelligence engine was then implemented to explain the black-box model results and produce a human-understandable output. In addition to explaining the predictions, the engine identified areas of improvement for the enterprise. Finally, a resource optimization and allocation model was created to distribute aviation maintainers throughout the enterprise to optimize mission capability and address a lever identified by the engine. DARTE is the result of the implementation of a robust analytics pipeline with far-reaching applications outside of readiness.

Although all of these models were designed to focus on the F/A-18 fleet, many of them have since been extended successfully to the E-2 Hawkeye and the V-22 Osprey. With the F/A-18 being a fighter jet, the E-2 being a turboprop aircraft, and the V-22 being a tiltrotor aircraft, it has been proven that DARTE can be applied to a wide variety of aircraft. Future work is not limited to F/A-18, aviation, or even fleet readiness. DARTE can be expanded to solve additional problems that could include other platforms (sea and ground) and systems to deliver capability at the speed of relevance.

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DAHLGREN DIVISION
LEADS WITH
INNOVATION

By Diana Stefko, Caleb Gardner, and Elliot Carter

THE NAVAL SURFACE WARFARE CENTER ON VIRGINIA'S NORTHERN NECK IS CONTRIBUTING TO READINESS AND THE FUTURE FLEET WITH A NUMBER OF INNOVATIVE PROJECTS.

Pandemic safety measures in the past two years precluded the chance conversations that normally occur in hallways and watercoolers on Navy bases around the world. Now that work life is returning to a pattern of new normalcy, we are providing a look at some of the projects that have kept the Navy's talented engineers and scientists busy during a time of maximum telework.

In the four snapshots below, we meet a number of experts from Naval Surface Warfare Center (NSWC) Dahlgren Division who are engaged in projects as wide ranging as antidrone lasers, and workflow methodologies that have been compared to a pizza delivery tracker.

Deploy the Antidrone Lasers

In films and on television, we witness laser weapons perform at peak destructive power to defend against a fictional enemy force and rejoice when the "good guys" triumph in the end. In reality, laser weapon system programs provide our military forces with a multitude of capabilities to defend and prevent threat vulnerabilities.

One such program is the Compact Laser Weapon System (CLaWS), which is a remotely operated, directed energy weapon system intended to target and defend against threat unmanned aerial drones. The system itself is equipped with an infrared camera with high-level optical tracking that allows CLaWS to provide intelligence, surveillance and reconnaissance capabilities and receive target cues from a separate radar system.

Naval scientists and engineers at NSWC Dahlgren Division supported the program as the government lead, providing laser weapon systems expertise and establishing the training program curriculum, including building a CLaWS system simulator.

Collaborative efforts span across multiple departments at NSWC Dahlgren Division, Naval Sea Systems Command and industry. Program Manager Ground Based Air Defense (PMGBAD), a sector of Program Executive Officer Land Systems, procured rapid development and delivery of CLaWS prototypes through the Department of Defense Ordinance Technology Consortium Other Transaction Agreement in 2017. Today, the prototypes provide a layered air defense capability to support the US Marine Corps.

The Dahlgren Division team provided extensive training development consisting of in-classroom and hands-on interactive training enabling Marines to become fully proficient at operating CLaWS effectively and efficiently.

During the two-week training session rotation occurring every six months, Marines familiarize themselves with the system's components and equipment. The goal of the training is for the Marines to understand how the system works thoroughly. Since the CLaWS system uses numerous subsystems to detect and analyze incoming aerial objects, educating the Marine operators on those subsystems' capabilities is imperative.

As part of the interactive training, Marines are shown how to use the hand-held remote controller—closely resembling a commercial gaming controller—to navigate the guidance capability.

Once Marines complete the in-classroom orientation training, the Dahlgren Division team then provides demonstrations on how the system is assembled and operated. In addition, Marines interact with the system by engaging with the CLaWS simulator, which Dahlgren Division developed specifically for training purposes. The culminating training session event consists of a live-fire exercise to validate system operations.

In 2021, the CLaWS program accomplished major milestones, including upgrading all CLaWS units to increase lethality and provide enhanced reliability. Furthermore, completion of all system manufacturing made for an effortless transfer to Marine Corps operational forces.

NSWC Dahlgren Division engineers Ryan Littleton (left) and Michael St. Vincent perform seeker calibration on the semi-active laser (SAL) seeker they helped develop. The new SAL seeker is smaller and lower in cost than previous seekers and will be compatible with the future generations of guided munitions systems.

Dahlgren Division continues to provide support for all training sessions as well as head the CLaWS simulator demonstrations and live-fire exercises. The program reached the final stage of the research and development phase and transitioned the sustainment effort to PMGBAD in late 2021. In addition, Dahlgren Division retains a primary support role in the sustainment efforts moving forward in 2022.

Always on Target

Engineers at NSWC Dahlgren Division have developed a new, lower-in-cost, semi-active laser (SAL) seeker.

SAL seekers are a key enabling technology for guided munitions that allow warfighters to target stationary and moving targets in areas where GPS is unavailable.

SAL seekers function in tandem with an operator that directs a pulsing, infrared laser at targets. The seeker, typically in the nose of laser-guided munitions, detects the laser energy reflecting off the target and guides the munition to the operator's mark with high precision. This partnership assures that the correct target is engaged.

The seeker developed by engineers at Dahlgren Division is smaller, three-to-five times cheaper than comparable laser seekers, and is based on modern electronics designs not only to ensure relevance, but also to improve performance and implement the next generation of signal processing and countermeasures. As precision weapons requirements continue to expand, the design is ready to support integration with imager systems. The upgraded terminal

seekers will be instrumental in the development of future guided munition systems.

"In response to the shift in force design, warfighting function and the trends going forward, we're technologically pivoting to stay ahead of the game," said program manager for the Enhanced Expeditionary Engagement Capability program Luke Steelman.

Traditional SAL seeker systems use a gimbaled detector element to track the laser spot as it moves relative to the weapon. Engineers at Dahlgren were able to develop a new combination of fixed optics and software algorithms to replicate the capability without the need for those expensive and sensitive moving parts. This has not only led to a smaller and more cost-effective product, but also one that is instrumental in ensuring compatibility with the next generation of system currently under development.

What's more, the new seeker design also includes an integrated height-of-burst sensor that is able to measure proximity to the ground and signal the weapon's fuze to create a very precise airburst function without the need of an additional sensor on the guided munition, further saving space and reducing cost.

Dahlgren has produced more than 50 prototypes, 30 of which have been live-fire tested on multiple weapon systems—including the 81-mm Advanced Capability Extended Range Mortar (ACERM)—and successfully guided systems to stationary and moving targets.

Michael St. Vincent, project lead engineer, said that direct feedback from warfighters was critical to the successful development process.

"We would get feedback from warfighters—what kind of targets they are targeting, what they are like, and also what requirements they need to meet," said St. Vincent. "If they needed more range or more field of view . . . we would do simulations and make some changes and new iterations that moved closer to what they want."

Dahlgren has long had a hand in terminal seeker technology, but in recent years the focus of the warfighting function has moved to exceedingly longer-range engagements. These long-range engagements keep warfighters and targeting assets far away from adversaries, but often preclude the use of laser-guided munitions.

Despite increasing engagement distances, Steelman says that laser-guided munitions that use the SAL seeker will always be a mainstay in warfighters' toolboxes for one reason: target assurance.

"If the operator is putting a dot on a target, he is telling me 'this is your target, not the one to the left, not the one to the right, that one,'" St. Vincent noted. "Laser guidance will always provide that 99.99-percent assurance that a specific truck or boat is your target."

Charting the Course

Many have experienced the onset of warmer weather with a strong desire to get out of the house and travel, whether to a sunny beach or a camping adventure. Charting the most reliable route means figuring out which roads to take for the quickest, smoothest ride and arrive without encountering any mishaps along the way. You may not realize it, but the concept of flight path optimization is the same as operating a car and planning a road trip, just on a more complex scale.

Similar to the way a driver steers the car and uses a map to select the quickest route to avoid traffic congestion, flight path optimization uses mathematical algorithms and trajectory software to guide various types of missiles and projectiles to intended targets.

John Lawton—Guidance Navigation and Control principal engineer for the Aerosciences Modeling and Engagement Branch at Dahlgren—develops advanced mathematical techniques for optimal control in flight path guidance systems. "At the core of the concept, flight trajectory optimization is optimizing the path that the missile or projectile follows to either maximize or minimize a particular objective function, meaning where you want the missile to go and what you want it to ultimately accomplish," said Lawton.

According to Lawton, flight path optimization (referred to as a flight trajectory) is applied to multiple projects involving weapons steering projectiles.

As the former Guidance Navigation and Control lead engineer, Brad Atkins supported trajectory design development to maximize optimal performance by maneuvering the best flight paths. "We are exploring the realm of performance with trajectory shaping to meet high performance mission and defensive goals. Using quick numerical algorithms that work with the actual flight physics models, we are testing and evaluating trajectory for guiding various ammunition to the objective in the quickest time possible," said Atkins.

Lawton, Atkins, and a collaborative group of engineers and scientists across NSWC Dahlgren Division developed the optimization algorithms and used simulation software to test trajectory functions of flight paths.

Depending on the model and objective, range distances and flight times vary and different algorithms are applied to determine the flight path design.

When determining which algorithm technique to apply during a flight path simulation, the group considered a range of potential obstacles. "We're designing algorithms that enable the warfighter to decipher given constraints, such as country borderlines or physical terrain in the area, and define the best path for guided weapon systems in order to meet mission goals and avoid those constraints," said Atkins.

Atkins and his team also engaged in real-time flight path testing methods using a small, portable drone-like helicopter device known as a quadcopter. A newly built facility housing a 750-foot flight space provides the opportunity to conduct quadcopter flight path testing using motion capture cameras. Located in the Innovation Lab at Dahlgren Division, the Artificial Intelligence for Guidance Navigation Control Aviary offers the team the accessibility to test new control algorithms on quadcopters with the focus on advancing specific research topics.

"Whether we are designing a flight path trajectory for defensive or offensive weapon systems, utilizing mathematical algorithms and computer simulation software expands our ability to optimize flight path projections and advance the technology to another level," Lawton said.

Guidance Navigation and Control lead engineer Brad Atkins (left) and principal engineer John Lawton stand beside various-sized projectiles at the Potomac River Test Range Table signage at NSWC Dahlgren Division.

In addition to developing flight path optimization, the team partners with numerous departments to incorporate their algorithm processes into other current projects, such as the Enhanced Expeditionary Engagement Capability program and the Rapid Optimization of Trajectory Hypersonics project.

There's An App For That

New software capabilities are reaching the fleet quicker than ever from NSWC Dahlgren Division thanks to an integrated workflow that experts liken to a meal-delivery tracker.

Between February 2020 and June 2021, Dahlgren Division finished 13 authorized updates for the Virtualization Pilot Ship (VPS) program used aboard USS *Monterey* (CG 61), each of which would require a year or more to complete through standard development processes. "We've never done that before with any other system," said Display Domain lead Hud Lemons. "That pace is kind of unprecedented for getting these capabilities developed, tested, authorized and ready for the ships."

"If we are going to deliver new capabilities at the speed of relevance, the only way that we could do it was force of change," said Lemons. Jessica Hildebrand, VPS project lead, added, "We're taking best practices modeled on Agile that private industry has been using for years and applying it to our combat systems." Agile Scrum refers to a workflow made popular by software development companies, where teams sprint to complete tasks in quick increments, rather than tackling an entire project in one extended push.
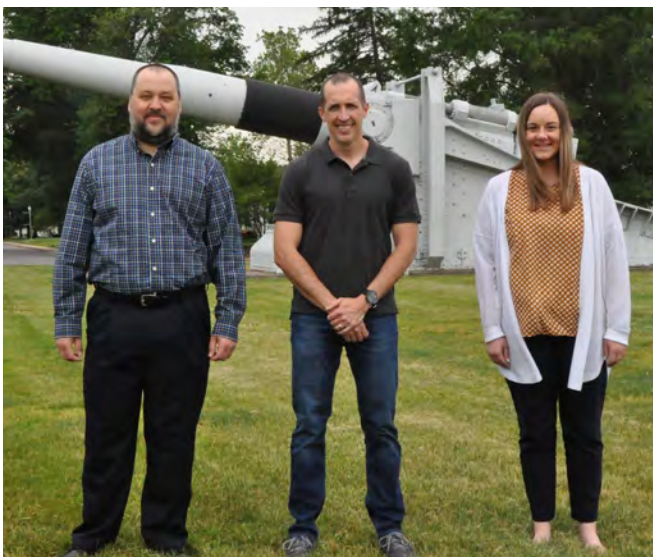
Over the past year, NSWC Dahlgren Division finished 13 authorized updates for the Virtualization Pilot Ship (VPS) program with an integrated workflow that experts compare to a meal deliver tracker. From left to right: combat systems certification official Dale Geiger, display domain lead Hud Lemons, and Virtualization Pilot Ship project lead Jessica Hildebrand.

Past generations of certification teams have had to aggregate reams of information produced during development and testing efforts to build formal reports that reach hundreds, or even thousands of pages in length. "It can take weeks or months to receive and review all of this," said Rob Cunningham, a Virtualized Combat Systems certification lead at Dahlgren Division. "Only then do you begin to assess objective quality evidence [OQE] and review the system against those criteria." Continuous access to the development environment and resulting artifacts is an opportunity to streamline the decision-making process in ways that uphold the Navy's highest standards. Sailors depend on these authorizations and certifications in order to understand the capabilities and limitations of the systems.

Certification is a byproduct of a disciplined engineering process based on review of OQE. The integrated workflow ensures continuous access to development artifacts in order to minimize risk in support of authorizations (use of an engineering product at sea) and certification for deployment.

The team at Dahlgren has been conducting authorizations for the VPS program using integrated tools, including automated testing and analysis, that provide a continuous view into product quality. The process aligns with agile workflows used in the private sector, to break up large serial processes into more manageable chunks that are accomplished iteratively.

The result bears some outward similarities to web-based applications that are familiar in the consumer world. "It's kind of like the tracker for your pizza order," observed Dale Geiger, the combat systems certification official at Dahlgren Division who is responsible and accountable for adherence to the Program Executive Office Integrated Warfare Systems Element and Combat System Certification process. In his analogy, the system engineering process functions like an interactive website that follows a meal through the different stages in a kitchen, with detailed information embedded at the appropriate places.

"Let's say someone has a question about the underlying data," said Cunningham. "Just click on that here—we can pull up the information about that piece. Someone else has a question about testing. Click—we can go into a specific test event and see what happened." Cunningham noted that the integrated environment provides stakeholders with the ability to easily dive deep into objective quality evidence, and that "the entire certification assessment is entirely real time and linked together on a webpage."

In one recent VPS authorization effort, the Dahlgren team identified and resolved a technical issue on the VPS program within a matter of days. An update was developed, tested, integrated and authorized all within the toolset, where the same issue might have required weeks to accomplish in a traditional workflow. On larger scale efforts, Hildebrand projects that a similar approach will deliver new capability anywhere from a year to a few months versus multiyear endeavors as done today.

A 40-foot tower constructed at NSWC Dahlgren Division is topped by a radar prototype used in foreign comparative testing. The middle-level contains a command-and-control room. This effort supports the Navy's Future X-Band Radar program.

Future Radar Systems

On a recent warm afternoon at the Potomac River Test Range, recreational speedboats and jet skis plied the cool waters as a handful of Navy engineers gathered shoreside under a reconnaissance and surveillance tower, to begin powering up a mobile engineering lab that is mounted 40 feet in the air. One member of the Navy group pointed out a good target of opportunity in the distance, and as that speedboat slowed to round a curve in the river, the shore party engaged their radar system and began to evaluate the resulting data.

The day's test bears some outward resemblance to opening moments of a clash between hostile surface warfare vessels, with the 40-foot tower acting as a proxy for the radar mast on a ship. If it had been a real hostile encounter, those personnel could quickly help bring salvoes of naval fire raining down on their target. This being the peaceful Potomac River, however, the test and evaluation exercise ended at the data collection stage. The team also displayed a constant awareness of the need to be a safe and nondisruptive presence on the river. "We are good from a safety perspective," lead engineer Said Darham noted earlier that afternoon, citing a robust list of checks and cross-checks that had been completed prior to the test event.

Since the summer of 2020, Darham and his team of engineers at Dahlgren Division have been using the radar prototype as a test asset and risk reduction system in support of the Navy's Future X-Band Radar (FXR) program. If all goes according to plan, FXR will one day replace the legacy SPQ-9B radar system, which has almost two decades of field experience spotting far-off targets from aircraft carriers, amphibious assault ships, amphibious transport dock ships, guided-missile cruisers, destroyers, and Coast Guard cutters.

The project sponsor for FXR called on the expertise at Dahlgren to support foreign comparative testing and determine how the latest technology in use by allied and partner nations stacks up against domestically-manufactured X-band radars. The team at Dahlgren noted that equipment currently under assessment compares favorably on several metrics. "Size, weight, power, cost, and cooling are paramount," Darham explained, adding that "the radar prototype we are testing can go a long way towards meeting those objectives."

The equipment now undergoing testing on the Potomac did not actually start as a radar. According to Darham, the engineers started with a commercial-off-the-shelf antenna designed specifically for military aircraft. After modifications at Dahlgren, the aircraft system now points out over the water and can respond to the unique features of a naval environment. This is the equipment housed inside the tower-top mobile engineering lab. Testing is conducted at the Potomac River Test Range because it combines some of the benefits of a controlled laboratory environment, with real world activity like speedboats and shore vegetation that act like "sea clutter" and "land clutter" for radar testing purposes.

"The clutter profile that an aircraft antenna sees is very different from the one that a ship antenna sees," Darham explained. "We want to continue to collect data with the aircraft AESA, generate clutter maps and implement clever algorithms to distinguish between what is a target of interest and what is not." Darham also referred to comparisons of various performance metrics, such as electromagnetic interference survivability, out-of-band blocking capability and the interconnected statistics for size, weight, power, cost and cooling, which are known collectively as "SWaPC2."

"The sponsor and industry partners are helping establish future baseline concepts for FXR that meet the Navy's need for next generation radars," Darham explained. "Having an X-band radar prototype in a naval-like environment serves as a test and evaluation playground to support current and future active sensor thrusts."

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Diana Stefko and Elliot Carter are senior writers/editors and Caleb Gardner was an associate writer/editor at NSWC Dahlgren Division public affairs.

FLIP STOOD
TALL
FOR
OCEAN SCIENCE

By Captain Edward Lundquist, USN (Ret.)

THE NAVY'S FLOATING INSTRUMENT PLATFORM IS ON A FINAL SEARCH FOR A FOREVER HOME.

Oceans represent the battlespace that must be understood to be owned. To prevail at sea, navies must know as much as possible about the environment where they are or will be operating. To understand the ocean, scientists must surround themselves with it. That requires specialized sensors, platforms, and professionals.

In the 1960s, the US Navy came up with a solution to remain at sea for extended periods to conduct acoustic research and collect data using a unique platform that radiated very little ambient noise.

The Office of Naval Research (ONR) built FLIP, the 355-foot (108-meter) Floating Instrument Platform. It looked something like a baseball bat that could be towed to a location like a ship and then ballasted so it would stand upright like a spar buoy, with just the 55-foot (17-meter) platform section protruding above the surface.

FLIP was launched in 1962, and categorized as a nonpropelled research barge for testing a then-classified Navy program called SUBROC, a submarine-launched rocket used to attack enemy submarines. The weapon was fired submerged, entered the atmosphere and flew to its target location, and then reentered the water to detonate its 250-kiloton thermonuclear depth bomb.

FLIP has been used extensively by the Navy to conduct research in deepwater acoustics and signal processing. While originally built for acoustics research, FLIP has more recently been involved in more broadly based science such as air-sea interaction studies. FLIP has been used to examine ocean circulation, storm wave formation, and how thermal energy is transferred between the ocean and the atmosphere.

What makes FLIP so unusual is that it actually flips from the horizontal to the vertical. The vessel transitions from the horizontal to vertical by flooding the ballast tanks, starting from the stern forward, changings the vessel's displacement causing the stern to sink. Once all the tanks are flooded, FLIP stands upright in the vertical orientation—as tall as a five-story building. When the mission is complete, high-pressure air stored in bottles in the ballast tanks is released into the tanks to force the seawater out. It takes about 20 minutes to reorient the vessel.

The furnishings and fixtures are duplicated, or designed to be used in both the horizontal and vertical configuration, so a table, sink, toilet seat, or the three diesel generators can be rotated on gimbals to a new position and locked into place. To solve the flipping challenge, most compartments on FLIP have two doors, one to use when horizontal, and the other when FLIP is vertical. Decks have doors and bulkheads become decks.

FLIP was designed by the naval architecture firm Glosten Associates and built by Gunderson Bros. Engineering Corporation in Portland, Oregon. FLIP was constructed from 700 tons of Tri-Ten steel and concrete ballast for a displacement of 800 tons. It wasn't the only research platform based on the spar buoy design. Around that same time, a similar platform called SPAR (Seagoing Platform for Acoustic Research), also designed by Glosten Associates, conducted research for the Navy in the Western Atlantic.

FLIP embarked a crew of five and up to 11 scientists on missions of up to 35 days without being resupplied. FLIP makes its own water—about 1,500 gallons a day—and its own electricity with a pair of 150-kilowatt diesel generators and a backup 40-kilowatt generator. Because FLIP is nonpropelled, it costs much less to operate than a research ship. A coastal research ship might use 1,000 gallons of fuel each day (and a bigger crew as well) when on station, whereas FLIP uses less than 100.

FLIP was operated by the Marine Physical Laboratory of Scripps Institution of Oceanography in San Diego, and permitted researchers to study sound waves, wave height and air-sea interaction; water temperature and density, meteorological data, and marine mammal populations, all at various depths in the ocean without the interference of ambient noise from a ship's propulsion system. Researchers could mount a variety of sensitive instruments on the hull and on deployment booms that fold out from the sides—more than could be employed from a typical research vessel.

Hydrophone arrays and other sensors could be positioned at various depths to conduct acoustic measuring, heavy instrument packages could be lowered to the deep ocean for various studies, pressure sensors and lasers were used to measure precise changes in wave height, and meteorological sensors could collect data above the sea surface.

According to Tim Schnoor, an operations Analyst with ProteQ supporting the Office of Naval Research (who formerly worked at ONR managing the Navy's University National Oceanographic Laboratory System fleet), FLIP arrived on the scene just as the space race was getting under way. Today, in its twilight, FLIP represents 60 years of science, technology, and engineering triumphs.

In its earlier days, FLIP supported a number of test and evaluation efforts of Navy programs. "It wasn't really involved in basic research or science, but was focused on the other end of the research and development spectrum in acoustic evaluation of existing programs," said Schnoor.

In the early 1990s, ONR invested resources into refitting FLIP as more of a research platform and found new scientific uses for FLIP and its unique capabilities, to include meteorology and oceanography.

FLIP could be anchored or drifting, but FLIP was a very stable platform in either situation. When the platform is in the vertical position, there is virtually no vertical

movement in most sea states. Once it gets where it's going to work FLIP has the endurance to remain on station for extended missions, either drifting or moored to the bottom.

FLIP required an ocean-going tug to tow the platform to the work area, and anchor handling equipment if it was going to be moored to the bottom. In 2001, FLIP used a single anchor in water 14,000 feet deep off Hawaii, with a 30,000-foot long, 1 ½-inch double braided nylon anchor line between the anchor and the platform. It took an hour for the anchor to reach bottom after being dropped from the support ship, and the anchor was held on the ocean floor with 12 tons of anchor chain. At the end of the mission, the anchor and chain were left behind.

Because FLIP was so quiet, it was ideally suited to support marine mammal surveys. Observers could count and observe different types of marine mammals with hydrophone arrays suspended below the surface and observers positioned on top of the platform to correlate the sounds from the animals with visual observations.

Some of FLIP's research projects involved multiple platforms and systems. The High-Resolution Air-Sea Interaction Departmental Research Initiative (Hi-Res DRI) project, conducted off the California coast in 2010, studied the air-sea interaction, examining ocean circulation, storm wave formation, and how thermal energy is transferred between the ocean and the atmosphere. Hi-Res DRI involved moored buoys, the coastal research vessel R/V Sproul (owned by the State of California and operated by Scripps), and a twin-engine, fixed-wing DHC-6 Twin Otter aircraft from the Naval Postgraduate School's Center for Interdisciplinary Remotely-Piloted Aircraft Studies. Hi-Res DRI leveraged those assets to develop the next generation of numerical simulation models of the coupling between the ocean-wave-atmosphere systems.

FLIP looks like the bow of a ship attached to a long pipe. When it transitions, FLIP can attract attention. According to Capt. Tom Golfinos, FLIP's long-time officer-in-charge, it can appear like an at-sea disaster in the making, causing professional mariners to flip out.

"We were vertical in a three-point moor when we see a large merchant ship coming right at us. I called him on the bridge-to-bridge radio to ask him to stay clear," Golfinos recalled. "Finally, he turns away, but he slows and calls us to ask if we need any help. I tell him we're a research platform and we're fine, and to please stay clear. He says, 'Are you sure? It looks like you are sinking.'"

FLIP's Future

FLIP is 60 years old. Over the years the Navy maintained FLIP's research capabilities with the ability to install the latest generation of scientific instruments on the hull or on the platform's three booms.

There are things FLIP can do because of its size and stability that just can't be duplicated. But that's changing.

Research funding has been reduced. From 2008 to 2017, the funded research days for FLIP decreased from 100 days per year to 30.

Rob Sparrock, the program officer overseeing ONR's research vessel program, said a FLIP overhaul has been deemed too expensive, especially relative to how many more years of additional operations that could be achieved, and a replacement would be cost prohibitive.

Tugs guide the Department of the Navy's Floating Instrument Platform (FLIP) from its berth at the Nimitz Marine Facility in Point Loma, California. Unless a more suitable final resting place is found to highlight her historic engineering and scientific achievements, she will likely be disposed of. Photo by John F. Williams

It takes about 20 minutes for FLIP to transition from the horizontal to the vertical. Built in 1962, the 355-foot research vessel, owned by the Office of Naval Research (ONR) and operated by the Marine Physical Laboratory at Scripps Institution of Oceanography at the University of California. Photo by John F. Williams

"It would cost about $8 million to make FLIP useable for another five or ten years, but that funding could be better used elsewhere," Sparrock said. "We came up with lots of creative ideas, but there wasn't enough inertia or funding to keep it going."

But while FLIP can only make observations in one location at a time, much of the research that used to require the capabilities that FLIP provided can now be conducted using other means.

Today there are viable alternatives to collecting data that were once only possible with manned platforms. Electronics, sensors, and instrumentation have become smaller, and there are a numerous floats, vehicles, and spar-like buoys or craft that can float and anchor or drift unattended for extended periods. A fleet of smaller unmanned buoys can conduct some of the same data collection, but in many more locations at the same time.

For example, researchers from the University of Miami's Rosenstiel School of Marine and Atmospheric Sciences developed the Air-Sea Interaction Buoy (ASIB), which can perform many of the same functions as FLIP, but can be deployed in many locations at the same time for less cost.

"The buoys may not be as capable, but they can be more numerous," said Sparrock. "You're close to getting the same value of research."

So, what will happen to FLIP?

"We've made the decision not to put funds into FLIP, but we haven't decided how to dispose of it yet," Sparrock said. "We're are asking for shipyard to provide bids to dispose of FLIP so we can budget for it in coming years." "There are plenty of people advocating for retaining FLIP and its capabilities, but fewer that would allocate their funds."

FLIP is so historic that nobody wants to see it scrapped. "I'd like to see a naval base or maritime museum adopt FLIP, and install the 55-foot section in the upright position so people can see it and actually go on it," Sparrock said. "The other 300 feet can be sunk as a reef for divers."

Sparrock said there are many ways FLIP—or at least parts of FLIP—can be preserved as an attraction and educational resource. FLIP would make a unique attraction that could be seen from a distance, but have a relatively small footprint. Meanwhile, the Navy History and Heritage Command completed a site visit and has retrieved items of historical significance

Sparrock said he's still hopeful a maritime museum will want it as something people could go into, and learn how ocean research was conducted.

"We're only limited by funding, not imagination," Sparrock said.

About the author:
Capt. Lundquist writes on naval, maritime, and defense issues, including developing science and technology for warfighters.

DIGITAL ADAPTIVE OPTICS:

THROUGH THE BLUR

By Dr. Kyle Drexler and Skylar Lilledahl

WEATHER CAN CONFOUND THE DIGITAL EYE AS MUCH AS IT CAN HUMAN SIGHT. RESEARCHERS AT THE NAVAL INFORMATION WARFARE CENTER PACIFIC ARE LOOKING AT A SOLUTION TO MAKE THINGS MORE CLEAR.

Atmospheric turbulence is a limiting factor for even the best imaging systems, and can blur important target features and degrade the information collected by the system. As information warfare plays an ever-greater role in daily operations, there is an enduring requirement to provide warfighters and decision makers with the best information possible. Digital Adaptive Optics (DAO) was developed to compensate for the distortions caused by the ever-changing temperature and pressure fluctuations of the atmosphere.

For example, older adaptive optic systems such as Shack-Hartmann wavefront sensors rely on reference sources and moving parts to correct for atmospheric wavefront distortions in feedback loop systems. A reference beacon is not too difficult a requirement in traditional astronomical applications of a Shack-Hartmann system, but it is a luxury rarely available in modern engagement scenarios.[1] There also are post-process algorithm solutions to this problem, such as multiframe blind deconvolution algorithms that use multiple frames of data to correct for image degradation.[2] This multiframe approach has the downside of decreasing the operational bandwidth of the imaging system. A future-focused adaptive optics system capable of performing in demanding atmospheric application areas must be self-reliant in its turbulence mitigation technique, and only require a single frame of data.
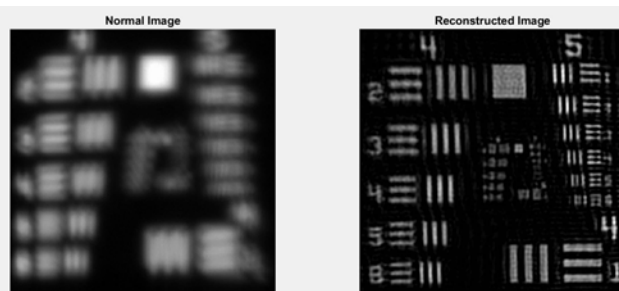

Figure 1. A normal image versus Digital Adaptive Optics reconstructed image in lab-based turbulence taken at the Naval Information Warfare Center Pacific. Images were obtained simultaneously in synchronized experimental setup.
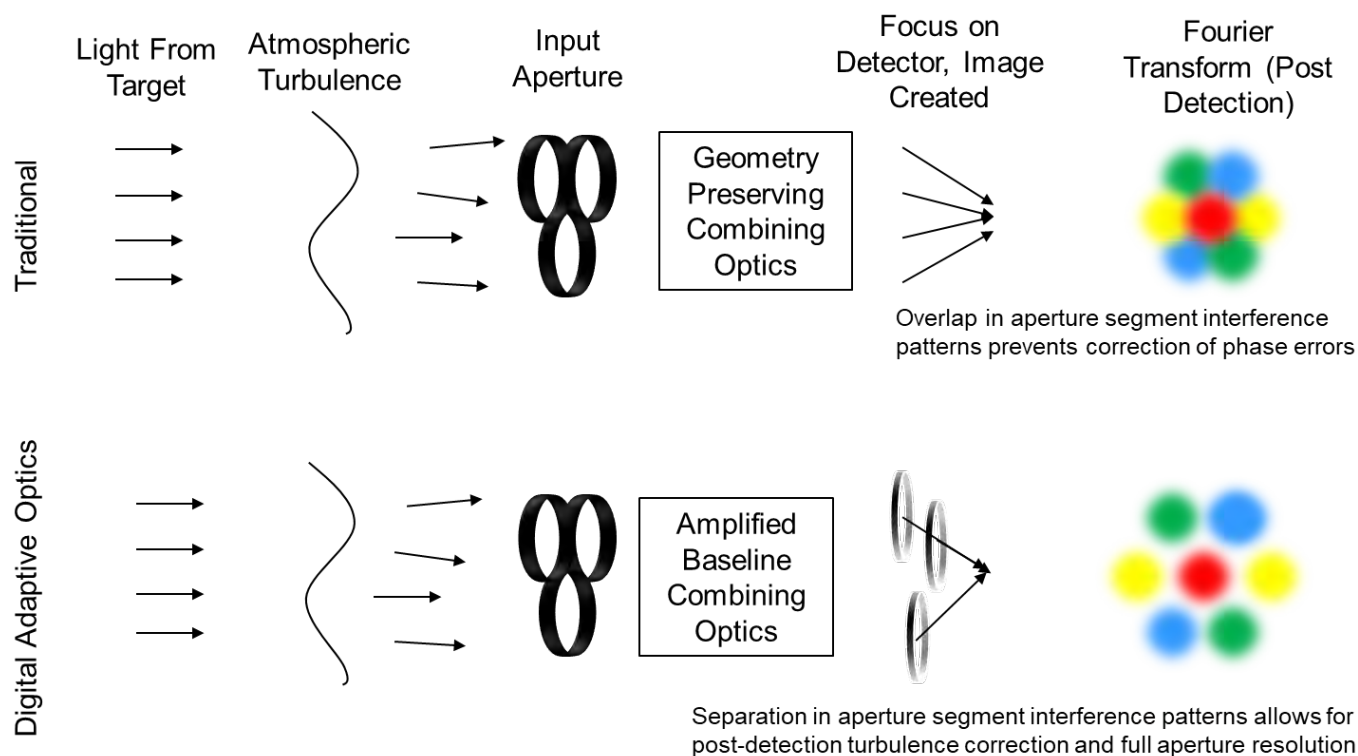
Figure 2. A three-aperture example, comparing the effects of a traditional imaging system to the system in Digital Adaptive Optics.

DAO, an opto-computational solution, is currently being developed by Naval Information Warfare Center Pacific. The DAO system combines the system stability of the multiframe algorithmic procedure with the single frame correction of the Shack-Hartmann technique. DAO is a self-referencing interferometer approach that does not require a reference source, moving parts, or multiple frames of image data. One promising feature of the technique is that it can be added inline to existing imaging systems.

As the name suggests, DAO measures and corrects for atmospheric turbulence digitally on individual frames of image data. This is accomplished using specialized optics to subdivide the input aperture of the imaging system into laterally separated sub-apertures. This light is then passed to the focusing optics to create an image with an interference pattern on the sensor. Figure 1 shows a diagram of how the spatially separated apertures result in a modification to the information within the system. In a traditional imaging system, the corrupted frequency information is overlapped and nonrecoverable, while the system with an optical separation allows the corrupted frequency information to be extracted and solved.

Recent work, shown in Figure 2, with a three-aperture DAO system has produced promising results demonstrating the mitigation of turbulence in a laboratory setting with a turbulence generator. Currently, the group is focused on creating a DAO interferometer with a greater number of sub-apertures to improve the mitigation in higher turbulence environments.

The DAO technology provides an imaging system with the means to passively correct for atmospheric induced errors. This technology will enhance imaging systems and enables system operators to provide the best intelligence, surveillance, reconnaissance, and targeting information to warfighters and decision makers in increasingly complicated environments.

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About the authors:

Dr. Drexler is an engineering scientist at the Naval Information Warfare Center Pacific and is currently engaged in advancing the state of the art in electro-optical propagation and atmospheric turbulence estimation.

Skylar Lilledahl is a scientist at the Naval Information Warfare Center Pacific focusing on optical atmospheric propagation.

CRANE ENGINEER
RECEIVES AWARD FOR RESEARCH ON
RARE, SUPERIOR METAL

By Sarah K. Miller

MANY ELEMENTS ARE LONG KNOWN, BUT REMAIN DIFFICULT TO USE PRACTICALLY. A MULTINATIONAL RESEARCH TEAM LED BY NSWC CRANE IS HELPING TO MAKE ONE RARE BUT VERY IMPORTANT METAL MORE USER-FRIENDLY.

A Naval Surface Warfare Center (NSWC) Crane Division mechanical engineer received an international award for analyzing the cutting of tantalum, a rare metal that is highly corrosion-resistant. Crane's Dr. Jason Davis led the US-Japanese research team from the Center for Materials Processing and Tribology at Purdue University. The yearly award is given by the Belgium-based Tantalum-Niobium International Study Center.

The team received the 2021 Anders Gustaf Ekeberg Tantalum Prize for its paper "Cutting of tantalum: Why it is so difficult and what can be done about it," published in the International Journal of Machine Tools and Manufacture.

Davis, who was the lead author of the research paper and lead researcher, says this recognition is meaningful to him and the team.

"I worked on this research during my doctoral studies at Purdue and this is my first peer-reviewed publication as a lead author," said Davis. "Tantalum research from all over the world was considered for the Ekeberg Prize. I believe this award will bring more attention to the Center for Materials Processing and Tribology at Purdue and validates the excellence of the research they perform."

The Ekeberg Prize is an annual award recognizing excellence in published research about the element tantalum (Ta). The Tantalum-Niobium International Study Center describes the long term future of the tantalum market as one that "will depend on technology-driven innovations and a new prize dedicated to this rare and critical element will encourage research and development. The Ekeberg Prize increases awareness of the many unique properties of tantalum products and the applications in which they excel."

Dr. Jonathan Dilger, the director of research for NSWC Crane, says these efforts continue to positively impact NSWC Crane's mission to support the fleet.

"I'm quite proud of the achievements of Dr. Davis that are recognized with the receipt of this prestigious international scientific medal," said Dilger. "Dr. Davis's research was co-sponsored by the NSWC Crane Ph.D. Fellowship Program and DoD SMART Scholarship Program, with investments that continue to pay dividends for our regional ecosystem and for the warfighter."

The authors of the winning paper are Dr. Jason M. Davis, Dr. Mojib Saei, Debapriya Pinaki Mohanty, Dr. Anirudh Udupa, Dr. Tatsuya Sugihara, and Dr. Srinivasan Chandrasekar. The team members mostly work at the Center for Materials Processing and Tribology at Purdue University, while Sugihara is based at the Department of Mechanical Engineering at Osaka University, Japan. Davis also works at the US Special Warfare and Expeditionary Systems Department at NSWC Crane.

Researching for a Solution

Dr. Davis has worked in Small Arms at NSWC Crane for 15 years, and says he has seen the difficulties and limitations with how commonly-used metals are employed in weapons manufacturing.

"A lot of weapon performance is built on how weapons are manufactured. I've seen this challenge with metals that are difficult to use, and tantalum is one," says Dr. Davis.

Dr. Davis says tantalum has many unique properties besides low thermal conductivity that make it worthwhile to research.
"Tantalum is highly resistant to heat and wear," says Dr.
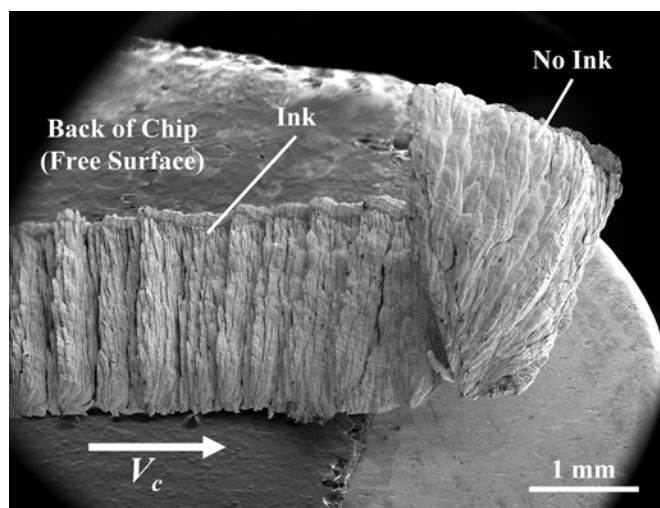
A scanning electron microscope image of a chip produced by cutting a tantalum workpiece that is coated with an ink medium only along part of its cutting length. The initial part of the cutting length is uncoated. The noninked region shows a very thick chip (around 34-fold thickening), with mushroom-like free-surface morphology, formed by sinuous flow and folding. In contrast, the chip from the inked-region is quite thin (around 5-fold thickening) and forms by segmentation flow.

Davis. "It is extremely corrosion resistant, like glass. In the healthcare industry, it is used for medical implants, like hip joints, as well as dental implants, like denture posts. The human body doesn't react to it; it's like it's not there. It is also used in capacitors due to its very thin dielectric layer which results in a high capacitance level per unit volume."

Tantalum is used in a variety of industries because of its unique and high-quality properties, but Davis argues it is not used as often as we might think.

"Tantalum is difficult to work with, so people choose to work with metals with inferior properties," said Davis. "It's a very difficult metal to cut with conventional methods, and therefore difficult to 'machine' and use. Our basic research shows a method that works."

In the article, the team of researchers write that "Tantalum has long drawn the ire of machinist, being particularly difficult to cut. . . . Often referred to as being 'gummy,' cutting of tantalum is characterized by very thick chips, large cutting forces, and a poor surface finish on the machined surface." These unfavorable attributes of the cutting have usually been attributed to several things, such as its relative softness and low thermal conductivity.

The article's authors write it is actually because of "the prevalence of a highly unsteady plastic flow – sinuous flow – characterized by large-amplitude folding and extensive redundant deformation. This 'sinuous flow' and the 'folding' that occurs in materials are more significant in tantalum than metals such as copper and aluminum."

In the case of copper and aluminum, there are options available for machinists to alleviate some sinuous flow through simply changing cutting parameters: increase the cutting speed, use a tool with a more positive rake angle, work harden the metal prior to cutting, and/or take lighter cuts.

Davis described the process for a machinist.

"When cutting copper and aluminum, the cutting forces are relatively low; so, the tool rake angle can be made more positive without too much concern of it breaking. Work hardening decreases the degree to which the metal plastically deforms, thereby decreasing the degree of folding. Smaller depths of cut also decrease the force. In addition, copper and aluminum are somewhat forgiving in that a single cutting pass will sufficiently strain harden the material below it and make the next few cutting passes easier until the strain affected material is removed. The high cutting forces and folding associated with tantalum put these options out of reach for the machinist."

The research didn't just study what made tantalum different than other metals to machine; the research conducted what could be done with the element in order to work with it.

"By application of a surface-adsorbing (SA) medium, e.g., permanent marker ink, to the initial workpiece surface," writes the articles authors, "we show that sinuous flow

The Anders Gustaf Ekeberg Tantalum Prize is awarded annually by the Tantalum-Niobium International Study Center in Lasne, Belgium, since 2018. Swedish chemist Anders Ekeberg discovered tantalum in 1802.

can be disrupted and replaced by a more energetically favorable flow mode – segmented flow – with thin chips and >70% reduction in the cutting force." This shows, the article argues, a "promising new opportunity" to improve its "gumminess."

Davis described how this research is different from other tantalum research.

"This research is unique in that it clearly establishes that this effect is not due to a chemical reaction since tantalum is highly corrosion-resistant. In the cases of copper and aluminum, this is not as easy to defend due to their reactivity with many chemicals. The research using tantalum leaves no doubt the effect of the surface-adsorbing media is altering the deformation through a mechanical means (i.e., a change in surface stress)."

Davis said this improvement provides exciting results for future capabilities.

"The research we conducted can lead to an increase in the use of tantalum, which could result in better performing technologies. Our research shows that if you can machine tantalum, it opens up a wide variety of uses most people thought wasn't possible. Tantalum has really perplexed machinists to use . . . it's pretty exciting to think we solved it. "

From Basic to Applied Research

According to a description on the National Science Foundation's website summary of the updated Frascati Manual—an internationally recognized document that provides methodologies for research and development—basic research is "experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view." Applied research is "original investigation undertaken in order to acquire new knowledge," and "directed primarily towards a specific, practical aim or objective."

For gun barrel manufacturing, many refractory metals (or metals that are resistant to thermal wear) are difficult to machine. Metals used in the process would exhibit poor surface quality and shorten tool life, among other challenges.

The broaching process was particularly difficult for rifling a refractory-lined gun barrel—and so far it has been unsuccessful. Through a SMART (Science and Mathematics Access to Retain Talent) seed grant, Davis is now applying the new knowledge of cutting tantalum to rifling a gun barrel.

The basic research conducted by Davis and his team not only reveals the fundamental reason behind the difficulty in cutting these soft and/or highly strain-hardening metals, but also provides a means to suppress the behavior through the use of a mechanochemical surface effect.

"The basic research shows a method that works, that's the important part," said Davis.

The proposed effort will aim to demonstrate that conventional broaching can be used to rifle a refractory-lined barrel, expanding the use of refractory liners to small-caliber weapons as well as providing much needed guidance for traditional machining of refractory metals for other defense applications, such as hypervelocity projectiles.

"Other processes such as grinding, honing, and comminution stand to benefit as well. In principle, many of the same physical parameters are present as in a cutting process," said Davis. "I am excited to see how others make use of this research."

About the author:
Sarah Miller is a contractor with Peerless Technologies writing for NSWC Crane's corporate communications office.

DIVISION NEWPORT
USES PRIZE CHALLENGES TO
ADVANCE
UNDERSEA WARFARE

By Evan Crawley

AN EFFORT TO IMPROVE THE PROCESS OF REVERSE ENGINEERING TO MANUFACTURING IS UNDER WAY THAT USES THE UBIQUITOUS HANDWHEEL—AN INDUSTRIAL-AGE MAINSTAY STILL ON MOST NAVAL VESSELS—AS A TEST CASE FOR INNOVATION.

In his experience as the Naval Undersea Warfare Center (NUWC) Division Newport's additive manufacturing lead, mechanical engineer Lewis Shattuck of the Sensors and Sonar Systems Department has seen the need to streamline the process from reverse engineering to manufacturing a needed component.

In collaborating with the Naval Sea Systems Command (NAVSEA) Technology Office (SEA 05T) and representatives with other warfare centers, it became clear that a specific example was needed for this refinement process. So, an item found on all naval ships— the handwheel—was selected as the prototype example.

"Handwheels are pretty ubiquitous among ships, as they have a number of different diameters and configurations," said Ben Bouffard, the Technology Office's division director. "Over the past few years, we've walked the deck plate with Sailors and asked, 'what are your headaches?' The handwheels have repeatedly come up."

Ranging from two-inch polymer supply-line valves to metal handwheels several feet in diameter, ships may have hundreds of different variations of handwheels. They're used to open and close a wide variety of valves and can be made from a number of different materials. These factors create a challenge if one were to break, since it is difficult to keep every type of handwheel on ships and this might result in critical equipment lying dormant in need of a particular part.

"Handwheels were identified as an ideal means to prototype this parametric tool," Shattuck said. "The prize challenge construct was recognized as an efficient and cost-effective means to develop a solution."

NSWC Division Newport, SEA 05T, NSWC Philadelphia Division, the NavalX Northeast Tech Bridge, and 401 Tech Bridge are working together to manage the Rapid Design Tool for Advanced Manufacturing Navy Challenge, announced last year in an effort to solve this problem.

A $30,000 prize is on the line for the company that can develop software tools to automatically produce computer-aided design files for the needed handwheel, allowing for on-demand and at-sea production of replacement parts.

Given all the different configurations of handwheels, bringing extra ones to sea is unrealistic. The process of reverse engineering and 3D printing the necessary parts aboard also can be time-consuming and difficult. After analyzing this problem, it was determined the solution is to develop a system where Sailors can easily measure the needed part and seamlessly translate that into digital data for a 3D printer.

Christian Cowan (from left), executive director of the 401 Tech Bridge, Dr. Steve Bordonaro, director of the NSWC Division Newport's Northeast Tech Bridge, and Christian Schumacher, technical program manager for Division Newport's Argus Maritime Defense Systems, share the details of the "Unmanned Surface Vehicle for Waterside Security" Prize Challenge at the 401 Tech Bridge's facility in Portsmouth, Rhode Island, in July 2021. Photo by Evan Crawley

"We need to make sure that the executable file that comes out is something that can be used right away," said Scott Storms, an engineer at NSWC Philadelphia. "We're looking for a smooth user interface for a standalone software tool in a common environment. If an input is incorrect, the system must be able to be notify the Sailor that they are incorrectly inputting the measurement so they can go back and measure again or check the numbers."

"This is another relatively new and exciting way to get a problem solved by reaching out to industry and innovators that don't usually work with Department of Defense," said Dr. Steve Bordonaro, director of the Northeast Tech Bridge. "Through the tech bridge, we really try to make that process easy for the program managers. The prize challenge is a quick and efficient way to reach out to industry to get a problem solved and it has a broader reach than the Navy usually has."

Handwheels are not the only example of how Division Newport is utilizing the prize challenge, though.

Last summer, Division Newport's Northeast Tech Bridge and the 401 Tech Bridge announced on its second prize challenge, "Unmanned Surface Vehicle for Waterside Security," which sought the creation of an expeditionary unmanned surface vehicle for security in harbors and ports. There is a $50,000 prize associated with the challenge that was open to domestic and international technology companies.

Bordonaro and Christian Schumacher, technical program manager for Division Newport's Argus Maritime Defense Systems, discussed the details of the prize challenge at the 401 Tech Bridge's new facility in Portsmouth, Rhode Island.

The US Navy is seeking a unmanned surface vehicle that is modular and "attritable," meaning that the vehicle should be low in cost with an ability to be reused several times with minimal maintenance. Because the need is for an expeditionary vehicle, the vehicle must be produced or assembled at the point of use, in less than two hours, and be capable of carrying or towing a variety of payloads. The vehicle must be able to be shipped in a 20-foot shipping container and provide the flexibility needed for various missions.

On 14 July 2021, the Division Newport team displayed a towed-array cable, a net-launching device, and bathymetric equipment to help company representatives visualize the payload requirements of the vehicle. They also addressed a variety of technical questions from the audience.

This theoretical challenge only required a written proposal that was evaluated by a team at Division Newport. In addition to a cash award of $50,000, this prize challenge will serve as a source selection for a potential follow-on prototype in an amount up to $1 million. Proposals can be from individuals, companies, or academic teams, or be a collaboration among those parties.

The cash awards for prize challenges help engage nontraditional problem-solvers.

"As a technical program manager, one of my challenges is finding the time and money for innovation — to figure out ways to further enhance our system," Schumacher said. "This was my first time participating in a prize challenge and it's great to have some help in this area. I'm looking forward to seeing what the participants submitted."

The Northeast Tech Bridge is part of a connected NavalX Tech Bridge network that enhances collaboration between Navy labs, industry, academia, and other military branches.

The 401 Tech Bridge, a nonprofit entity in Rhode Island and business unit of the University of Rhode Island Research Foundation, serves as a super-connector for companies that are developing leading-edge advanced materials, technologies, and products. The 401 Tech Bridge has a partnership agreement with Division Newport to support the Northeast Tech Bridge, increasing collaboration, knowledge sharing, and innovation by connecting Navy and industry technical problems to companies, universities, and innovation partners.

Lee Silvestre, coordinator of the NavalX Northeast Tech Bridge, said the 401 Tech Bridge can help technical program managers work with non-traditional companies or individual innovators because they have those contacts in place.

"They can help develop and administer the challenge," Silvestre said. "They also help with the contacts aspect and with the evaluation."

"The Navy is always looking for good ideas and we're interested in connecting with industry and academia," Bordonaro said. "The tech bridges provide an excellent way to make these projects happen."

More information on Prize Challenges can be found at challenge.gov and 401TechBridge.org/funding-opportunities. If you are a Navy program manager with funding to solve a technical challenge, reach out to the Northeast Tech Bridge at NWPT.NUWC_NPT_NE_TECH_BRIDGE@navy.mil and they will run a prize for you.

About the author:
Evan Crawley is a support contractor with McLaughlin Research Corp. within NUWC Division Newport public affairs.

Sailors assigned to the *Minneapolis-Saint Paul* (LCS 21) precommissioning unit train using computer-generated simulations during Surface Training Advanced Virtual Environment scenarios at Surface Combat Systems Training Command Detachment Southeast, LCS Training Facility. All Sailors and officers assigned to a littoral combat ship train in watch stations using virtual reality technology, and are required to demonstrate proficiency in their respective watch stations before manning live, shipboard watches. Photo by MCC David Holmes

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