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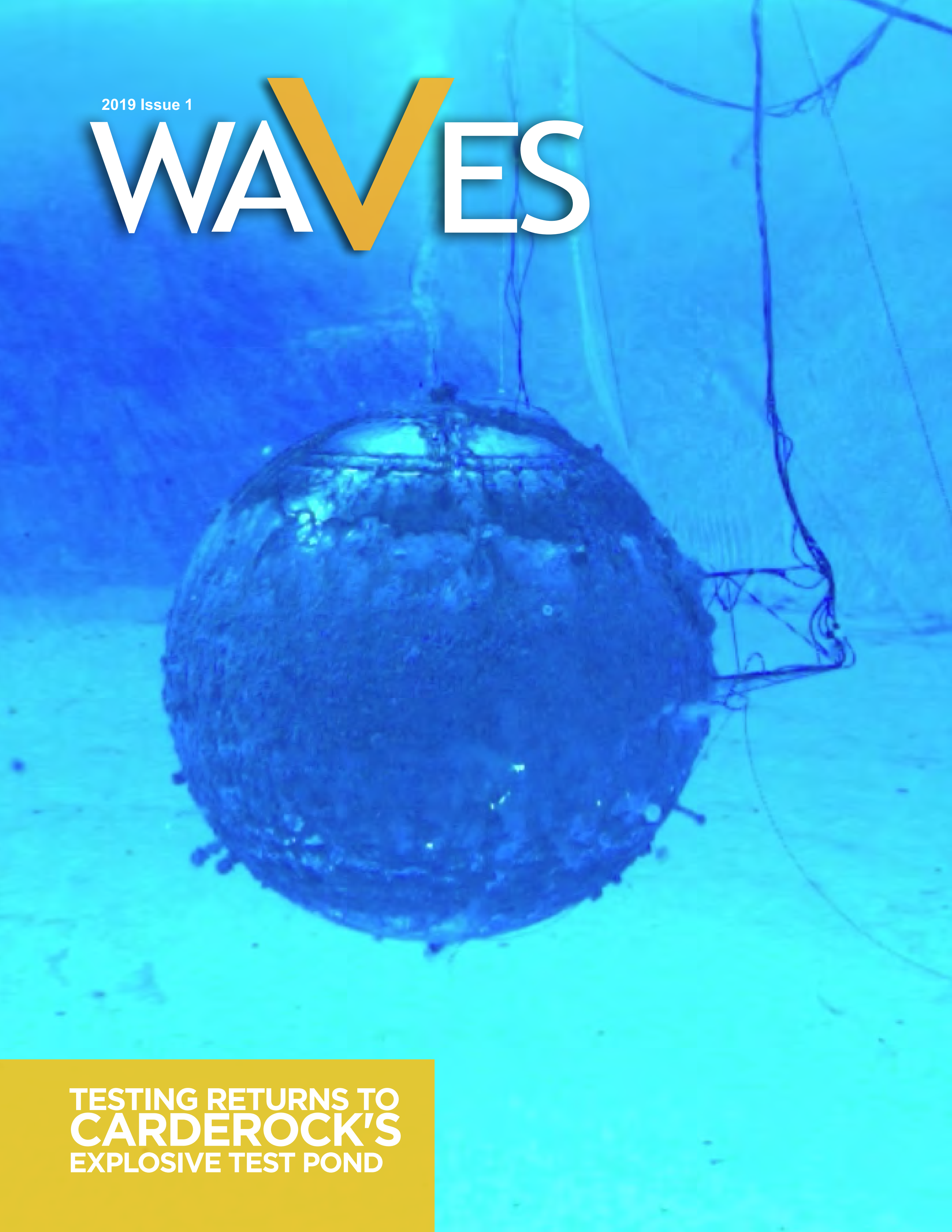
WAVES



TESTING RETURNS TO CARDEROCK'S EXPLOSIVE TEST POND

Content

WAVES

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In this issue

Everyday I come to work, I am more proud of the devoted people here at Carderock whose hard work gives our greatly appreciative Sailors and Marines the competitive edge. One of the ways we like to reward people for thinking outside the box is the through the Technical Director's Innovation Challenge, which was started by my predecessor in 2014. The results through the years have produced some very interesting ideas, and this year is no different. In this issue of Waves, the spotlight is on several of these TDIC initiatives from fiscal 2018.

Carderock's Explosive Test Pond re-opened in the fall and has since been busy with testing. The cover of Waves showcases the underwater explosive bubble of a recent test. The many facilities here at Carderock continue to be a highlight of anyone's visit to Carderock, which has seen many visitors this year, including several congressional delegations and staffers. I love showing off the important work being done here and how it supports the warfighter.

Along those lines, Carderock is leading an Advanced Naval Technologies Exercise later this year to support the Marines. Our team will head to Camp Lejeune, North Carolina, to test many technologies, not only from Carderock, but also from other government entities and industry, that could potentially help the warfighter in advanced maneuver, logistics and force protection.

Carderock's role in research, test and evaluation has made the Navy and Marine Corps stronger in so many ways, and I'm proud to be part of this great team.

Larry Tarasek

Cover

A still image taken from high-speed footage of charge characterization testing in October 2018 at Naval Surface Warfare Center, Carderock Division's Explosive Test Pond in West Bethesda, Md. The Explosive Test Pond recently opened after a two-year renovation. (Video provided/Released)

Brian Caine
TUBA program manager

By Brooke Marquardt, Carderock Division Public Affairs

Brian Caine, TUBA program manager, receives the Navy Meritorious Civilian Service Award on Nov. 7, 2018, from Naval Surface Warfare Center, Carderock Division Commanding Officer Capt. Mark Vandroff for his contributions in the area of acoustics systems for undersea warfare. (U.S. Navy photo by Devin Pisner/Released)

With a passion for travel and staying active, Brian Caine is the TUBA Program Manager and recently, the recipient of two different awards.

Caine graduated from the University of Maryland in 1998 with a bachelor's degree in mechanical engineering and John Hopkins University in 2004 with a master's degree in systems engineering. While still working on his undergraduate degree, Caine applied for a summer internship at Carderock Division, but instead was offered a spot in the Cooperative Education (Co-op) Program. Caine has worked in the same program at Carderock Division since 1996. The Co-op Program has gone through many name changes throughout the years, and today it's known as the Department of the Navy Pathways Internship Program. Caine continues to advocate for the program and recruit student engineers through it.

"Coming out of college, I didn't want a job where I was sitting at a desk all the time, so it was a great balance of being in the field, being on the ships, travelling, seeing the things you build in the environment they were made for, and then being able to bring that knowledge back here and to the lab to improve upon or make the necessary adjustments to make it the best that it can be. What keeps me coming back is seeing our concepts turn into realities, and then seeing them installed and operating on ships," Caine said.

The TUBA Program celebrated its 50th anniversary in 2017, and contrary to popular belief, TUBA is not an acronym. Like many aspects of the program itself, origins of the name date back to the 1970s and are shrouded in mystery. The program supports the submarine fleet; builds acoustic systems that deploy with submarines; sustains and maintains capabilities in the field; and trains personnel on the process to use the acoustic sonar data-collection tools. The role of the program continues to expand, and the majority of it is classified, but there are about 20 government employees, several industry partners, university labs and uniformed Navy personnel scattered across the country to support the program. Because the things the TUBA team works on are so niche, and there is a lot of on-the-job training, Caine recommends that new employees come in with the right attitude, learn as much as they can and find a mentor to learn the right processes to be successful.

"This is one of the reasons that this program has been around for 50 years. We're really good at continuous improvement and we hold ourselves accountable. If anything were to go wrong, we have formal processes on how to solve the issue at hand and prevent it from happening again," Caine said.

On Sept. 18, 2018, Caine received the National Defense Industrial Association (NDIA) Undersea Warfare 2018 Bronze Medal, which recognizes contributions of dedicated individuals who expand the technology knowledge base of undersea warfare.

"In general, we've done a lot of good things over the last few years that have gotten a lot of visibility, filling a need quickly and successfully. Some of those projects highlighted our team's ability to adapt, evolve and respond rapidly. Different teams have come to us and asked us to do things and we've been able to execute. This brought us more visibility. I was honored and humbled to be presented the award," Caine said.

Additionally, on Nov. 7, Caine was presented with the Navy Meritorious Civilian Service Award, the third highest honorary award the Navy can give to a civilian employee.

"The Naval Surface Warfare Center is proud to present the Navy Meritorious Civilian Service to Mr. Brian J. Caine for his personal dedication and commitment in the area of undersea warfare from June 2006 through September 2018. Mr. Caine's contributions in the area of acoustic systems for undersea warfare applications are directly reflected in his role as technical program manager for the TUBA Program. His leadership in the area of systems development, full-scale testing, sensor-performance evaluations, and acoustic calibration has had a direct and positive effect on the success of United States Navy operational forces, as well as the intelligence community. Mr. Caine is a recognized authority on acoustic collection systems, and his contributions in technology and practices have added to the United States' dominance in the area of anti-submarine warfare," Commanding Officer Capt. Mark Vandroff read from the award citation as it was presented to Caine.

Technical Director's Innovation Challenge encourages employees to chase an idea

The Technical Director's Innovation Challenge (TDIC) was established in 2014 to address the hunger employees at Naval Surface Warfare Center, Carderock Division often have to chase opportunities to innovate.

The aim of the challenge is to stimulate innovation across all of Carderock's technical and business areas: concept development, science and technology, research and development, test and evaluation, fleet support, in-service engineering, acquisition support, logistics research and development and business processes.

Participants progress through three phases: concept exploration, maturation and implementation. They have latitude during the initial phase to go where the research leads, even if it deviates from the original plan, and they are encouraged to apply the basic principles of human-centered design and are mentored to do so throughout the project.

The 2018 TDIC projects ranged from exploring new ways to store and manage data, to pressure measurement, and adding new parts to existing ships. In the words of Nobel Prize-winning economist Thomas Schelling, "During the course of ordinary analysis, one thing a person cannot do, no matter how rigorous his analysis, or heroic his imagination, is to draw up a list of things that would never occur to him." The TDIC addresses this gap while simultaneously tapping into the interests, passion and ingenuity of the Carderock workforce. The following projects were briefed in October and represent a few of the TDIC projects.

Structural design optimization: producibility vs. weight

By Benjamin McKnight III, Carderock Division Public Affairs

In April 2017, the Congressional Budget Office estimated that the U.S. Navy would have to spend an average of $26.6 billion a year in shipbuilding costs for 30 years to reach its 355-ship goal. According to the same CBO report, to build and operate those 355 ships would cost about $102 billion each year through 2047. Skylar Stephens and Nathan Hagan of the Criteria and Risk Assessment Branch at Naval Surface Warfare Center, Carderock Division, believe that cost can be reduced.

Through the Technical Director's Innovation Challenge, Stephens and Hagan undertook a project to determine how the Navy can save money on its ship production by changing the criteria used to make a vessel.

"We try to optimize our structures based on how low we can get the weight down and still pass all of our criteria, but that really doesn't do us justice," Stephens said. "It does not account for the life-cycle support cost of the ship, and it oversimplifies the contributions that are associated with acquisition cost estimates of a vessel."

Simply put, there are a multitude of other factors that Stephens thinks need to be considered in ship building, and accounting for said factors could reduce the amount of money spent on a ship throughout its life. The project, titled "Producibility Structural Design Optimization," looks to identify more efficient metrics of ship-building standards so engineers can include them into their programming.

"As part of the effort, I interviewed lots of subject-matter experts who had written papers in this area, people like Bob Keane (a former U.S. Navy chief naval architect)," Stephens said. "What we found is different definitions of producibility."

Stephens identified producibility as factors such as how many labor hours it would take to build a ship, how susceptible parts would be to damage and corrosion or how much it would cost the Navy for ship repairs in the long run.

"Producibility is in all of those things; it's not just how easy it is to make, it's also how easy it is to maintain the vessel for a life-cycle support," Stephens said.

Tackling this project included taking a human-centered design workshop at the U.S. Office of Personnel

Management in Washington, D.C., a course which Stephens credited as a key factor in their research and success.

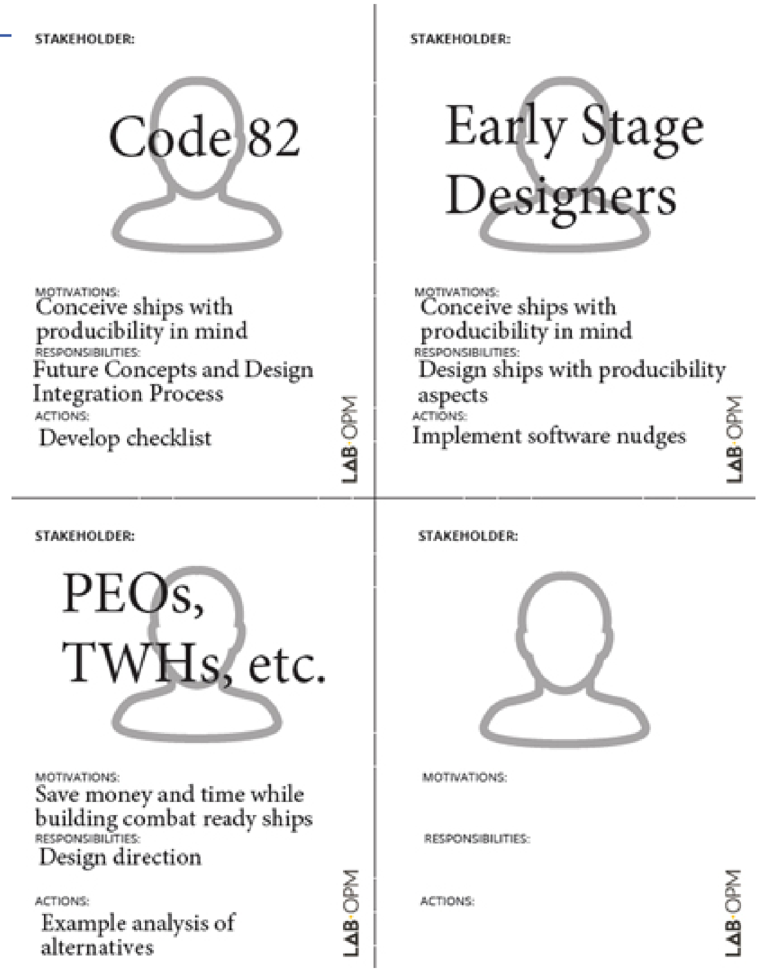
"That process of thinking and listening to people is critical and something we don't get in our day-to-day work," Stephens said. "Seeing people like Jeff Hough (Carderock's distinguished engineer for ship design) and Bob Keane discuss what producibility is and what the Navy needs to do to address it, you learn a lot more in a situation like that."

The project is far from complete, but they do have pieces to their puzzle that Stephens thinks he can use in his other Carderock assignments. According to Stephens, their current producibility variables can be assigned as either quantitative or qualitative metrics, with the former being the easier of the two to implement.

"To move it forward, we need to integrate it into the tools that we use here at Carderock," Stephens said.

With his Integrated Structural Design Environment Team, Stephens is attempting to include the quantitative metrics they discovered into the software that is used for designing ships. His hope is that showing the positive changes that can come with using the quantitative elements of producibility in programming will lead to funding for execution on a larger scale.

"It won't necessarily be an optimization algorithm that gives me the most producible design, but at least it's a step forward," he said.



During a human-centered design course offered by the Office of Personnel Management, participants discussed the roles of stakeholders in ship design. This HCD event was part of the Technical Director's Innovation Challenge project by Carderock's Skylar Stephens and Nathan Hagan titled Structural Design Optimization via Producibility. (figure from final presentation)

The process of test and simulation planning with Dr. Art Reed

By Benjamin McKnight III,
Carderock Division Public Affairs

To run a successful experiment (test or simulation), one must have a formal plan. Dr. Art Reed, the Navy's senior research scientist and technical consultant for high-speed ship hydrodynamics, believes such planning is paramount not only to experimental progression, but also to tasks such as developing proposals and program plans.

Reed hosted a seminar titled "Test and Simulation Planning" in early December, breaking down the steps of the formal experimental planning process and the importance of each step. During the seminar, Reed spoke on how he first learned about the formal experimental planning process when he got involved with the Lockheed Corporation (now Lockheed Martin) conducting testing on the research vessel Sea Shadow in the 1980s.

"They came in and they asked, 'Where's your process documentation?' and the answer was, 'We have none.' Being involved in those efforts in the '80s and then the Sea Shadow trials in 1993 got me involved in starting to develop some of that documentation," Reed said.

According to Reed, there are four processes that make up experimental design that are recorded in four documents. The first, and most important, step in the process is setting objectives, logging them in a top-level objectives document that can range anywhere from a one-page memo to a 30-page report.

"If you don't have the correct objectives, you're not going to do the right experiment," he said. "Your top-level objectives need to answer 'what and why.' Anybody who's reading those objectives without having a 'why' to understand the 'what' can't determine whether the objective would make any sense."

In the second step, Reed said, "You have to decide how you're going to go about proving this hypothesis." The work done at this stage goes into the data and analysis plan (DAP).

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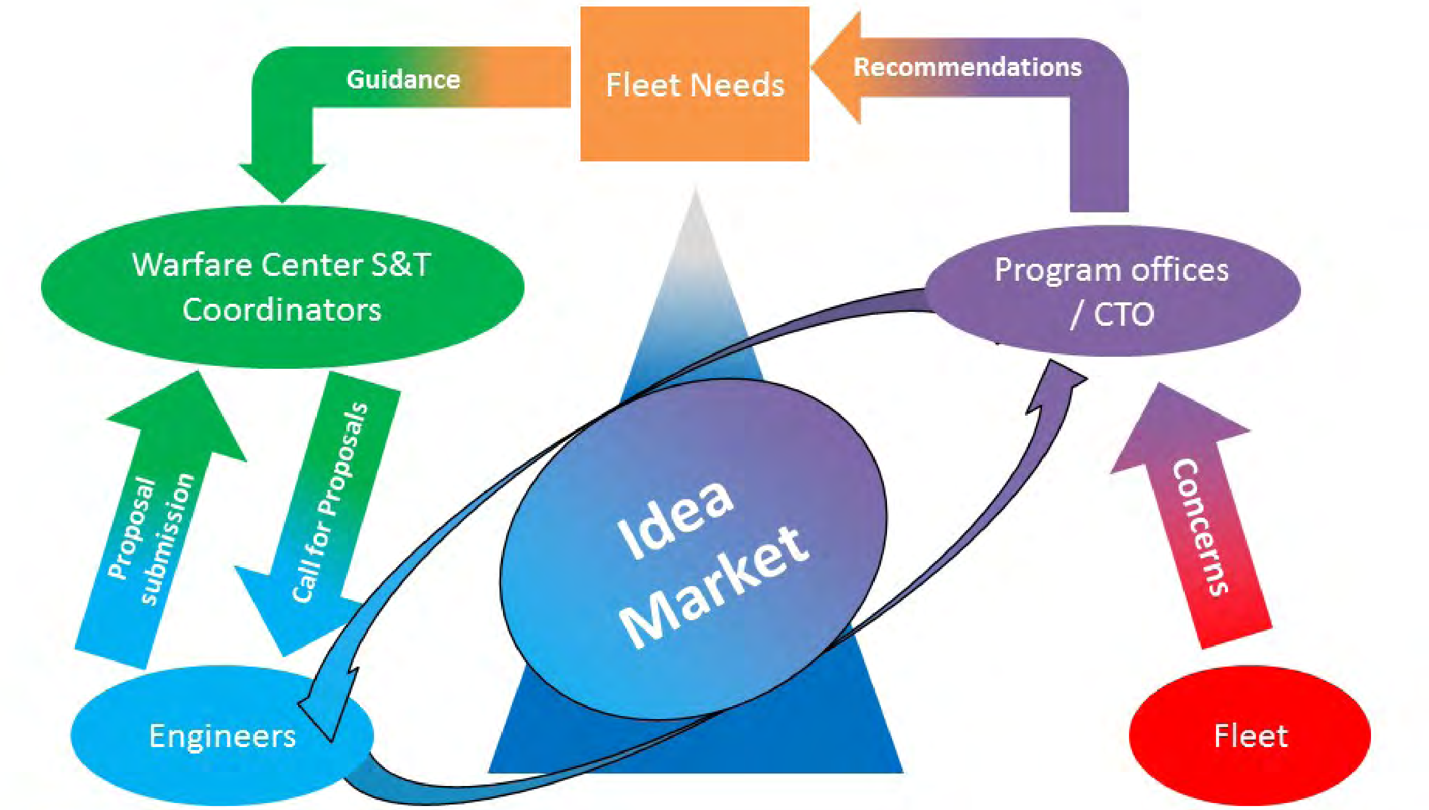

An example of how ideas can be crowdsourced among engineers and other stakeholders during proposal ideation. (Taken from a slide of the Idea Market Brief)

DAPs consist of multiple top-level objectives, each containing five subsections of material including information such as data analysis quality, preferred data sets and analysis plans. A DAP needs to be signed off by both management and a sponsor or sponsor's agent after it has been peer reviewed, a practice that Reed emphasized multiple times throughout his lecture.

"You can't do it in a vacuum. You need to be consulting with your colleagues to make sure you're not missing something," Reed said.

While experiments are meant to confirm hypotheses, Reed said that it is critical for those conducting an experiment to understand the statistical uncertainty of results. One may have an idea of what they believe will come from an experiment, but they should not be married to the idea that their perceived end results are guaranteed to happen.

The experimental planning phase, third in Reed's four-step process, is heavily dependent on the scientific method. Reed said that one must follow the scientific method "not because it is mandated, but because we are scientists and engineers." At this point, experimenters should be answering a series of questions and creating contingencies in case things do not go as planned. Reed believes that following the scientific method in experimental planning will lead to reaching meaningful conclusions.

The test or simulation readiness review (TRR/SRR) is the final stage of the of test and simulation planning process. By now, experimenters should have a nearly complete plan in which their superiors are confident. Reed detailed an extensive checklist, the TRR/SRR checklist, that he suggests be used to confirm an experiment's readiness for execution. This checklist comprises items such as ensuring there is a test schedule, that training has been completed for test personnel and that a dry run of the test has been complete. Here, testers have a chance to tweak their experiment plan, experiment matrix and make last-minute adjustments to make sure that nothing has been forgotten.

Reed said that the TRR/SRR step needs to be formal, as shortcuts will diminish its purpose. Once again he advised using cohorts by having a peer dry run, as well as a formal dry run. The work at this point should not be too demanding, as the harder tasks have already been completed. "If the TRR/SRR preparation takes too much effort, you are not ready for the experiment," Reed said.

For years Reed has ascribed to the test and simulation planning process and has given this lecture numerous times in the past. He said a no-fail experiment is not guaranteed, but he considers the test and simulation planning process one that will mitigate most errors and gaps in experimentation. These processes feed right into the technical-excellence policy being rolled out at Naval Surface Warfare Center, Carderock Division, where people with projects could potentially use this process as formal documentation for their research experiments and tests.

A stern flap extends from the stern of the guided-missile destroyer USS Stockdale (DDG 106) in port at Pearl Harbor on July 9, 2012. A stern flap is an extension of the hull bottom surface which extends aft of the transom and is used to modify the flow field under the hull afterbody, decreasing flow velocity and increasing pressure, resulting in reduced drag, reduced turbulence, and thus, reduced hull resistance. (U.S. Navy Photo by Mass Communication 1st Class Tony Spiker/Released)

Stern flap integration hull form selection

By Benjamin McKnight III, Carderock Division Public Affairs

What if the Navy could have more volume for their ships and maintain its power at the same time? A team of engineers at Naval Surface Warfare Center, Carderock Division contends that if designers change the way they approach their initial design, both feats can be achieved.

Michael Lacny and Dominic Cusanelli from Carderock's Full Scale Trials Branch and Wesley Wilson in the Computational Analysis and Design Branch collaborated on a Technical Director's Innovation Challenge (TDIC) project to prove why ship designers should start including stern flaps as essential pieces to a vessel's build rather than an attachment later down the line. Their project, titled "Stern Flap Integration with Hull Form Selection," aimed to show how adding stern flaps in the early stages would have multiple benefits that would interest the Navy in terms of both finances and performance.

The primary function of the stern flap is to reduce the drag on the hull, which leads to a handful of positive second- and third-order effects including decreasing the amount of power necessary to operate and saving fuel. Stern flaps have traditionally been placed at the transom of a ship after the design and build is complete, and often to enhance the performance of an existing hull. Because every inch of space is crucial on a watercraft, the group believes that integrating stern flaps in preliminary ship designs would additionally lead to more available volume or possibly a smaller engine. Cusanelli, who has been at Carderock for 35 years, said that the idea of the stern flap as a post-production addition is a dated concept. "I have been involved in these designs since 1988 when I put the first one on a ship," he said. "We're trying to get rid of this perception and say, 'You can include it as part of your design spiral.'"

Actually testing their concept was a major challenge for the team as the cost to build physical, testable models of the hull forms and stern flaps far exceeded their limits. Lacny said that they used a combination of computer-aided design and computational fluid dynamics (CFD) software to run their experiments, the latter of which they trusted Wilson to complete. "We've known Wes and the capabilities of his office for quite some time and use him frequently for this type of stuff," Cusanelli said.

For CFD to work the way they intended, the group had to find a way to incorporate real, full-scale data into the program. "The hardest part was getting all the inputs into CFD then finding out we don't have acceptable data in real-world scenarios. We were doing bare hull in CFD meanwhile in the real world, every appendage is on the ship." Additionally, to fit within the scope

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3D-printed models of stern flap possibilities created by Michael Lacny, Dominic Cusanelli and Wesley Wilson in their Technical Director's Innovation Challenge project, "Stern Flap Integration with Hull Form Selection." (Photo illustration by Nicholas Brezzell/Released)

of the TDIC, the first attempt was to see if simpler and faster hydrodynamics analysis tools that would be more appropriate in an early-concept design study, could predict the performance changes of the stern flap. Analyses were performed using the CREATE-Ships Integrated Hydrodynamics Design Environment (IHDE), which is being developed at NSWC Carderock as part of the DOD High Performance Computing Modernization Program (HPCMP) CREATE software development program.

While the challenges made for a complex project, they still saw results that they knew were steering them in the right direction. Lacny displayed multiple designs of hull forms with a diverse set of stern sizes and their corresponding stern flaps that were in turn tested in CFD to explore the effects of the stern flaps on the ship performance. Some designs had a wider stern, others had a deeper stern, and a few more expanded both the width and depth. Doing the extreme of the third option proved to be the least effective in terms of their desired end goal, but the former options proved to be effective for maintaining power requirements while increasing volume.

"That was the most rewarding part, knowing that I am able to do this in software and it wasn't breaking," Lacny said. For Cusanelli, working on the project was just short of a dream come true. "I've sort of had this idea forever and seeing Mike take it, run with it and get some progress, it's more rewarding than anything," he said.

Although the TDIC is over, their work has not gone unnoticed. Lacny said they were asked whether a stern flap would be good for the hull form of a ship being designed now but, "the hull form was shaped different, so at that time we said maybe it wouldn't be beneficial." More tests need to be done as they continue to try and sway others toward their unconventional idea. According to Wilson, "To do so, however, will require some additional exploration in how to leverage more trusted physics predictions with higher fidelity CFD tools. With increasing computational power available via high-performance computing resources, this is becoming more tractable and could help to yield significant design improvements that incorporate stern flaps as part of the design."

Enabling access to data

By Benjamin McKnight III,
Carderock Division Public Affairs

When engineers conduct experiments, the data from the work need to be stored somewhere for future reference. Using hard drives and other forms of removable memory is a popular method because it is secure, but this might not always be convenient when another person needs to recall that work. Engineers at Naval Surface Warfare Center, Carderock Division have run into the issue before and want to put an end to it once and for all.

Bradley Campbell of Carderock's Simulations and Analysis Branch and Eric Giesberg from the Full-Scale Trials Branch used Carderock's Technical Director's Innovation Challenge as an opportunity to present an idea that would make data that are often hard to find accessible to all of their fellow engineers.

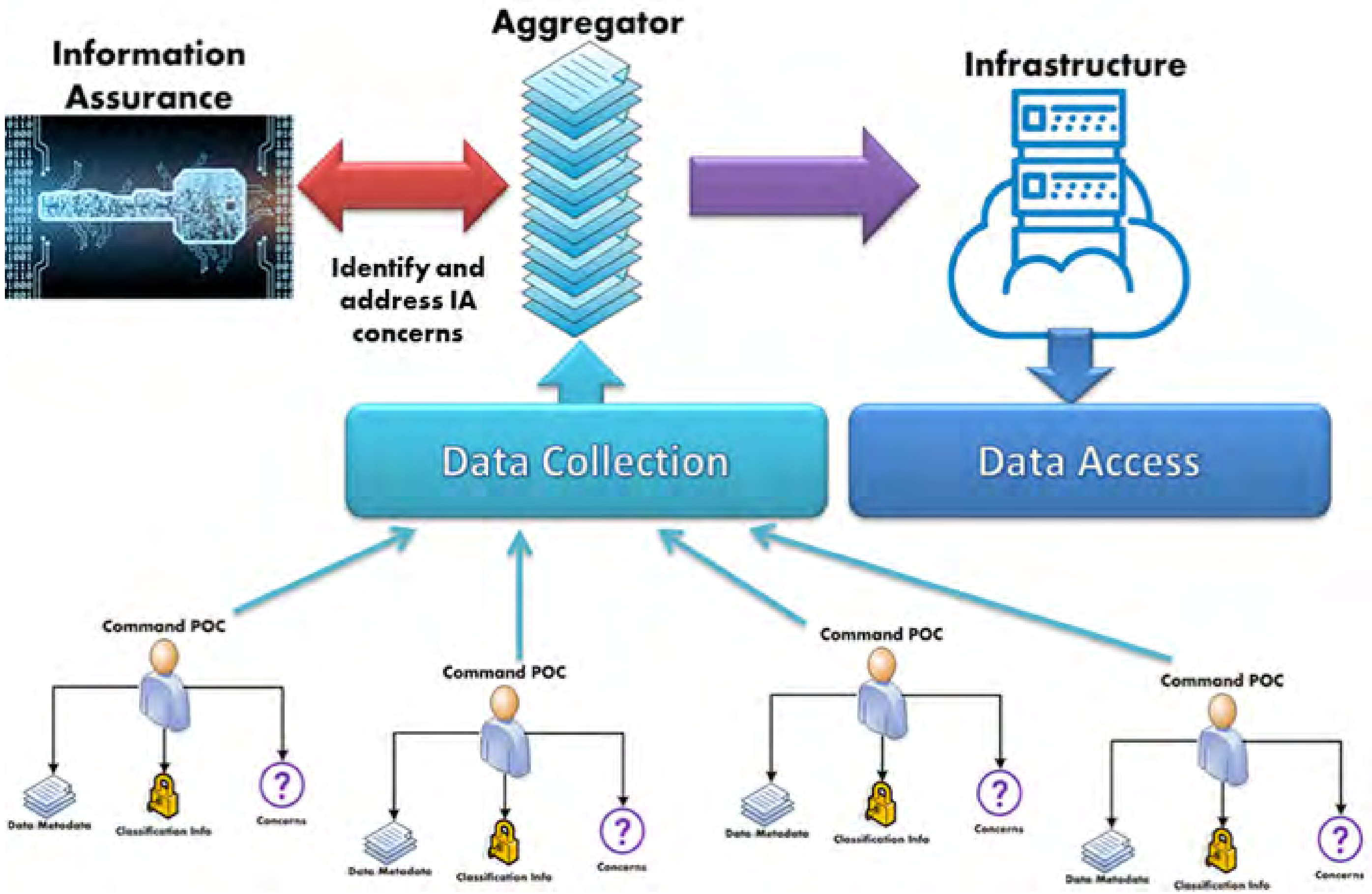
Titled "Data Curation: Enabling Access to T&E Data," Campbell and Giesberg foresee a day when a person in need of information from another experiment can simply go into a secure database and pull the necessary data from it. Their end goal is to bring consistency to data storage for Carderock.

"It's a complicated problem, especially if you start thinking about making something flexible enough for even other groups to use," Giesberg said.

According to Giesberg, they made an attempt a couple years ago, but did not find legitimate solutions at the time. However, the technological advancements through the years made now a good time for the duo to reengage with the problem and suggest a usable product.

"New technologies have helped enable a lot of things, that's why we came back and proposed it as a TDIC," he said.

Both Campbell and Giesberg understand that many



others, like them, aren't software- and programming-focused individuals. As a remedy, they want their database to be simplified enough on the front end that its users will not need to know the metadata behind what they are searching for.

Their first hurdle was fully grasping the programming aspect of the project. "We're both trained as engineers, not software people, so that was our first chance of working together on something like that," said Giesberg, who has been onboard Carderock for seven years.

From there, they had to find the type of database that would best work for their situation. Although there are plenty of ideas to draw from, Campbell and Giesberg needed to be assured that they would have a level of flexibility that has become common in more recent database concepts.

"The standard go-to databases in the past have been called SQL (structured query language) databases, which are rows of columns," Campbell said. "You have tables, which has rigid structures of columns and you fill in those, and that's it." Instead, they opted to look into NoSQL databases, a newer technology that gave them the latitude to upload data in a nontraditional format and organize it within the program.

As part of their research, Campbell and Giesberg attended the 2018 Scientific Python Conference in Austin, Texas. At the conference, they were exposed to Kitware, a New York-based technology company working on a project called Girder that has many parallels to the concept that the two of them were looking into.

"We ended up meeting with a few of the Kitware employees down at their Virginia office and decided to take a bigger look into Girder," Campbell said. They presented pieces of what Girder could do, showing off a product that could be likened to a share drive with options for administrators to control the information put into the system all the way down to a folder's metadata. With it being an open-source platform, Giesberg said working with Girder created a secondary challenge for the pair on how to properly use open-source for the information they deal with. Girder only covers the back end of their project, though, and the two are still looking for a suitable way to provide the front-end solution for regular users who simply need to access or upload data.

For the time being, Campbell and Giesberg have taken to consulting with others to make advancements or contribute to other similar ideas, such as working with the Naval Surface Warfare Center, Corona Division's cross-Warfare Centers Naval Innovative Science and Engineering (NISE) 219 effort to catalog sets of data, where Carderock is leading the infrastructure part of the overall effort.

Campbell and Giesberg hope that the steps taken now can eventually turn into a division-wide change on how data curation is viewed and that one day, they will have a way for their counterparts to securely and efficiently share data.

Carderock to host technology exercise in July

By Edvin Hernandez and Kelley Stirling, Carderock Division Public Affairs

An unmanned vehicle, part of the multi-utility tactical transport family of systems, operates on Red Beach during the Ship-to-Shore Maneuver Exploration and Experimentation (S2ME2) Advanced Naval Technology Exercise (ANTX) 2017 at Marine Corps Base Camp Pendleton, Calif., on April 25, 2017. ANTX brings industry, academia and the Naval Research and Development Establishment together to demonstrate emerging technology and engineering innovations that address priority Navy and Marine Corps missions. (U.S. Navy photo by John F. Williams/Released)

Naval Surface Warfare Center, Carderock Division will be hosting the Advanced Naval Technology Exercise (ANTX) for advanced maneuver, logistics and force protection in July at Camp Lejeune, North Carolina. This will be Carderock's first experience hosting an ANTX.

Rod Peterson, Carderock's Marine Corps Vulnerability and Protection Program manager (Code 664) and lead organizer of the event, described ANTX as a great occasion to showcase what Carderock has to offer. During the fall of 2018, government and industry vendors submitted the technologies they would like to test during the July 2019 ANTX, which provides an opportunity to test prototypes to participate in an interactive and progressive series of exercises. In this collaborative and low-risk environment, engineers will be able to demonstrate their technologies and innovations at the unique facilities in Camp Lejeune.

"However, the individual who invents the technology first is not necessarily the winner or the best, unless he integrates it into the operator's hands and gets them to successfully adapt it to their way of fighting," Peterson said.

The operator in this case will be the Marines, and the technologies to be evaluated will align with maneuver, logistics and force protection.

In all, Peterson said they received more than 50 submissions with at least 80 technologies to be evaluated. Industry had the majority of submissions, while the government or a government-industry team combo made up the rest. Carderock is involved with eight of these submissions, either as a technical participant or in a lead role.

"The idea is to see where these technologies fit into achieving the mission for the ANTX focus—Fight the Naval Force Forward," Peterson said, adding that ANTX is basically phase one of the process. "Once you get through the ANTX, if you have technology that looks to be very promising and the users, operators and the technologists all score them fairly high, then there's a potential for further development."

Selected participants will be invited to phase two, which includes a six- to 18-month follow-on development process, where they will continue experimenting and prototyping their projects. Successes from phase two may then end up with a contract package.

Peterson said they are in the final planning stages and conducted a Technical Interchange Meeting (TIC) in March at Camp Lejeune, which is where all the details got flushed out. The vendors got to see the lay of the land and explain, in detail, what they will need for the July demonstration.

"The TIM is where the possibility of teaming of technologies occurs," Peterson said. "From there, we can bring the vendors together and see what kind of system can be assembled and evaluated at the ANTX event."

After that, there will be a final planning meeting in May, where the organizers will finalize the schedule for each focus area and each vendor in detail.

Peterson expects the ANTX event to be very challenging, but he looks forward to seeing the technologies that may come from it to support the warfighter.

Explosive Test Pond ribbon-cutting ceremony

By Brooke Marquardt, Carderock Division Public Affairs

The Explosive Test Pond at Naval Surface Warfare Center, Carderock Division officially reopened with a ribbon-cutting ceremony on Oct. 10. The Explosive Test Pond is shaped like a pentagon: each side is 125 feet long, the pool is 25 feet deep and it holds 3.5 million gallons of water. It includes a water filtration and chlorination system to provide high-clarity water and enables pristine, high-speed footage of underwater explosive testing. It is rated to support explosive charges up to 3 pounds. Additionally, the pond can support remotely operated vehicles (ROVs) and unmanned, underwater vehicle programs, with an on-site ROV lab.

The availability of the Explosive Test Pond is a tremendous advantage to Carderock Division and the Navy. It provides a unique capability to conduct and evaluate underwater explosion (UNDEX) testing in near-laboratory conditions with the ability to collect high-speed footage. The Explosive Test Pond supports a full-instrumentation suite that includes pressure, strain, velocity and displacement sensors to evaluate the effects and response of UNDEX testing on different structures and materials. It is a convenient and cost-effective solution for small-scale investigations, provides visual validation for code development and analysis, proof-of-concept testing and it allows for the ability to characterize explosive charge output for the development of new explosives. Lastly, it allows Carderock to maintain an explosives program and personnel that relates to all programs up to the full-scale shock trials.

Leaders in Naval Surface Warfare Center, Carderock Division's Platform Integrity Department and command leadership cut the ribbon officially opening the newly renovated Explosive Test Pond in West Bethesda, Md., on Oct. 10, 2018. From left: Laurence O'Neill, head of the Dynamic Measurements and Testing Branch; Larry Ripley, head of the Survivability and Weapons Effects Division; Jeff Mercier, head of the Platform Integrity Department; Larry Tarasek, technical director; Capt. Mark Vandroff, commanding officer; and visiting Capt. Grahame Dicks, commanding officer of Naval Support Activity Washington. (U.S. Navy photo by Nicholas Brezzell/Released)

Laurence O'Neill, head of Carderock's Dynamic Measurements and Testing Branch, said that the Explosive Test Pond had been under renovation for a little over three years. It was originally closed to allow for flattening the bottom of the pool, re-lining the pool and sealing cracks. Less noticeably, the pond got a new water filtration system. New piers were also built.

Though the ribbon cutting was Oct. 10, the first explosive test was the day before. The team was testing a new development explosive for a project that is working to characterize a new type of explosive.

Commanding Officer Capt. Mark Vandroff remarked on the anticipation and excitement from Carderock Division employees for the renovations to be complete. He noted that the employees working with the Explosive Test Pond should remember two things: "Nothing is more important than your personal safety; and these tests and the knowledge we gain from them directly goes toward the safety of our Sailors, Marines and warfighters."

Carderock-based group earns patent in swift fashion

By Benjamin McKnight III,
Carderock Division Public Affairs

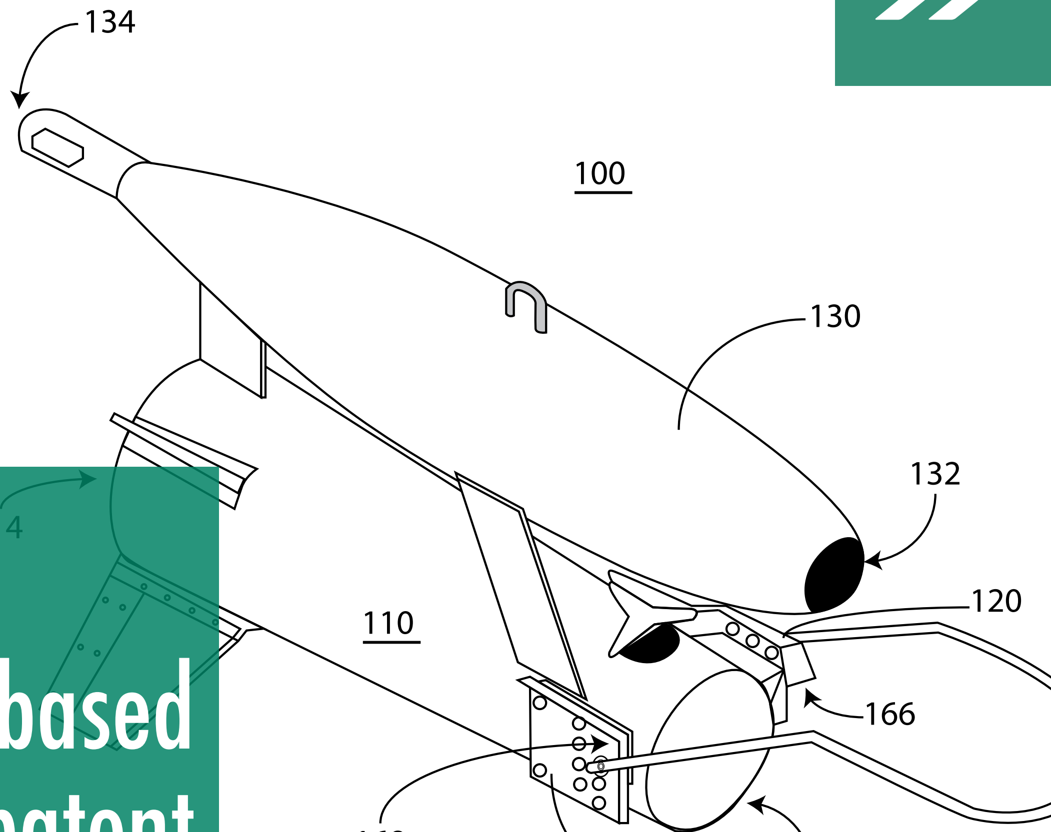


Figure 1A

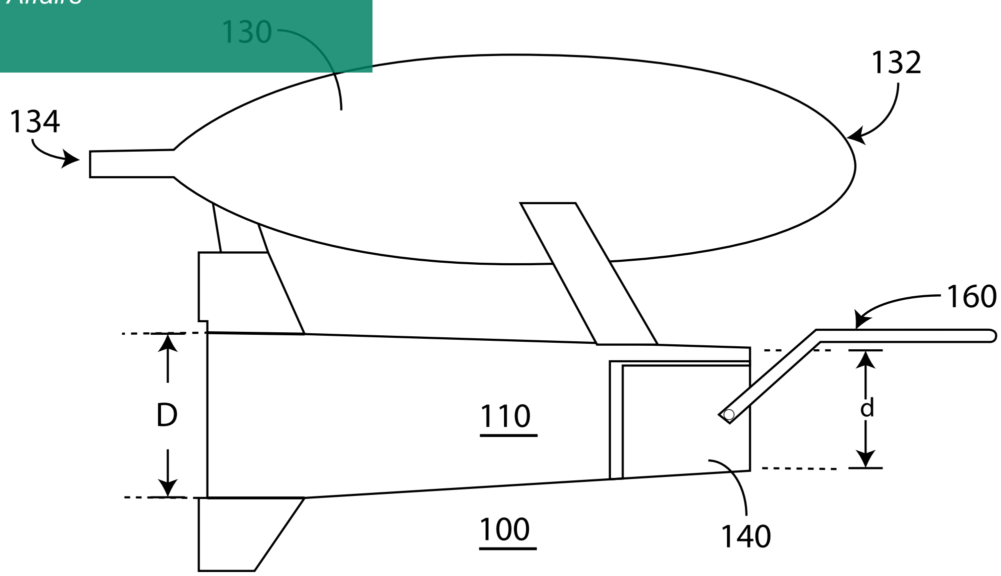


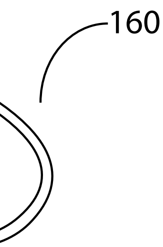
Figure 1B

A perspective illustration of an underwater vessel assembly for optimizing the pitch attitude. (From U.S. Patent No. 10,155,574 B1)

The process for attaining a patent for an invention usually takes up to two years, if not longer. Once complete, though, the feeling of accomplishment is unparalleled. A group of naval engineers from Naval Surface Warfare Center, Carderock Division recently achieved this feat and did so much faster than normal.

Sasha Tsarev, Christopher Nunes and Dana Colegrove of Carderock's Maritime Systems Hydromechanics Branch teamed up to create a tow point adapter plate for underwater vessels. With the help of Carderock patent attorney Dave Ghatt, the patent was filed on May 10 and was granted less than eight months later.

According to the patent's abstract, "the invention is directed to a towing adaption system for optimizing the pitch altitude, hydrodynamic lift and drag forces on an underwater acoustic vessel."



Traditionally, a vessel is towed by a cable that connects the device to the ship. Steady towing requires the towed device to sit at a certain depth that, when deviated from, makes the process much less efficient. The Navy was in the midst of combating towing difficulties on newer ships when Tsarev and his counterparts were approached with the task of finding a solution.

"At the same time, they were actually going to other facilities, a contractor and a university to seek other ideas," Tsarev said. His group proved to have the most beneficial fix for the Navy in terms of both performance and cost effectiveness, so much so that they received a letter of appreciation from the U.S Navy Unmanned Maritime Systems Program Office for their work.

Throughout the design and experimentation process, the group knew that they would need to claim ownership of their invention before someone else did. Although subject-matter experts are naturally key figures in the invention process, a different type of subject-matter expert comes into play to handle the legal work.

"The inventors submitted an invention disclosure to our office, which is a usual process for obtaining a patent," said Ghatt, who has worked in Carderock's Office of Counsel since 2006. From there, the disclosure went on to the Invention Evaluation Board, which reviews invention disclosures submitted by Carderock engineers and scientists and determines which of the invention disclosures are to be filed for patents.

To accurately translate the ideas from an engineered device to a written patent application, Ghatt and Tsarev worked together to ensure that both parties had all aspects of the invention covered. Patent lawyers are required to have both a law degree and an undergraduate science or engineering degree, an educational path that helps them understand the engineers' work on a basic level.

"We don't work as closely with the technology as the inventors do," Ghatt said. "So even though we have a background in science, we still struggle at times to figure out what the invention is." Both parties leaned on each other heavily to fully and properly outline the patentable features, having regular conversations about the intricacies of the plates.

Ghatt was admittedly concerned early on that attaining this specific patent would be difficult. Before coming onboard at Carderock, he worked at the United States Patent and Trademark Office. With years of experience on how the patent process works from inside the office, Ghatt said that the key to getting this specific invention patented was contingent on what features made it unique. Those features and elements are outlined in the "detailed description" section and set forth in the "claims" section of the patent application, the latter of which is protected by law.

"The back of the patent is the most important part legally. That's where you distinguish your invention from whatever was done before," Ghatt said. "I didn't just claim a plate with holes; I claimed a plate with each hole having certain hydrodynamic characteristics that help us optimize the way we're pulling the vessel through the water."

When the patent was officially awarded on Dec. 18, there was a sense of surprise from everyone involved. "The last time I checked, the average time for a patent pendency from filing to when the patent is issued was almost 24 months," Ghatt said. "That's the quickest, in my experience, that we've ever gotten a patent from filing to being issued."

Both sides were very grateful for the other in the effort to get the patent on the invention. "As an engineer you don't necessarily have to understand how to file for a patent, because the process we have here at Carderock was really good in helping us figure that portion out," Tsarev said. "We went back and forth reviewing it, but he (Ghatt) did a lot of the legwork."

Ghatt echoed a similar sentiment about Tsarev, Nunes and Colgrove, crediting them with breaking down the technical aspects of the adapter plates at each request. "Tsarev would send me the notes even though they submitted their disclosure, I'd start writing it up and if I had questions I'd call him. It was a routine procedure, but he was very receptive," Ghatt said.

While the receipt of the patent was fast, the implementation of the invention was even quicker. Tsarev, who has been onboard for almost 12 years, is accustomed to a larger time gap between the design, the production and the regular use of equipment. According to Tsarev, their drawings of the tow point adapter are being used to build more devices for testing at the South Florida Ocean Management Facility, a Carderock detachment.

"A lot of times we work on designs and it takes years before they're built or actually used somewhere in the Navy," he said. "This is cool because I know that they're using it right now, doing more testing with it and it's helping them achieve the larger objective of their mission."

CCD developing a safe-speed module for unmanned vehicles

By Dr. Timothy Coats and Brock Aron,
Combatant Craft Division

A U.S. Navy boat operator is executing a supply run, transiting from an offshore vessel to the beach. Standard operation for an experienced coxswain is to throttle up and throttle down in an effort to transit the sea in a manner that is safe for the craft and the payload while covering the distance as quickly as possible. The coxswain's intuition and experience allow him to navigate the sea in a way that prevents human injury and craft and payload damage that would otherwise be caused by wave impact accelerations that can occur when transiting heavy seas at high speeds.

Surrogate Unmanned Surface Vehicle (USV) Lab Afloat.

When the coxswain is removed, such as in an autonomous unmanned boat or unmanned surface vehicle (USV), coxswain intuition and experience is not a factor in the decision-making process.

Using $75,000 of Naval Innovative Science and Engineering (NISE) Section 219 funding, the Naval Surface Warfare Center, Carderock Division's Combatant Craft Division (CCD) employed lessons learned from their wave-slam phenomenology product known as StandardG, which offers a standardized process for computing statistical acceleration values, to develop a USV safe-speed module to essentially provide the USV artificial intuition based on craft accelerations in a seaway.

The NISE project intended to focus on developing a low-cost system ($2,000 per craft) that monitors craft vertical accelerations and recommends a "safe" speed to the craft control system.

For small craft, vertical accelerations are correlated to wave impact severity and potential craft system damage. The focus on vertical accelerations was made to reduce complexity and ultimately reduce development time, while still meeting current needs. In the future, it is planned to explore additional measurements and sensors that will provide additional input into the decision algorithms. The NISE safe-speed module will find further employment on the USV Lab Afloat/Ashore and the Combatant Craft Division team is expecting to offer this technology to pending programs of record.

Rear Adm. Anderson visits Combatant Craft Division

Dennis Danko (right), program manager for the Stiletto Maritime Demonstration Program, talks to Rear Adm. Tom Anderson, commander for Naval Surface Warfare Center, about the technology available aboard Stiletto during a visit to Naval Surface Warfare Center, Carderock Division's Combatant Craft Division at Joint Expeditionary Base Little Creek-Fort Story, Virginia, on Nov. 8, 2018. (U.S. Navy photo by Roseller Lim/Released)

Rep. Byrne Seapower Subcommittee tours Carderock

U.S. Rep. Bradley Byrne (center) from Alabama, a member of the House Armed Services Committee-Seapower Subcommittee, tours the Maneuvering and Seakeeping Basin as part of his visit to Naval Surface Warfare Center, Carderock Division in West Bethesda, Md., on Sept. 25, 2018, with Commanding Officer Capt. Mark Vandroff (right) and Technical Director Larry Tarasek. (U.S. Navy photo by Nicholas Brezzell/ Released)

U.S. Senate staff visit Carderock

Jeff Mercier (center), Platform Integrity Department head, shows component-level fatigue test articles to U.S. Senate staff in Building 19's B-bay Fatigue and Grillage Test Facility during their visit to Naval Surface Warfare Center, Carderock Division in West Bethesda, Md., on Oct. 26, 2018. (U.S. Navy photo/Released)

USNA midshipmen visit Carderock

Midshipmen from the United States Naval Academy listen as Capt. Mark Vandroff, commanding officer of Naval Surface Warfare Center, Carderock Division and a 1989 USNA graduate, explains the operation of Carderock's Maneuvering and Seakeeping Basin in West Bethesda, Md., on Nov. 6, 2018. (U.S. Navy Photo by Nicholas Brezzell/Released)

Lighter-than-air craft in the world of wars

By Kelley Stirling, Carderock Division Public Affairs

The first aircraft carrier is typically considered to be a warship that launched fixed-wing aircraft, like when Eugene Ely flew a Curtiss Pusher from the makeshift flight deck of the light cruiser USS Birmingham in 1910. But if lighter-than-air craft are taken into consideration, the first "aircraft carrier" is really the George Washington Parke Custis, a barge that launched Union Army balloons during the Civil War.

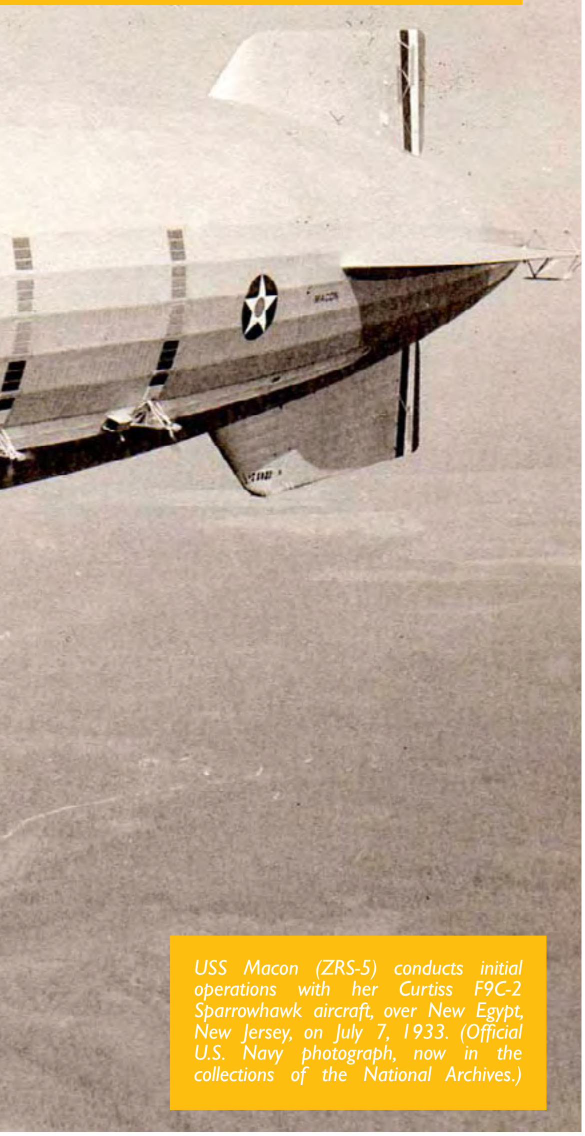
Going back to the first flight of a man into the air in 1783 when the Montgolfier brothers of France launched a hot-air balloon with a person onboard, it didn't take long for men to figure out how to use them as a weapon of war.

"In 1783, man learns how to leave the ground. And not until 1794 is it put to military use. So, if you can go up in the air, there's got to be some way you can defeat your fellow man with it," said James Harrison, director for the Expeditionary Warfare Ships Division at Naval Sea Systems Command, during another of his lectures at Naval Surface Warfare Center, Carderock Division in West Bethesda, Maryland, on Nov. 28.

The French Aerostatic Corps was formed in 1794, during the French Revolutionary War, and in practically every war since and until the 1950s, lighter-than-air craft have been used on some level.

During the Battle of Bull Run, the first major battle of the American Civil War, Thaddeus Lowe flew over the battlefield and landed behind Confederate lines. He escaped and brought back a map of the battlefield. Although too late to use for that particular battle, Lowe was named the chief aeronaut and the Union Army Balloon Corps was formed in 1861, and the Union began using them for reconnaissance.

A few years later, after the Franco-Prussian War, when France had used balloons to escape Paris and send messages out, France was highly interested in developing a steerable airship, especially since the balloons that left Paris ended up just wherever the wind took them. So, in 1884, the French built the first navigable airship, which is basically a blimp. This is where the Zeppelin comes in. Already famous for his role in the



USS Macon (ZRS-5) conducts initial operations with her Curtiss F9C-2 Sparrowhawk aircraft, over New Egypt, New Jersey, on July 7, 1933. (Official U.S. Navy photograph, now in the collections of the National Archives.)

Franco-Prussian War, Ferdinand von Zeppelin became eager to build a rigid structure airship after he heard about France's recent development of a blimp. He retired in 1890 to solely focus on this goal and build his dream using aluminum as his building material. He flew it in 1900.

"He's three years ahead of the Wright brothers, but he is behind the other airships," Harrison said.

LZ-1 crashed after three flights, and even though his investors lost confidence, Zeppelin was determined to continue his quest, creating more "Zeppelins," as now the name is synonymous with the rigid-structure airship, no matter the builder.

In comparing Zeppelins to the fixed-wing aircraft that were just coming about, the airship could go 25 knots to the plane's 35 knots, but the range for the Zeppelin is 680 miles compared to the plane's 25 miles. And the Zeppelin is able to go up to 2,500 feet compared to the plane's 100 feet, and lifting capacity is 25,000 pounds, versus 200 pounds. This ratio continued until planes become considerably more sophisticated a few decades later.

As the U.S. entered World War I, airships were used on both sides for reconnaissance. The Germans had the Zeppelin, of course, but the U.S. was also using their blimps, mostly for maritime patrol, as well as strategic bombing.

By 1917, the heavier-than-air craft were still faster and could go higher in altitude than a Zeppelin, but the range and lifting capacity of the airships still far exceeded that of an airplane, with a range of 4,600 miles versus the 300 miles of the Sopwith Camel fighter aircraft, and 68,000 pounds of lifting capacity versus the fighter's 500 pounds.

"But the Zeppelins are proving to be pretty vulnerable in combat compared to the now, substantially faster fighter aircraft," Harrison said.

The U.S. Navy got into the rigid-structure airship business with the building of USS Shenandoah. During Harrison's lecture, Dana Wegner, Carderock's curator of ship models, noted that it was Carderock's founding father, Rear Adm. David Taylor (1864-1940), who began the airship program for the Navy, laying the groundwork for Shenandoah during his time as the chief of the Navy's Bureau of Construction and Repair. Wegner also said it was Taylor who discovered that the Germans were using a duralumin product, rather than the standard aluminum the Americans had. He was able to get a company started, which is now Aluminum Company of America, or ALCOA, to create the stronger duralumin for use in airships, as well as the skin of aircraft.

"Shenandoah is going to do a number of operations, doing basically scouting, which is seen as the most obvious role because of its ability to cover long distances," Harrison said. "Although it only goes 70 knots, which is very slow for aircraft, it's very fast for a ship."

Shenandoah crashes in 1925, but the next one, USS Los Angeles, never crashes and is retired in 1932 after funding ceases.

The Navy contracted the Goodyear company to build a couple of rigid-structure airships, USS Akron and USS Macon, which they did in their factory in Ohio.

Something that set Macon and Akron apart was they operated with fighter aircraft. The Curtiss F9C Sparrowhawk would travel attached to the bottom of the airship, launching and recovering to a trapeze.

"They actually quickly got really good at this. By the time the Macon went out for its last few successful missions, they were competent enough that they were operating without landing gear," Harrison said. "This made the aircraft about 20 to 25 knots faster and also extended its range by about a quarter by not having to drag the wheels around."

Unfortunately, just as the Navy was getting to understand how to use this airship, both the Akron and Macon were lost in storms, in 1933 and 1935, respectively. The airships still struggled with dealing with heavy weather. Rear Adm. William Moffett, who was really the big proponent for the Navy for lighter-than-air aircraft, was onboard the Akron.

"So, the loss of the Akron, was not only the loss of the ship, but also the loss of his voice and his enthusiasm within the Navy," Harrison said.

Once the U.S. entered World War II, the Navy was using blimps as anti-submarine warfare (ASW) convoy escorts. The Navy had ended its blimp program in the 1920s, but with the onset of World War II, it built 134 K-class blimps, which were helium filled and did not have a rigid structure like the Zeppelins.

"Just like everything else in World War II, it was built in huge numbers," Harrison said.

Even though blimps had an ASW mission, they never "killed" a U-boat. However, they flew nearly 60,000 flights in over 500,000 flight hours, basically 12 hours per operational flight. They escorted about 80,000 ships, and only one ship in either war was ever torpedoed when a blimp was escorting the convoy, and that was in World War I.

"We often think of warfare in terms of hard kill, but there is also sometimes a soft kill, just in the area of dominance by intelligence," Harrison said.

The Navy continued to operate blimps after the war, with the program being terminated in the 1950s.

"Going all the way back to 1783 when man first flew, militaries have looked for roles for lighter-than-air craft. They really have fallen into niche roles, not always well received by military forces," Harrison said. "I think it's fair to say they've never been so compelling as a tool that they've managed to persist."

Idaho Public TV features ARD

Alan Griffitts, site director for Naval Surface Warfare Center, Carderock Division's Acoustic Research Detachment, talks to Idaho Public Television on Dec. 7, 2018, about ARD's mission for the Navy and its stewardship of the environment at Lake Pend Oreille in Bayview, Idaho. (U.S. Navy photo by Katie Ellis-Warfield/Released)

Happenings
at Carderock

Carderock's own 'Hidden Figure': Rose Morton Sayre

By Brooke Marquardt,
Carderock Division Public Affairs

Naval Surface Warfare Center, Carderock Division hosted guest speaker Marie Sayre Cole, whose mother was Carderock's own "hidden figure," on Nov. 7. While the 2016 movie "Hidden Figures" was based on a book of the same name that focused on the roles of black women who worked at NASA during the 1960s, there were many women who were put in these roles as "human computers" and remained behind the scenes.

Cole is a distinguished engineer at IBM Systems in their Supplier Technical Management Division. Her presentation, "Uncovering Hidden Figures Through Mentorship and Sponsorship," was about her mother, Rose Morton Sayre, who was a Carderock Division mathematician working primarily on hydrodynamics from 1948 to 1958 in what was formerly known as the Data Reduction Branch. Her work consisted of the numerical computing for wind tunnel and model basin experiments, though she also focused on developing analytical solutions related to bubble and fluid motions.

Sayre graduated from the Women's College of the University of North Carolina with a Bachelor of Arts in mathematics in 1948. At the time, it was the largest women's college in the United States and many of the government labs, including Carderock Division, recruited from there. The university went on to be renamed in the 1960s to be the University of North Carolina at Greensboro and began to also admit men. Cole said that the post-World War II era provided many new opportunities for women to join the workforce in technical fields.

One of Sayre's first documented projects was to perform the analysis of wind tunnel experiments on a tow carriage for seaplanes. In her writing about this project, she wrote about her assignment as a mathematician and reporting computations. Cole said that her mother's contributions from her branch must have been well-recognized, because she was given a role as a mentor for other women, she was named a lead mathematician, and she was moved into the "closed study" section of the hydrodynamics department.

In the hydrodynamics department, she worked with two managers of significant importance to her successes. The first was Morris Macovsky, who became well-known for developing the technology that allowed the Polaris missile (UGM 27) to be launched from underwater. The recorded collaboration between Macovsky and Sayre included anti-mine and pressure-mine counter measures. Her second manager was Dr. John P. Craven, well-known for his contributions to USS Nautilus (SSN 571) and other nuclear-powered submarines. They collaborated on creating a sonar hydrophone design for submarines. Cole said that these two men acted as sponsors for Sayre; she thinks that they made sure that she got good assignments and that her contributions were recognized.

Sayre also had a technical mentor and primary collaborator, Dr. William Haberman. His area of expertise was fluid motions and bubble-flow dynamics; he would go on to work for NASA. During his tenure at Carderock Division, he advocated for additional educational opportunities for his staff, Sayre included. It was rare at this time for women to be given credit as co-authors on technical reports, but Sayre had several. Haberman and Sayre co-authored her first journal paper. Sayre

Pictured far left is Rose Sayre, a mathematician who worked at Naval Surface Warfare Center, Carderock Division in the 1950s. (Courtesy photo provided)

passed away in 1999, and in 2014, Cole and her brother were contacted by two professors in Switzerland who were writing about some of the history of hydrodynamic developments in the 1950s, and they wanted to include the work that Sayre and Haberman did together. Some of the work that they collaborated on earned Sayre the nickname "Bubble Lady," and she even has a dimensionless quantity named after her called the Morton number.

While at Carderock Division, she met Clifford L. Sayre Jr., when he joined the hydrodynamics department in 1952. He also worked in the Model Basin from 1950 to 1951, and they married in 1953. Sayre left her work at Carderock in 1958 when she became pregnant with her first child, Cole's brother.

Cole said that Sayre raised her and her brother to be engineers, but Sayre herself never went back to work in a technical position. However, the "Bubble Lady" leaves behind a legacy of technical expertise and a family tradition in STEM. Her grandson is a biochemist and her granddaughter is a computer engineer at the Space and Naval Warfare Systems Command in San Diego.

The fiscal 2019 Leadership, Education and Development (LEAD) cohort

From Carderock Division Public Affairs

Naval Surface Warfare Center, Carderock Division created the Leadership, Education and Development (LEAD) Program in 2014 to provide engineers, scientists, technicians, business and financial professionals with the strategies and tools necessary to lead across the division. The one-year program is meant to be a long-term organizational strategy to enrich the workforce, transfer knowledge and invest in the growth of the Division.

In the LEAD Program, the cohort will develop and strengthen their leadership skills through leadership training, mentoring, development planning, networking and organizational observation.

The fiscal 2019 LEAD cohort is the fifth since the program's inception in 2014.

Leadership, Education and Development fiscal 2019 cohort poses with Naval Surface Warfare Center, Carderock Division Technical Director Larry Tarasek in West Bethesda, Md., Nov. 9, 2018. From left, front: Van Lien, Tarasek, Susan Hovanec and Danielle Gerstner. From left, back: Michael Persinger, Alex Punzi, Caroline Sheck Vail and Jeremy Turner. (U.S. Navy photo by Nick Brezzell/ Released)

The fiscal 2019 Leadership, Educatio

Danielle Gerstner

Danielle Gerstner is a senior materials engineer in Carderock's extreme materials group of the Non-Metallic Materials and Engineering Branch. Gerstner earned her Bachelor of Science in materials science and engineering from the University of Nevada, Reno in 2006. She has 11 years of naval materials work experience in research, development, test and evaluation, engineering and problem solving for Naval Air Systems Command and Naval Sea Systems Command. Gerstner also has more than a year of engineering and facilities management experience at Carderock. She is a recognized Missile Defense Agency materials engineering subject-matter expert for the following naval weapons systems: AEGIS-BMD SM3 Blk. IB, SM3 Blk. IIA and Common Kill Vehicle (CKV), and most recently, hypersonics.

Susan Hovanec

Susan Hovanec is a materials engineer in the Carderocks Additive Manufacturing Project Office. She has a Bachelor of Science in chemistry from Elon University and a master's degree in materials science and engineering from North Carolina State University. In her current role, Hovanec supports the additive manufacturing technical warrant holder at NAVSEA as an engineering manager. She provides technical guidance and is responsible for the execution of projects to develop NAVSEA specifications and standards to enable a clear path to the qualification and certification of additively manufactured parts for use in the naval fleet.

Van Lien

Van Lien is a mechanical engineer serving in Carderock's Ship Structures Branch. Lien has a Bachelor of Science and Master of Science in mechanical engineering from the University of Maryland, Baltimore County. She began her career with Carderock in 2008 and has been focusing the majority of her effort on wave loads, which has allowed her to gain a significant amount of knowledge on primary loads and secondary loads through simulation and experimentation. Major projects Lien has led or supported throughout her career include the international collaboration project between U.S. and Japan, High Speed Multi-hull Vessel Optimization, LCS Independence Class, LCS Freedom Class, FFG(X), and USCG ice breaker. Lien is an International Ship and Offshore Structure Congress loads committee member, where she contributes and collaborates with other government agencies and academia to make recommendations for standard design procedures and criteria of ship structural research.

Mike Pe

Mike Persinger is an e
Vulnerability Assess
undergrad, he studi
at the University of
currently pursuing a
Johns Hopkins Uni
engineering. Persin
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Alex Punzi

Alex Punzi is a hardware engineer in Carderock's Hydrodynamics and Maneuvering Testing Branch. He studied at Penn State University, earning a Bachelor of Science and Master of Science in mechanical engineering, as well as a Bachelor of Science in nuclear engineering. At Carderock, Punzi develops hardware and software for autonomous navigation and data collection systems for the free-running model group. He also has a strong background in manufacturing and uses this to identify and pursue ways to fabricate components and systems more efficiently and effectively.

Jeremy Turner

Jeremy Turner is a certified hydrodynamic surface ship trial director in Carderock's Full Scale Trials Branch. Turner has a Bachelor of Arts in fine arts from the State University of New York at Plattsburgh, as well as a Bachelor of Engineering in civil engineering and a Master of Engineering in ocean engineering from Stevens Institute of Technology. He is currently the project lead for USS Gerald R. Ford (CVN 78) sea trials, assessing performance and maneuvering capabilities aboard CVN 78. Prior to starting at Carderock in 2011, Turner acted as the director of field operations at the Center for Maritime Systems at Stevens Institute of Technology, performing coastal oceanography research and maintaining real-time environmental monitoring networks throughout the New York Harbor, lower Hudson River and along the New Jersey Coastline.

Caroline Scheck Vail

Caroline Vail is a mechanical engineer within Carderock's Additive Manufacturing Project Office. Vail received her Master of Science in mechanical engineering from the University of Maryland, Baltimore County and has been a principal investigator for additive manufacturing research efforts since 2012. Her efforts focus on research related to qualification and certification of metal additive manufacturing processes. She is the lead for the NAVSEA Additive Manufacturing Warfare Center Working Group and has worked multiple Navy-wide efforts in additive manufacturing including development of the first Department of the Navy Additive Manufacturing Implementation Plan.

University students update Carderock on their NEEC project

By Brooke Marquardt,
Carderock Division Public Affairs

Dr. Stephanie TerMaath, professor of mechanical, aerospace and biomedical engineering at the University of Tennessee, Knoxville, mixes the materials used to create composite patches on Jan. 23, 2019, at Naval Surface Warfare Center, Carderock Division. (U.S. Navy photo by Ryan Hanyok/Released)

University of Tennessee, Knoxville (UTK) doctoral student Will Ferrell and Dr. Stephanie TerMaath, professor of mechanical, aerospace and biomedical engineering, presented their updated research on composite parts fabricated through polymer additive manufacturing as part of a collaboration they have been working on with Naval Surface Warfare Center, Carderock Division on Jan. 22.

For the past few years, the UTK team has been working alongside different branches at Carderock to better understand how printing parameters, such as nozzle temperatures, cooling, sample size and print time, affect the mechanical properties of the material. The ultimate goal is to qualify components made from these materials for use in shipboard applications.

This three-year project is part of the Naval Engineering Education Consortium (NEEC), which is a program that provides funding for relevant research at academic institutions and provides opportunities for students to participate in hands-on research during the academic year to develop their technical abilities. The educational objective is to prepare students for careers with the Navy while accomplishing the technical objective. This program provides the students with daily hands-on technical training; interaction with Navy personnel and recruiters; and helps them to develop a diverse, multi-disciplinary workforce. Currently, there are three NEEC projects funded at Carderock, overseen by STEM and Outreach Program Director Charlotte George.

The technical objective for the UTK NEEC contract, which ends in May, is to explore and demonstrate the potential of an integrated experimental and computational approach to the qualification process of composite parts fabricated with embedded fibers. These UTK students have worked with Carderock employees in the Integrated Manufacturing and Project Management Office, as well as the Advanced Materials and Structures Branch, as TerMaath also had an Office of Naval Research Young Investigator Project (ONR YIP) on composite patches. Materials engineer Dr. Maureen Foley from Carderock is the technical point of contact for the NEEC with UTK.

Originally working through the building-block approach through comprehensive experimental testing, the UTK team found this to be cost prohibitive due to the sheer number of tests needed. They instead have been developing an integrated and automated simulation environment to supplement physical testing.

"We are developing a simulation environment for additive manufacturing and composites to predict material behavior using multi-scale analysis. The goal is to evaluate material combinations and process specifications prior to comprehensive testing. Using this approach, we no longer have to test everything, and instead, we can rapidly investigate new and emerging materials and test only the most promising for a given application. It would be the ideal case that someone could go into a database and look at all of the material choices, select the constituents and configuration, perform a multi-scale structural analysis through modeling and simulation, run some tests to evaluate reliability and optimize the design and then in the end, come out with a new, reliable part," TerMaath said.

With this computational environment, the team would be able to test material properties, boundary conditions, probabilistic distributions, loading conditions, uncertainty and data quality information, loading conditions and analytical models. Through multi-scale analysis, they would also have the opportunity to recommend guidelines and extrusion settings. Allowing the user to first select their constituents and configuration has the benefit of allowing them to rapidly explore many different combinations. They would then be able to perform a multi-scale structural analysis, varying the fidelity at each scale and investigating multiple loading conditions. Lastly, the probabilistic capabilities would allow for the evaluation of the material's reliability and design optimization to minimize the cost and weight of the material and maximize performance.

While they were at Carderock, the UTK students leveraged the ONR YIP grant that TerMaath had in the area of composite patches to extend the collaborative activities that could take place. The students have worked alongside aerospace engineer Daniel Hart in Carderock's Structural Composites Branch in the lab laying down the materials to create composite patches. It takes between 12 and 14 hours for a patch to be ready to be tested. Once these patches are created, they are put through tension and compression tests to evaluate how much the patch elongates and how strong it is before it breaks.

In the classification stage, they have concluded that specimen size affects strength and repeatability. Specific geometry and specification to the number of beads required in cross sectioning these parts may be pertinent to achieve geometry independent properties. They also found that matching the specimen size and processing conditions is necessary for accurate qualification. In the processing stage, they concluded that the layer time and process control can lead to stronger prints and less variable prints. Lastly, in the methodologies, they concluded that sequential prints could produce slightly weaker prints, but with increased repeatability and more prints per unit; cutting methods need to be reported for consistency; and printer variability exists and should be included in the variability processes where machines need to be qualified, as well.

Ongoing work includes predicting fracture behavior of a demonstration part; informing finite element models using peridynamics results; and quantifying uncertainty using non-deterministic analysis on uncertain material parameters, such as fiber length, density and orientation, as well as air voids and dimensional variation.

Diversity at University of Tennessee, Knoxville

Dr. Stephanie TerMaath, a professor of mechanical, aerospace and biomedical engineering at the University of Tennessee, Knoxville, strives to make her program as diverse as possible. With her projects with the Navy, she has been recruiting from the Society of Women Engineers and the Research and Instructional Strategies for Engineering Retention program at UTK funded by the National Science Foundation (NSF RISER) to accomplish this goal. UTK also participates in the Tennessee Louis Stokes Alliance for Minority Participation (TLSAMP). This program is a collaborative effort of ten Tennessee universities and colleges to significantly increase the number of underrepresented minority students statewide. Nine out of the 16 UTK students are TLSAMP or women students.

Carderock employees visit University of Tennessee, Knoxville

By Charlotte George, Carderock NEEC coordinator

Employees from Naval Surface Warfare Center, Carderock Division visited the University of Tennessee, Knoxville (UTK) in September in support of their Naval Engineering Education Consortium (NEEC) partnership.

Carderock's NEEC project with UTK focuses on polymer additive manufacturing (AM) materials technology. Specifically, the project aims to understand the parameters that govern the mechanical properties that are developed through AM and develop simulations and testing techniques to predict the material properties and failure mechanisms of components made through AM.

Dr. Stephanie TerMaath, the principal investigator for this NEEC project, said the students are using computational simulation, AM demonstration and experimental testing to investigate the feasibility of an integrated building-block approach for the qualification of chopped-fiber reinforced composites fabricated with fused filament fabrication process.

The lead Carderock mentor for this project is Dr. Maureen Foley, a materials engineer with Carderock's Integrated Manufacturing and Project Management Office. She has worked extensively with students at UTK for the past two years cultivating their understanding of materials technology research and applications.

The primary reason for Carderock's recent site visit to UTK was to support a technical review of the NEEC project and meet the students working on NEEC-sponsored projects. Both undergraduate- and graduate-level students are sponsored through this effort. Each NEEC project gave a brief overview of the project work and some discussion of the projects were held to further the interactions between Carderock employees and UTK students. In addition, the Carderock employees received a brief from a group of senior mechanical engineering students that are working on a composite-patch project related to TerMaath's Office of Naval Research Young Investigator Project.

While there, Foley gave a guest lecture to a mechanics of materials class at UTK regarding her work for Carderock integrating composite materials components to the fleet to reduce maintenance requirements and total ownership costs.

UTK's NEEC students collaborate with Oak Ridge National Laboratory, which is located in Oak Ridge, Tennessee, not far from UTK, to manufacture test articles and further develop their knowledge of additive manufacturing. Carderock engineers were also given a tour by one of the graduate students working on the project of the Oak Ridge National Laboratory Big Manufacturing Demonstration Facility.

NEEC was established by Naval Sea Systems Command (NAVSEA) to develop and attract new professionals for the Warfare Centers workforce. The objectives of NEEC are to perform naval-relevant research to resolve the Navy's technological challenges; hire students graduating with naval engineering research experience; and develop exceptional working relationships with naval engineering professors. Currently, Carderock has three NEEC projects: two at the University of Michigan and one at UTK.

"The intent of NEEC is for the Warfare Centers to work with students at research universities so they know about the extent of Navy problems and also about the opportunities to join our technical workforce," said Kirk Jenne, director of the NEEC.

Dr. Foley and her colleague, Brendon Arnold, as well as Carderock NEEC Coordinator Charlotte George, provided an information session open to all students regarding career opportunities at Carderock. On-site interviews were also held, with preference to NEEC students. This is the first formal recruiting effort at UTK, with the goal of increasing the number of NEEC students hired by the command.

"The research we are doing with the University of Tennessee is extremely relevant to our needs for the Navy," Foley said. "These students are working through ways that we might be able to better understand the variability of the materials and printers and developing computational tools that can be used to perform simulations to be able to predict crack behavior. And when they graduate, hopefully they will come work with us."

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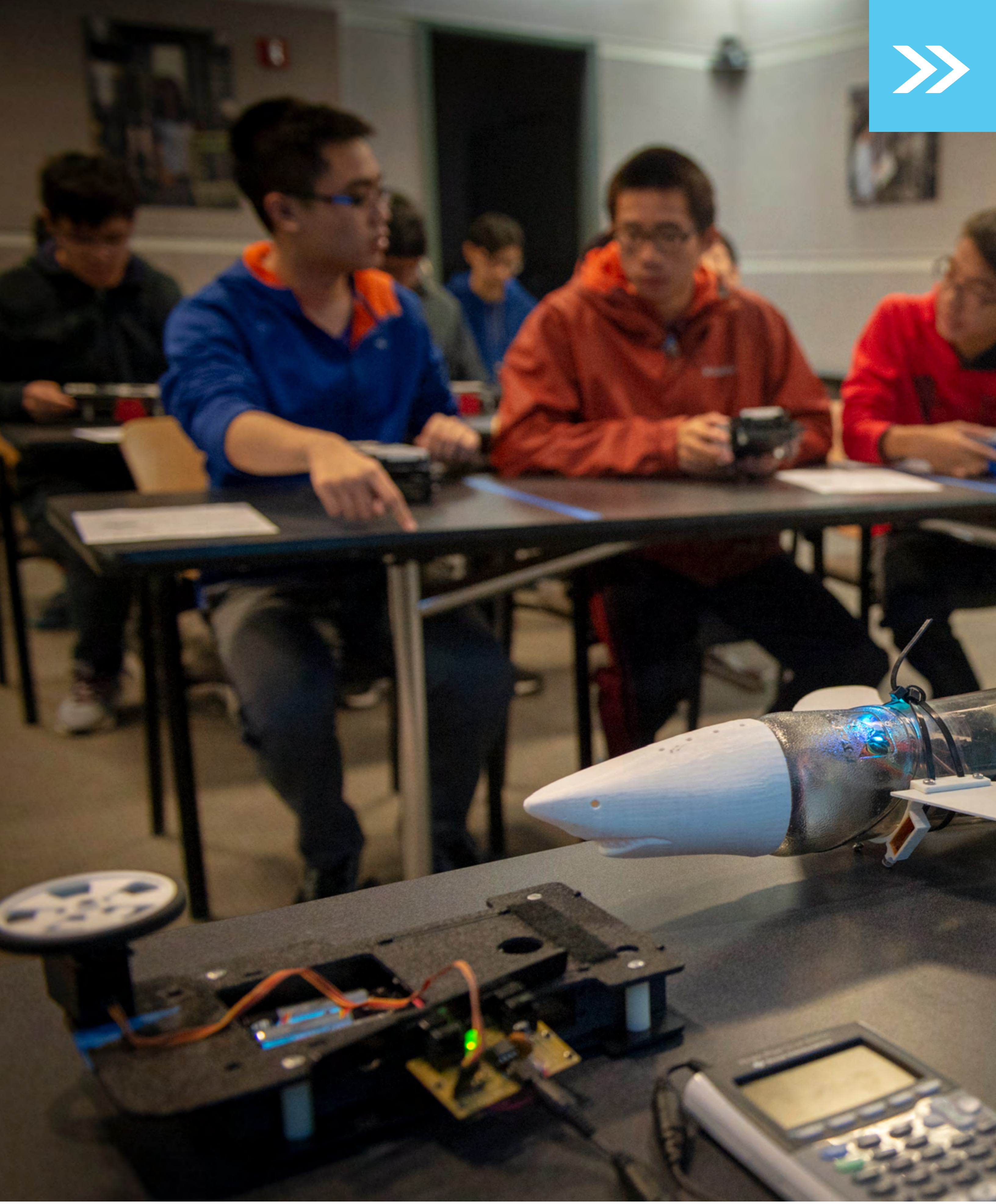
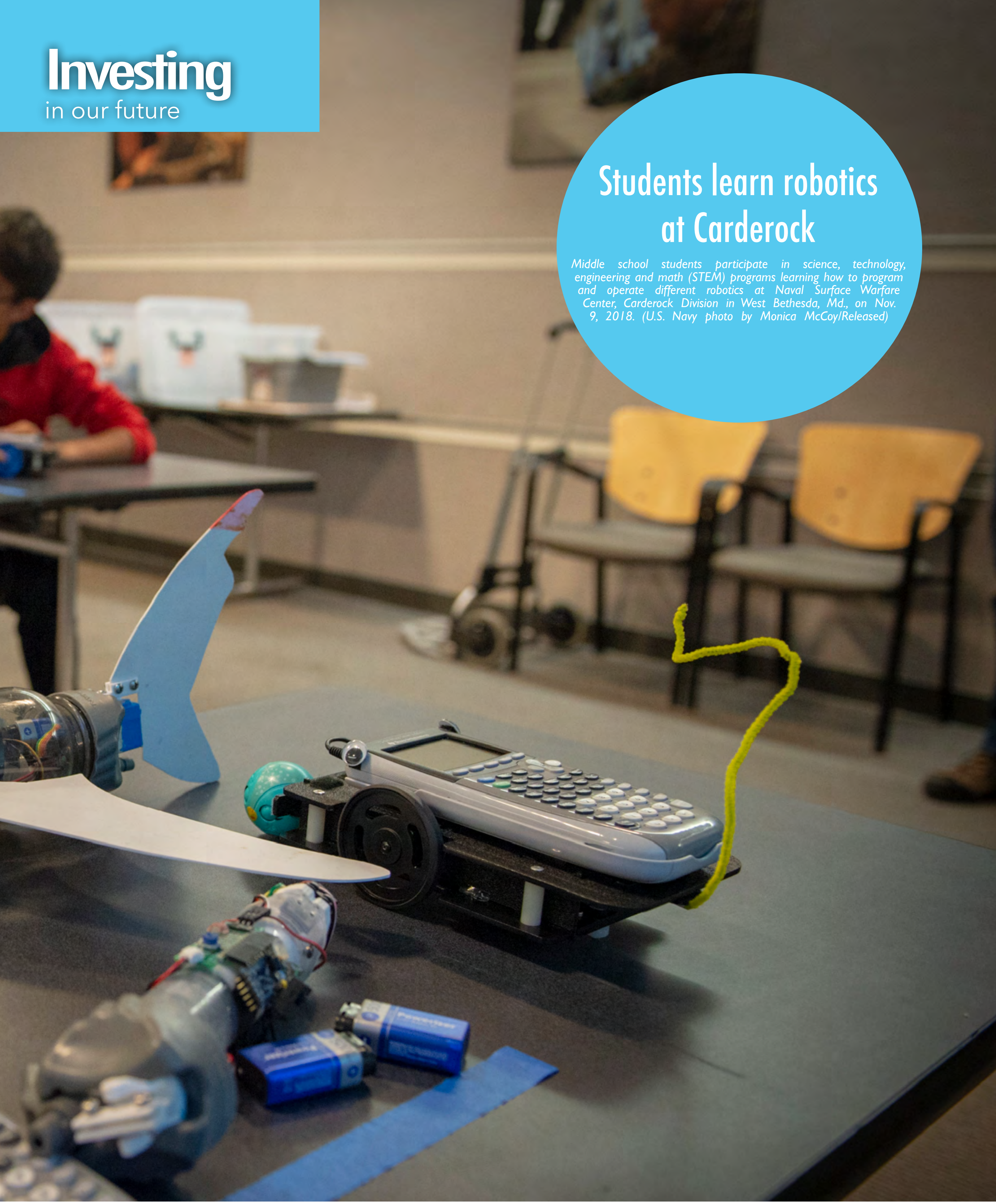
Dr. Maureen Foley (right) and Brendon Arnold (center), both from the Integrated Manufacturing and Project Management Office at Naval Surface Warfare Center, Carderock Division, stand with William Ferrell, a Ph.D. candidate from the University of Tennessee, Knoxville, in front of Big-Area Additive Manufacturing (BAAM) technology at Oak Ridge National Laboratory, in Oak Ridge, Tenn., during a visit Sept. 13, 2018. UTK's NEEC students collaborate with Oak Ridge National Laboratory to manufacture test articles and further develop their knowledge of additive manufacturing. (U.S. Navy photo by Charlotte George/Released)





Students learn robotics at Carderock

Middle school students participate in science, technology, engineering and math (STEM) programs learning how to program and operate different robotics at Naval Surface Warfare Center, Carderock Division in West Bethesda, Md., on Nov. 9, 2018. (U.S. Navy photo by Monica McCoy/Released)

Carderock's STEM program featured in Maryland Fleet Week

By Katie Ellis-Warfield, Carderock Division Public Affairs

Sailors from USS Maryland (SSBN 738), along with engineers from Naval Surface Warfare Center, Carderock Division, demonstrated calculator-controlled robots to students in the Navy Junior Reserve Officers Training Corps at Baltimore's Mergenthaler Vocational-Technical High School on Oct. 4 as part of this year's Maryland Fleet Week.

The calculator-controlled robots, part of the science, technology, engineering and math (STEM) outreach program at Carderock, allows students to program the robots to carry out a variety of tasks.

"School visits like this allow STEM professionals to meet and work with students on engaging, hands-on activities – to help develop their problem-solving skills, build their interest in STEM and give them a sense of what STEM careers are," said Charlotte George, Carderock's STEM and outreach director.

"It has been a wonderful opportunity to support this educational outreach event alongside the Sailors of USS Maryland," George said.

Sailors from USS Maryland, an Ohio-class ballistic missile submarine, also got a chance to talk to students and tell them what life is like on a nuclear submarine.

USS Maryland Commanding Officer Cmdr. Jesse Pruett enjoyed the opportunity for his crew to be in the namesake's state talking to students about the ship and what they do.

"Community outreach is very valuable for not just the Navy, but submarine forces as we are the height of technology," Pruett said. "It's really great to share my and my crew's experiences using advanced technology on the ship to encourage students to be more involved in STEM."

Capt. Martin Allard, NJROTC instructor at the high school, said having Sailors and Navy civilians come to talk to the students plays an important role in shaping students' futures.

"This is a wonderful opportunity for these students to see another way in the game of life," Allard said. "All of the Sailors here are engaged, talking with the students and listening, which is great."

The NJROTC program teaches students citizenship and leadership development, as well as maritime heritage and the significance of sea power.

"One of these kids is going to end up doing great things because of a visit like this," Allard said.

Mergenthaler Vocational-Technical High School Principal Jada Langston said that their NJROTC program develops strong leaders who step up to the plate.

"One of the things that the military provides is an opportunity to develop students' discipline, structure and gives them an opportunity to find inner confidence," Langston said.

Maryland Fleet Week is Baltimore's celebration of the sea services and provides an opportunity for the citizens of Maryland and the city of Baltimore to meet Sailors, Marines and Coast Guardsmen, as well as see firsthand the latest capabilities of today's maritime services.

Naval Surface Warfare Center, Carderock Division engineer Anthony Hagler demonstrates calculator-controlled robots to Navy Junior Reserve Officers Training Corps students at Baltimore's Mergenthaler Vocational Technical Senior High School on Oct. 4, 2018. With Hagler are Sailors from USS Maryland (SSBN 738), who were part of Maryland Fleet Week. (U.S. Navy photo/Released)

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Use of Digital Twins to Enhance Operational Awareness and Guidance

Dr. David Drazen, Dr. Alysson Mondoro and Dr. Benjamin Grisso, NSWC Carderock Division, Maryland

Abstract

In this paper, we will describe the concept of a system-of-systems digital twin where multiple twins for a representative surface combatant are used to provide increased situational awareness to the ship's crew. We describe the approach for calculation of fatigue damage and how multiple simple frequency domain tools could be used for course and speed recommendations at a range of timescales via a multi-objective routing tool. Extension of the system to include models of the propulsion train and insight into seakeeping guidance will be discussed.

1. Introduction

We are currently in the midst of what is being called a fourth industrial revolution, where society leverages vast amounts of data to derive new insights into the world. Recent advances in high performance computing, advanced data analytics, and artificial intelligence have resulted in numerous commercial deployments of "digital twin" systems with a focus on proactive condition□based maintenance (CBM). Blends of physics-based models and data-driven models allow for proactive identification of the likelihood of failure and allow for better management of the logistics tail associated with ship maintenance. While the use of CBM can realize cost savings for end-users, there are also significant operational benefits that can arise from the use of digital twins.

The concept of a digital twin as a technology trend has been on the rise for a number of years. It has appeared in Gartner's top technology trends of 2017, 2018, and 2019. Figure 1 is a screen shot from the IBM Watson News Explorer showing 96 articles based on the term "digital twin" and that were published over an approximately two month period in late 2018.

Figure 1. Screen shot of IBM Watson's News Explorer showing the number of articles referencing "digital twin". Last accessed Jan 6, 2019.

We are starting to reach a point where we now understand what the advantages and limitations are of digital twins. Gartner's 2018 Hype Cycle for Emerging Technologies puts "digital twin" at the Peak of Inflated Expectations. While we might be nearing this peak from an industry perspective, the advantages of a digital twin are evident to the authors and we maintain a healthy skepticism over what

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can and can't be achieved. This paper will present a description of how a digital twin can be utilized to enhance situational awareness for ship operators. The focus of the discussion will be on naval ships, but analogues can be drawn for commercial applications.

2. Definition of a digital twin

One issue we need to face is that different people have differing opinions of what a digital twin is. *Morais (2018)* defines a digital twin as a "digital representation of a physical object" and highlights that there should be a single digital version of each digital ship. Throughout the lifecycle, artifacts associated with the twin should be included to ensure it represents the as-is condition of the platform. These artifacts include such items as service records, repair and retrofit changes, class surveys, documentation of fouling removal, plus actual sensor data of what is going on throughout the vessel. Much of this falls under the concept of the digital thread, a linkage of data and artifacts across the lifecycle.

The digital twin, however, should only be as detailed as needed for the task at hand. Overly complex models could become expensive to build and maintain. *West (2017)* looked at the cost of an aircraft digital twin as envisioned by *Tuegel (2011)*: an ultra-realistic, O(trillion) Degree of Freedom (DOF) model of each individual plane as well as the attendant digital thread. While a lot of assumptions are made, the cost estimates for the digital thread reach \$80-\$180 billion along with \$1-2 trillion for development and sustainment of the digital twin, including the computational power needed to exercise such a twin. This, obviously, isn't sustainable and it drives home the point that the twin needs to be affordable enough for a return-on-investment based on the application of the twin.

We feel that the twin itself isn't necessarily a single item, but rather a system-of-systems model where the individual twins exchange information amongst one another. The real key is that the twin provides insight into real-time system health for individual assets, capturing differences in wear and tear for each platform. These insights allow for an assessment of the "as-is" condition, which can be used by the operators to predict expected performance over a range of timescales. For operations, *in-situ* measurements of the ocean environment might lead to recommended changes in course and speed, near-term weather forecasts could identify more optimal ship routes, and climatological descriptions of the ocean environment could provide insights on expected impacts to a platform during an upcoming deployment. Figure 2 provides an overview of how this might be put into action.

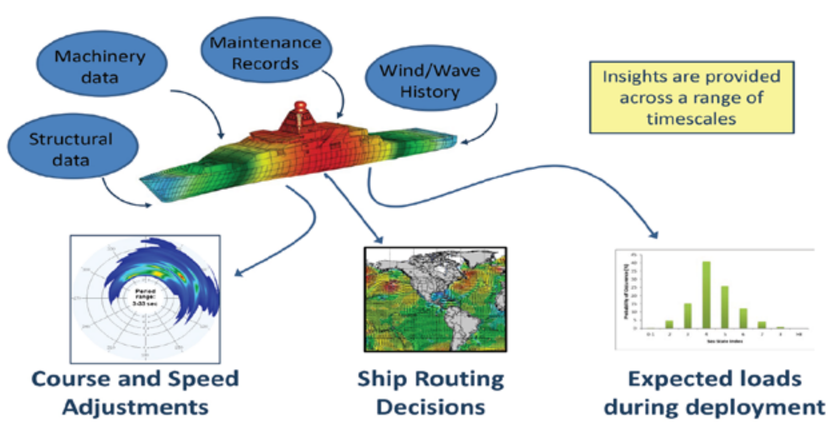

Figure 2. Example of a digital twin that highlights potential impact to operations based on environmental data over a range of timescales.

The definition that we've taken here is line with *Morais (2018)* and follows that of *Erikstad (2018)*. We agree that a twin is not an end product in itself, but rather an intermediary step that provides users with improved insights into the platform. *Erikstad (2018)* defines a number of design patterns for

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twins heavily influenced by the approach laid out within software engineering by *Gamma et al. (1994)*. Our views align with many of the structural patterns that he lays out: a baseline twin based on physics-based model behavior, a load-based twin that uses the operating context rather than the asset response, a ML proxy where behavior is based on data-driven modeling, and a benchmark twin where we use a model of the asset in conjunction with actual data to monitor the system for expected behavior.

3. Approach

The work described in this paper is still in progress and in the subsequent sections we will describe the process by which fatigue damage is calculated, how the ship routing would be conducted, and how we intend to utilize modelling of Hull, Mechanical, and Electrical (HM&E) systems to provide additional insights to the ship operators. Where needed, we have used a representative naval hullform for our studies, Naval Surface Warfare Center Carderock Division (NSWCCD) Model 5415. While this model only defines the outer lines of the hull, we can use the approach taken by *Gheriani (2012)* and use values representative of a destroyer for structural details and machinery.

First, we will describe, in general, the response of a ship in a seaway via frequency domain calculations. The elevation of the ocean surface is a stochastic process and computations are simplified by assuming it to a be stationary Gaussian random process. As the ocean forces ship motions, the response of the ship can also be modelled as a stationary Gaussian random process. If we limit the analysis to small wave amplitudes, this allows for the formation of a Response Amplitude Operator (RAO), which defines a linear relationship in the frequency domain between the forcing (ocean) and the response (ship motion). These approaches have been in use for many years (*St. Denis and Pierson, 1953*) and can be computed quickly with any modern computer hardware. Linear strip theory approaches are common for the generation of RAOs due to their advantage of low computational cost. RAOs can also be generated using non-linear 6 Degree-Of-Freedom (DOF) time domain tools such as the Large Amplitude Motion Program (LAMP, *Shin et al. 2003*).

Decomposing the wave elevation into its Fourier components allows for the generation of a wave spectrum (forcing) and allows for calculation of the ship response spectrum via

$$S_j(\omega) = \left|H_j(\omega, \theta; U)\right|^2 S_\eta(\omega) \quad (1)$$

where $S_j(\omega)$ is the spectrum of a given ship response j, $S_\eta(\omega)$ is the spectrum of the wave elevation, $H_j(\omega, \theta; U)$ is the RAO for that ship motion, ω is the radian wave frequency, θ is the wave direction, and U is the ship speed. For non-zero forward speed, the wave frequency in (1) should be replaced with the encountered wave frequency,

$$\omega_e = \omega - \frac{\omega^2 U \cos\theta}{g} \quad (2)$$

which takes into account the effect of ship speed and relative wave heading in deep water. Here ω_e is the encountered frequency, and g is the acceleration due to gravity. As we will discuss in Section 4, use of the expected ship speed based on the current state of the propulsion train will allow for calculation of encounter frequencies that can be used to better estimate ship motions and fatigue damage.

3.1 Fatigue Damage

Fatigue damage caused by interaction of the ship with the environment can have impacts on service life, impose operational restrictions, and potentially result in increased maintenance costs (both money and schedule). Issues are similar to those encountered by the USAF as described by *Glaessgen and Stargel (2012)* and insights on crack modelling from those platforms could be useful for naval ships. Aircraft, however, return to a base or aircraft carrier post-mission which allows for access to data typically inaccessible by decision makers during a mission. Naval ships have much longer deployment durations and longer time periods between access these data or to the ship itself. Furthermore, as we continue to build naval ships from material other than steel managing fatigue life becomes more important due to the nature of the failure modes.

Schirmann et al. (2019) looked at the use of a digital twin to inform cumulative fatigue damage assessments and evaluated four different routes in the Pacific Ocean. The authors found that one of the routes resulted in large amounts of damage along a given route, which they attributed to large head wind seas in that segment of the simulation. They use this example as an indication of the importance of modeling damage and how these insights can be used to balance operational needs (deployment vs servicing) across the fleet. *Thompson (2018a)* discusses the use of ship location, environmental data, and spectral fatigue approaches to estimate fatigue damage using "virtual" sensors, i.e. without *in-situ* hull strain or acceleration measurements. Using this virtual approach, *Thompson (2018b)* looked at the variation in estimated fatigue damage from ten naval vessels within the same class, but with half of the ships in the East and West Coasts of the United States. An operational profile and environmental exposure was based on ship speed and input from operators and then combined with environmental data from BMT's Global Wave Statistics database. The author found that damage estimates for the East Coast ships were higher than the West Coast by about 40-50% but notes that the conclusions are dependent on a number of assumptions and uncertainties in the data used. Improved real-time data, such as from a digital twin would be a first step in replacing these assumptions with facts. We take a similar virtual sensing approach for our fatigue damage informed digital twin.

Fatigue encompasses the formation and growth of cracks that may occur under repeated loads. As such, fatigue is a major concern in the long-term performance of ship structures since they are exposed to cyclic loading due to the operational use of the ship. There are two main approaches for evaluating the fatigue of a structural detail: (1) the approached based on Stress-Number of cycles (S-N) curve and (2) the fracture mechanics (FM) approach. This work focuses on the S-N approach and the assumption that fatigue damage accumulation is a linear phenomenon and can be modelled using Miner's rule (*Miner 1945*). Miner's damage accumulation assumes that a complex load sequence can be decoupled into cycles of constant amplitude and that each cycle contributes to the total cumulated damage. One of two methods could be used to determine the number of cycles at a given stress range that a structural detail is subjected to. A cycle counting approach can be used if time history data is available or a frequency-based approach if the stress response spectrum, $S_j(\omega)$, is known. For this work, since $S_j(\omega)$ is available, the single-moment (SM) method described by *Larsen and Lutes (1991)* is used. For further details on SM and a comparison with alternative approaches, the reader is directed to *Larsen and Lutes (1991)*; a brief summary is provided below.

The damage accumulation rate, as defined with the SM method, for a given operational condition i takes the form

$$\dot{D}_i = \frac{1}{2\pi}\frac{2^{3m/2}}{10^K}\Gamma(1+m/2)\left(\lambda_{2/m}\right)^{m/2} \tag{3}$$

where,

$$\lambda_{2/m} = \int_0^\infty \omega^{2/m} S_j(\omega)d\omega \tag{4}$$

when $H_j(\omega,\theta;U)$ is the RAO for that stress range at the detail of interest. The damage accumulation rate must therefore be calculated each time there is a change in operational condition (i.e. change in heading, speed, or seaway). The total damage accumulated over a route is

$$D = \sum_{i=1}^{I} \dot{D}_i t_i \tag{5}$$

where t_i is the time spent in operational condition i, and I is the total number of operational conditions along the route.

3.2 Hull, Mechanical, and Electrical (HM&E) Digital Twins

Our work in modelling of the propulsion train is still ongoing, but we will describe the motivation and the approach that we are planning to take. As we've discussed, the power of a digital twin comes into play when we can leverage our best understanding of the ship's current condition and use that to evaluate future performance. Most work in the literature surrounding digital twin focuses on the application to Condition-Based Maintenance (CBM), where components are serviced only when it is needed not just because an arbitrary date has been reached. *Lazakis et al. (2017)* used a combination of a Fault Tree Analysis (FTA) and a Failure Mode and Effects Analysis (FMEA) to identify critical machinery components in a Panamax size container ship. Once these critical items were identified, a neural network was built to predict future states of those items.

We are working on what *Erikstad (2018)* terms a "benchmark twin" where a twin of a piece of machinery, say a main propulsion engine, is developed and run in parallel with the data coming off of the system, see Figure 3 for an example.

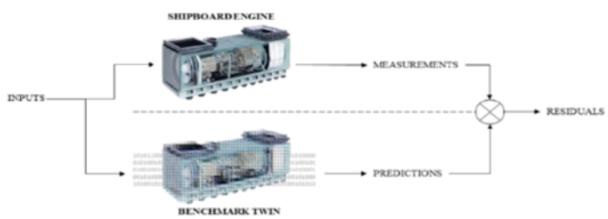

Figure 3. Example of data flow for a benchmark twin of a shipboard engine.

This paradigm allows for not only detection of anomalous behavior from the engine, but also prediction of output variables, e.g. shaft RPM and torque. *Cipollini et al. (2018)* used this approach to build a data-driven model (DDM) of a naval ship's propulsion model. Use of the DDM simplified having to build a complex state model of the machinery. The authors found success using simulated data for a COmbined Diesel ELectric And Gas (CODELAG) plant with a variety of machine learning approaches but found the best correlation with neural networks. Based on the data available, these Benchmark Twin approaches may or may not be sufficient for predictive fault analysis and we may need to pursue more "traditional" predictive analytics approaches to address those needs.

Those values, along with the current angle of the controllable pitch propeller (if relevant), the current ballast condition, biofouling condition of the hull and prop, and the associated characteristics of the propeller (J-K_T curves) allow for estimation of what the expected ship speed would be in a given environment. These updated estimates of capability can be incorporated into the ship routing algorithm as well as be used to update the operating profile of the ship for near-term and climatological forecasting. The updated ship speed can also be used in (2) to calculate the actual encounter frequency and in any subsequent RAO calculations for fatigue damage or ship motion calculations.

3.3 Ship Routing

Orlandi et al. (2018) describe the impact of different added resistance calculations on fuel consumption estimates for ship routing based on simplified models and forecasted environmental conditions. While the paper isn't clear on the specifics, it appears that they use a modified form of Dijkstra's algorithm for the selection of an optimal route. The environmental models have also

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included ensemble predictions of the environment, which allows for variability in the forecasted weather to be used for probabilistic routing options. The authors ran a number of simulated cases using an approximately 167m long ro-ro ship as a test case. The intent was to determine what the impact of various combinations of wind and wave added resistance calculations were on the coefficient of added resistance, C_{aw}. They found that the added resistance in waves calculation was the largest contributor to variation in fuel consumption (16%) when compared to their calm water baseline. They also found that the wind added resistance could impact the solution, but less so than the wave effects.

Orihara and Yoshida (2018) describe a method for not only weather routing a ship, but a means of comparing measured performance with computed estimates based on the encountered environment. Comparisons were made for 20-minute time histories of Speed Over Ground (SOG) and fuel consumption as well as standard deviations of pitch and roll. Via their "Sea-Navi" tool suite, end users can evaluate potential routes not only for weather routing but also for motion limits or for fuel conservation.

Much of the drive within the commercial shipping industry is focused on fuel efficiency as well as regulatory compliance as outlined in regulatory guidance (*IMO 2016*). For naval ships, these requirements are replaced with readiness and availability. Fuel consumption is taken into consideration when routing ships, but any conserved fuel is more likely used for increased range. To address the multiple needs of the Navy (and commercial industry), *Sidoti et al. (2016)* developed a tool that provides ship routers with the ability to balance multiple objectives (time, distance, fuel consumption, safety, etc.). A summary of the approach is given here, but the reader is directed to that paper and its references for a full description of the approach.

The authors used a multiobjective shortest path algorithm with time windows allowing for ships to pause at a given location via a waiting decision variable before continuing on to the final location at the next time step. Furthermore, their approach takes into account variability in the ocean environment via ensemble forecasts similar to the approach of *Orlandi et al. (2018)*. The approach is bounded by an envelope that is chosen prior to starting the calculations. The full set of Pareto solutions are obtained when the algorithm is complete and solutions that lie along the Pareto front are presented to the end-user for down selection. The power needed to achieve a desired speed is

$$P_{Total} = P_{CW} + P_{Sea} + P_{Swell} + P_{Wind} \tag{6}$$

where P_{Total} is the total power required, P_{CW} is the power required to achieve the desired speed in calm water, and P_{Sea}, P_{Swell}, and P_{Wind} represent the power needed to overcome the added resistances from the wind sea, swells, and wind itself. P_{CW} includes the calm water drag from testing, but also includes the power needed to overcome drag due to hull and propeller fouling as well as drag due to the surface current. The authors used strip theory calculations via the Ship Motions Program (SMP, *Conrad 2005*) to determine added resistance based the ocean environment and relative wave heading. These values are provided a Look-Up Table (LUT) in order to reduce the computational needs of the algorithm at run-time. Once the total power required is known, the equivalent calm water speed is determined and the fuel needs are calculated based on the fuel consumption relationship for a given engine.

4. Summary

Increases in computational power and access to relevant data has enabled use of digital twins for greater insight into asset performance. We feel that a system-of-systems approach where multiple twins of subsystems provide increased awareness of "as-is" condition can bring multiple benefits to naval ships. We've described an approach where we are working towards implementing twins of HM&E systems to inform propulsion system health and predict ship speed, twins of fatigue life to inform the impact of the ocean environment on ship service life, and a multiobjective routing tool to provide guidance over a short-term (0-5 day) time window. Extensions to *in-situ* guidance based on the current environment and insights on expected damage based on wind and ocean wave climatology were discussed, but not explored in depth. We are continuing to refine and integrate these subsystems together and validating them against data collected during sea trials.

Acknowledgements
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