The Coast Guard Journal of Safety & Security at Sea

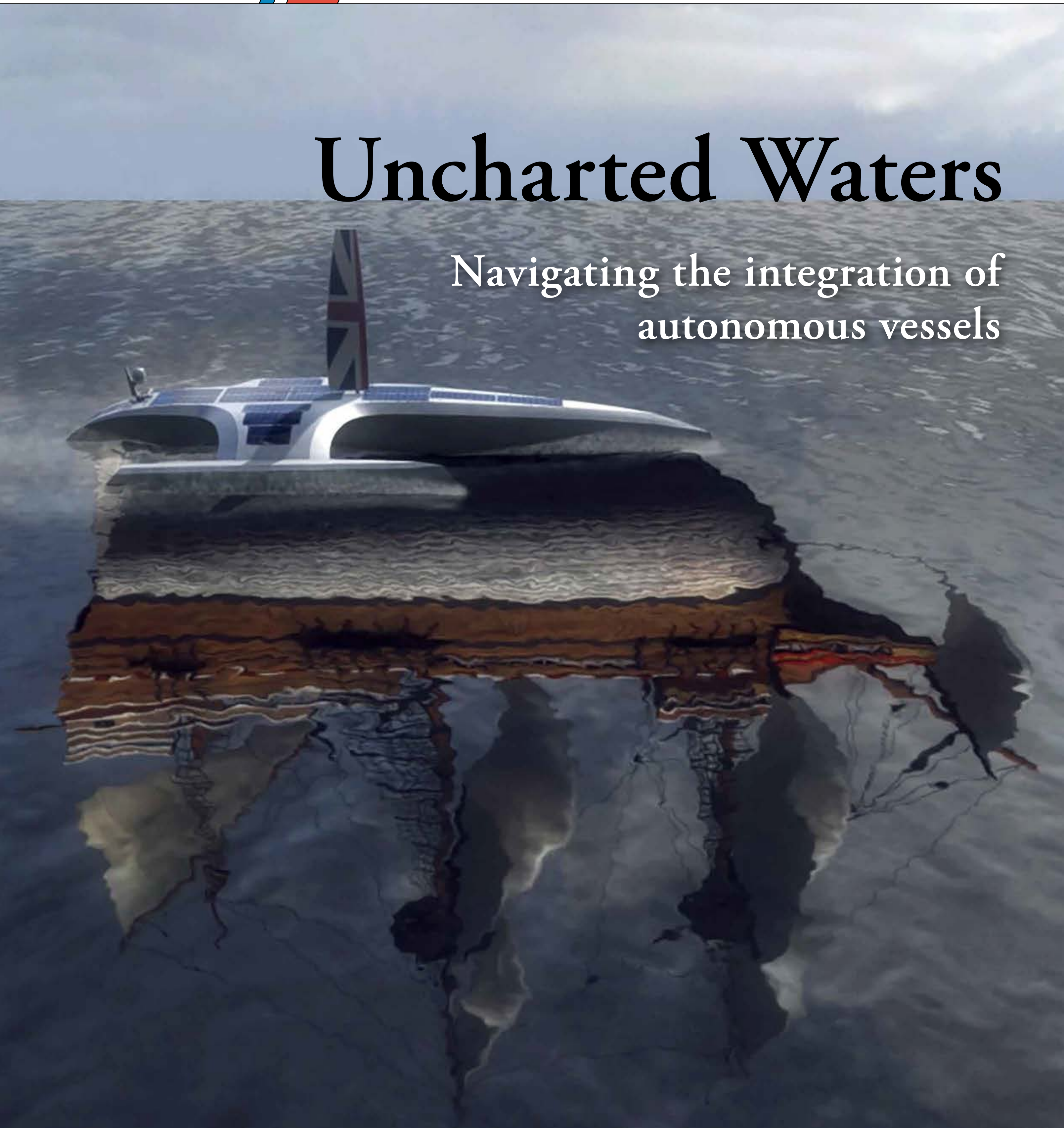
Proceedings

Spring 2022

of the Marine Safety & Security Council

Uncharted Waters

Navigating the integration of autonomous vessels



Civil Engineering Unit Providence, Rhode Island, uses an unmanned aerial system (UAS) to inspect a new aids to navigation at the Duck Island fixed channel marker near New Haven, Connecticut, in 2019. LT Kieron McCarthy piloted the UAS from a small boat and the team completed three inspections in 6 hours, saving more than 30 hours of work and reducing the risk from climbing the structures. This was a first in 2019, but unmanned technology, including surface vessels, is becoming more prevalent in maritime use and forcing a rethinking of the rules and regulations. Coast Guard photo by LT Kieron McCarthy

PROCEEDINGS

Spring 2022

Vol. 79, Number 1

Autonomous vehicles are not new technology. In July 2017, Petty Officer 1st Class David Edelson clears a path in Arctic ice for an unmanned underwater system from Coast Guard Cutter *Healy*. The small-unmanned platform can execute pre-programmed data collection missions and return to the surface for recovery. Nearly five years later, autonomous systems are becoming more prevalent in military and industry for everything from conducting research to moving goods. U.S. Coast Guard photo by Petty Officer 2nd Class Meredith Manning

Future Direction

On Deck

***On the Cover:** Four hundred years in the making, the* Mayflower 400 *was jointly developed by ProMare and IBM. It is piloted by artificial intelligence, and powered by solar energy. The initial September 2020 voyage, planned to coincide with the 400th anniversary of its namesake's Plymouth, England, to Plymouth, Massachusetts, journey, was delayed by the COVID-19 pandemic. A mechanical issue thwarted the second attempt in June 2021, but another attempt is expected in 2022. If successful, this would be the first fully autonomous vessel to transit open ocean.*

Image courtesy of ProMare/IBM

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Editorial Contact

Email: HQS-DG-NMCProceedings@uscg.mil

Mail Commandant (CG-5PS)
ATTN: Editor, *Proceedings* Magazine
U.S. Coast Guard Stop 7318
2703 Martin Luther King Jr. Ave. S.E.
Washington, DC 20593-7318

Web: www.dco.uscg.mil/proceedings

Phone: (202) 372-2316

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Proceedings is free of charge and published in April, August, and December.

Subscriptions:
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Assistant Commandant's Perspective

by Rear Admiral John W. Mauger
Assistant Commandant for Prevention Policy
U.S. Coast Guard

I am pleased to present this edition of *Proceedings* highlighting the innovative developments in autonomous vessel technology and the challenges faced by industry and regulators in the drive towards greater automation in the maritime landscape. At the national level, autonomous shipping is of strategic importance as the U.S. maritime industry seeks out more efficient, safe, and environmentally friendly means to transport passengers and cargo throughout the Maritime Transportation System. The industry also seeks to position itself as a global leader in the innovative use of autonomous vessels and automated systems.

In this issue, we partnered with leaders in the industry, academia, and government to author articles that capture the current state of autonomous technology in the maritime sphere and

Champion's Point of View

by CAPT Robert C. Compher
Commanding Officer
Marine Safety Center
U.S. Coast Guard

I am pleased to champion this edition of *Proceedings* which highlights the important developments in the increasingly automated maritime industry, as well as the challenges of ensuring this technology is employed safely and securely.

The landscape of maritime commerce is rapidly shifting as advances in digital technology drive industry towards increased automation. Globally, in Norway and Finland, vessels like the *Yara Birkeland* and Finnferries' *Falco*, respectively, have demonstrated through the future of research and development in this space. Additionally, we looked at the risks and challenges that must be overcome to enable safe and secure deployment of autonomous technology in the maritime domain.

With new this technology comes risks that challenge the norms of safety and operational requirements. Accordingly, the Coast Guard must understand these emerging technologies and their limitations, in order to provide a clear path towards sensible, prudent regulation in alignment with our global partners. Further, Captains of the Port must continue to engage with maritime stakeholders to manage new autonomous vessel projects, research, and testing while minimizing risks to local waterways.

Globally, the International Maritime Organization continues its efforts, working with maritime nations to establish governance of autonomous vessels and chart the path forward for modifications to international conventions. In parallel, domestic efforts are ongoing as the U.S. Coast Guard is currently evaluating amendments to regulations and policy needed to keep pace with the forthcoming changes brought by autonomous shipping. Concurrently, industry continues to innovate and develop new and exciting systems that highlight gaps in current international and domestic requirements. We will work through these challenges together to ensure alignment in our mutual goals for a continued safe, prosperous, and technologically advanced maritime sector.

As we move forward, autonomous technology provides a tremendous opportunity for our maritime workforce and creates a demand signal for young leaders who understand the technology and can help shape the future operating environment. I am excited to see contributions from our maritime academies who are integrating autonomous technology into their curriculums to train the next generation of mariners. I am also pleased to see articles from some of our junior officers who recently earned post graduate degrees and others who are pursuing excellence in the field. Our future is full of opportunity!

I would like to extend my sincere thanks to the authors who provided their viewpoints, and hope that this issue will be a starting point for continued dialogue as we continue our efforts to advance autonomous vessel technology while protecting the safety and security of the maritime transportation system.

testing and trials, the capabilities for safe navigation of fully autonomous shipping. Domestically, SpaceX rocket landing barges, small research vessels, U.S. Navy sponsored research and development projects, and others have demonstrated similar technological developments. This trend will continue as new innovations in automated systems, remote capabilities, artificial intelligence, and integrated port infrastructure advance the capability of vessels to operate more safely and economically.

Autonomous technology brings new challenges, pushing the bounds of international and domestic laws, regulations, and standards. In many cases, these guiding documents will require modifications to account for the changing risk profile these vessels and systems pose. Internationally, work on this front continues through the International Maritime Organization. Domestically, the Coast Guard continues to address policy and regulatory gaps while working closely with Captains of the Port and Officers in Charge, Marine Inspection to ensure a consistent and standardized approach to these new vessel projects is employed.

As this technology progresses, mariners' roles are changing. In the future, these positions will likely be increasingly technical and work in concert with automated systems in the course of vessel navigation, engineering, and maintenance. I applaud the efforts of our state and federal maritime academies to stay at the forefront of autonomous vessel innovation as they train the next generation.

Solutions to the challenges presented by autonomous vessels are not simple. They will require close cooperation between the technology industry, vessel operators, and regulators. The Coast Guard looks forward to the challenge of ensuring the safety and security of these new vessels and systems within the maritime transportation system.

MASS Environment and Industry Trends

The Coming Wave of Autonomous Vessels

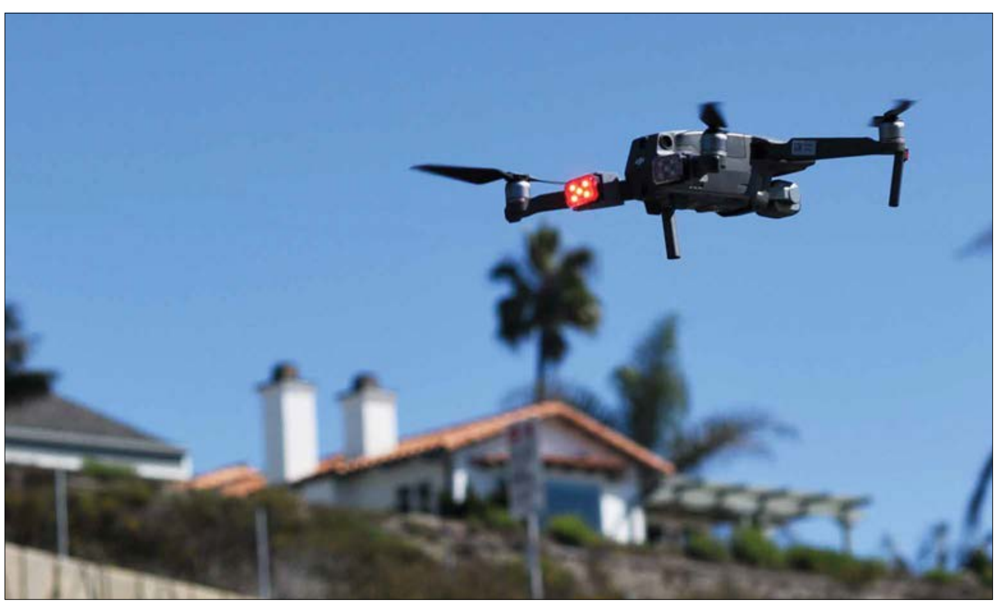
Implications, driving forces, challenges, and an intuitive framework

by LT Boone Swanberg
Staff Engineer, Marine Safety Center
U.S. Coast Guard

It doesn't matter whether you're watching the news, reading science blogs, or just scrolling through social media, the topics of artificial intelligence (AI), machine learning (ML) and the coming wave of autonomous machines that will result from it always seems to spring up. A quick internet search of the term "autonomous drones" leads to articles with titles like "Turkish drone maker denies autonomous strike capability,"[1] "Libya: A human target is shot down for the first time by a drone,"[2] and "Israel is leading the way as drone swarms come to the Middle East."[3] And autonomous cars are now seemingly discussed daily in the tech section of every newspaper and magazine. With the arrival of autonomous systems both in our skies and on our highways, the development and implementation of autonomous vessels also appears inevitable.

Despite the omnipresence of terms such as AI, autonomous vessels, and automation in our cultural dialogue, there seems to be a lack of understanding about what these terms actually mean. And there is apparently little widespread knowledge of the challenges autonomous systems face or the problems they hope to solve. Additionally, many experts and leaders within the field of autonomous systems have a mental framework that helps them when developing these technologies, but this mental framework has yet to trickle out to a wider society. My aim is to discuss, at a very basic level, the challenges facing autonomous systems and the problems these systems hope to solve. I additionally hope to establish a basic framework for understanding and interpreting current developments in autonomous systems in general, and in autonomous vessels specifically. The questions that will be posed in this article are:

- What is an autonomous vessel?
- What is the difference between automation and autonomy?
- Why are autonomous vessels being developed now?
- Is there a framework that can help us understand autonomous vessels better?
- What challenges still exist for autonomous vessels?



Drones are just one type of machine taking advantage of autonomous technology. Coast Guard photo by Petty Officer 3rd Class Alex Gray

The 378-foot Coast Guard Cutter *Sherman* lies moored in Alameda, California, in 2009. Built in the 1960s, engineers had to manually switch power sources from ship to shore until advances in automation took over this process. Coast Guard photo

What Is an Autonomous Vessel?

Autonomy is defined by the Merriam-Webster dictionary as "the quality or state of being self-governed."[4] The use of "self" here obviously contains some metaphysical baggage. However, from this definition, the concept of an autonomous vessel can be grasped; it is a vessel that has the ability to govern itself through the use of some automatic technological process. In practical terms, this means that the vessel would be governed without the need for human input under normal circumstances.

What Is the Difference Between Automation and Autonomy?

To articulate the distinction between automation and autonomy it may be useful to quote the American Bureau of Shipping (ABS) *Guide for Autonomous and Remote Control Functions* in full.[5]

> *Automation is the automatic control and operation of a process, system, or equipment by mechanical or electronic devices that take the place of human labor. These are normally routine or repetitious tasks under predefined scenarios and conditions. It is important to also define automatic control as the means to control via predetermined orders without intervention by the operator. These systems are common in the marine and offshore industry. Examples include automatic synchronization functions on electrical switchboards, automatic starting/stopping function of standby pumps, dynamic positioning systems, and autopilot controls.*
>
> *Autonomy differs from automation in that it requires self-governance and freedom from external control or influence. Autonomous functions are functions where machines perform each of the four steps in the operational decision loop—i.e., monitoring, analysis, decision and action—without the need for human intervention to achieve the system mission and perform tasks.*
>
> —ABS Guide to Autonomous and Remote Control Systems

The difference between automation and autonomy can seem somewhat pedantic at first. However, from the ABS definition we can parse out some major differences. Automation is normally present for "routine" or "repetitious" tasks under "predefined scenarios." Automation replaces human labor, but does it in a very defined and repetitive way. The Coast Guard Cutter *Sherman* was built in the 1960s and all the engineers on the cutter still had to manually parallel the two generators or parallel generators to shore power every time they wanted to switch power sources. This involved manipulating the field current, changing the oncoming generator's rpm, and closing the breaker at the right time. But thanks to advances in automation, simple tasks like this one have now been mostly replaced by automated systems that will do all of this for us. In the case of paralleling generators, the task is routine and predefined. It is a step-by-step process that is called out in an engineering operating procedure.

As opposed to automation, autonomy requires "self-governance and freedom." Autonomous systems perform "monitoring, analysis, decision, and action." In these four processes, decision-making can be seen as the central step. Through automation and smarter systems, the need for human input with regards to monitoring, analysis, and even action has been greatly reduced. However, even on most new ships, the decision-making is intimately vested with the human operator. Notably with automation, that process of analysis and decision is made, under normal circumstances, without human input.

Why Are Autonomous Vessels Being Developed Now?

There are two major forces that have been pushing society toward the development of autonomous systems in particular and toward the use of ML/AI in general. The first major force is that of Moore's Law, which basically describes the exponential rise in computing power over the past half century. The second major force is the prospect of shrinking labor markets in most of the developed world in the coming decades.

Moore's Law, a driving force for many of the technologies developed over the past six decades or so, was named after Gordon Moore who was a businessman, an engineer, and the co-founder of Intel. He made the observation that the number of transistors that could be put on a chip of a given size doubles about every two years.[6] The practical result of this phenomenon has been that, since the 1960s, transistor-based technology has simultaneously become much more powerful in its calculations, as well as cheaper on the open market. This explosion in computing power means that complex algorithms, neural networks, decision trees, Bayesian networks, and evolutionary algorithms can now be developed in an attempt to improve productivity and to automate aspects of life that were previously the exclusive domain of human action.

An in-depth discussion on AI and its associated approaches is beyond the scope of this article, however a basic explanation is instructive. Most, but not all, approaches to machine-based decision-making in use today will employ one or a combination of a few approaches. These approaches include powerful statistical methods like Bayesian networks; other ML algorithms and models that will automatically improve through experience and use of data; or some combination of these methods built into a larger structure.[7]

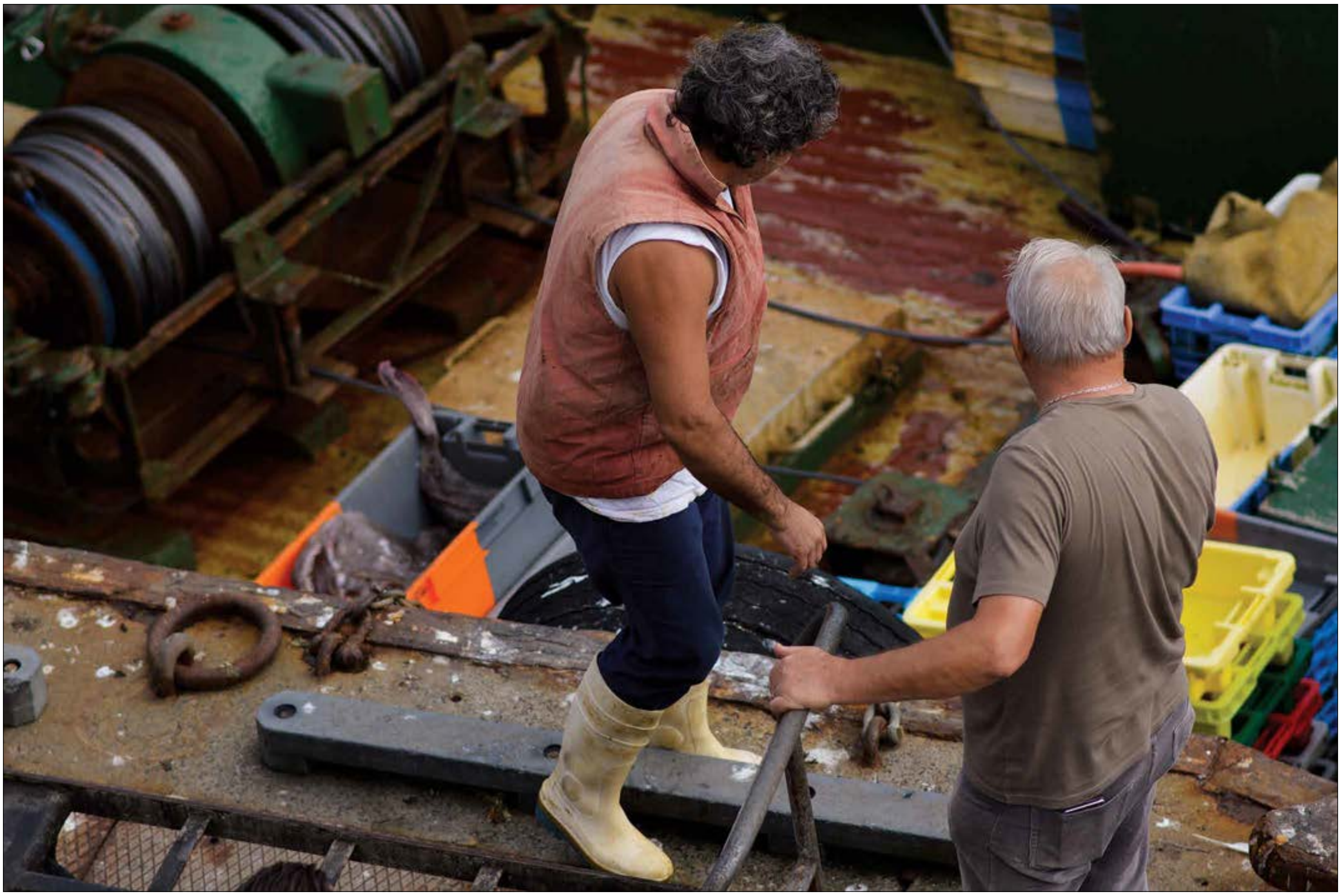
Due to the nature of modern ML techniques, most of these tools require massive data sets. It is worth noting though, that these data sets can be problematic due to the fact that many are biased, too small, or incomplete and noisy.[8]

Another major force driving the development of autonomous vessels is an aging population leading to the prospect of a shrinking labor market in most of the developed world. In 1990, the median age in the United States was about 33. By 2020, the median age was 39.[9] In 1990, about 21.5 percent of the population was under 14 years old, while only about 18 percent of the population was under 14 years old in 2019.[10] These trends are expected to accelerate in the coming decades. In 2000, the U.S. labor force participation rate was 67 percent, but this had dropped below 62 percent in 2021. Even prior to the impact of the COVID-19 pandemic, the labor force participation rate had fallen to around 63 percent.[11]

All of these trends indicate that in the near future labor will be a relatively scarce resource in the United States. Although the statistics cited here are from the United States, the rest of the developed world is, if anything, aging at an even faster rate due to less immigration and lower total fertility rates. When there is a shrinking labor force, productivity in the economy will decrease without a corresponding increase in the productivity of labor. This makes intuitive sense. If there are fewer people making things and performing services, fewer things and services will be produced unless people become better at producing those goods and services. And one significant way to make people more productive is through the intelligent use of automation and autonomous systems.

The twin developments of Moore's Law and the aging population of the developed world have greatly increased the push for autonomous technology in public policy and

A Bayesian network is "a model using knowledge developed from Bayesian statistics to make certain predictions based off of observed events. Algorithms have been developed that can help train and hone in these networks based off of datasets." See https://onlinelibrary.wiley.com/doi/epdf/10.1002/9780470061572.eqr089 for more information.



Autonomous vessel development is being driven by an aging population and the possibility of a shrinking labor market in most of the developed world. Ana Laurent | Shutterstock

through private venture. There is also a healthy element of "if we can, why not?" involved here. With this massive push for autonomous vessels, it is important that we develop a framework for understanding and measuring autonomy. It's also essential that we understand the far-reaching challenges and obstacles that face autonomous systems in a deep and real way.

Is There a Framework That Can Help Us to Understand Autonomous Vessels Better?

There are several guides for autonomous vessels and systems that have been published by classification societies such as DNV, ABS, Lloyds, and BV. While each have differences in their approaches to safe design of autonomous systems, there is also much in common. For illustrative purposes, examples from ABS' guidelines are provided, but the reader is encouraged to explore other standards developed by leading classification societies and industry organizations.

The first thing to understand is that autonomy in vessels doesn't have to be an all-or-nothing proposition. The vessel industry and classification societies recognize a difference between smart, semi-autonomous, and autonomous vessels.[12] Smart vessels would basically be human-operated vessels with intensive diagnostics and decision support. Humans would make almost all of the decisions on board the vessel but would have machine support at almost every level. Conversely, full autonomy would mean that no human input would be needed, and that humans would exclusively fill a supervisory role. The term "semi-autonomous" is used to describe the grey area between smart and autonomous. Semi-autonomous vessels include vessels where decision and action rely on some amalgam of both human and machine input.[13]

For the foreseeable future however, these autonomous and semiautonomous vessels will continue to have the need and provision for human operators. This is because, as discussed above, many of the tools used for autonomy rely on machine learning, decision trees, or other algorithms/statistical tools in order to make decisions. These tools need vast amounts of test cases and datasets to train them. Any autonomous machine will likely be only as good as its models and data will allow. In addition, the ever-present nature of unknown unknowns means there will be situations and cases where the machine is likely to fail in the decision-making process. There are likely to be many scenarios in which a human operator might be needed, and even if not needed, will be called upon to supervise.

ABS has also made some helpful distinctions with regards to how the human operator will be incorporated into the autonomous system. The first distinction is fairly straightforward. Will the operator be present on board, or will the operator be remote (not on board)? This distinction leads to some important implications. Vessels where the operator is remote will face two substantial problems. The first will be ensuring reliable and powerful communications channels. If a vessel requires an operator and that operator is remote, the importance of a safe, secure method of communication is key. The second problem is cybersecurity. If an electromagnetic communications channel provides an override function for an extremely expensive and large vessel, this will clearly be an enticing target for bad actors. For instance, imagine how much ransom a shipping company would be willing to pay if a bad actor were threatening to use the company's ship to shut down the Panama Canal for the next two months.

To combat this scenario, shipping companies with an operator on board will likely have to incur additional expenses to make the vessel habitable and pay a sailor to stay underway. However, the peace of mind knowing that the cybersecurity threat is lessened will mean that the onboard operator could be a wise investment.

Another distinction ABS makes is when and how human operators will be needed—continuously, periodically, or as-needed.[14] This distinction is also self-explanatory. The as-needed supervision is obviously the "most autonomous" of the three. This is because the decision to call for supervision will also need to be autonomous. With the aid of these distinctions—smart, semi-autonomous, autonomous, remote operator, onboard operator, continuous supervision, as-needed supervision—it is easy to understand how vessel autonomy would be more of a gradation than an all-or-nothing proposition. Understanding autonomy as a gradation will likely improve understanding of the development and implementation of autonomous vessels over the coming decades as this new technology develops.

Class Guidelines

ABS Guide for Autonomous and Remote Functions (2021)
https://ww2.eagle.org/en/rules-and-resources/rules-and-guides.html

Llyod's Register Code for Unmanned Marine Systems
https://www.lr.org/en/unmanned-code/

DNV Guidelines for Autonomous and Remotely Controlled Ships
https://rules.dnv.com/servicedocuments/dnv/#!/home

BV Guidelines for Autonomous Shipping
https://marine-offshore.bureauveritas.com/ni641-guidelines-autonomous-shipping

What Challenges Still Exist for Autonomous Vessels?

While challenges to any new technology are always present, there seem to be two major obstacles to developing a vessel that is completely autonomous, especially when it relies only on as-needed or remote supervision. The first is the challenge of unknown unknowns involving outsized economic, political, or social impacts, also known as black swan events.[15] The second challenge is purposeful manipulation of the autonomous technology by bad actors.

The heavy reliance of autonomous systems on large datasets and statistical/algorithmic methods means that there are difficulties when it comes to training machines to respond to unknown unknowns and black swans. Most of the fields where ML has achieved large success are typically in domains that are well defined and bounded. Chess is the perfect example of this type of a state space. The state space in chess, which simply means the space that contains all possible scenarios for a system, is estimated to be around 10 to the 43rd power.[16] Granted, this is a large number, but the entire game of chess still has a definable and bounded set of scenarios. The question was once asked, "Can you imagine how much more complex the state space of chess would be if you had to account for a cheating opponent? Or a pigeon that landed on the board and disrupted the pieces?" This vivid hypothetical does a good job at illustrating the epistemological difficulties of defining and predicting scenarios in the real world.

Machine learning and AI have transcended simpler games such as chess but still struggle in the unbounded world of reality. Many of these problems of unknown unknowns and black swans can be significantly mitigated by the use of human supervision either continuously, periodically, or as needed. The as-needed supervision would be called upon anytime something unexpected or a situation outside of normal parameters was determined. The immense cost of black swan events would likely justify most determinations for calling on human supervision to be highly biased towards false positives. Or simply, the system would prefer to call a human when a human wasn't actually needed rather than the inverse.

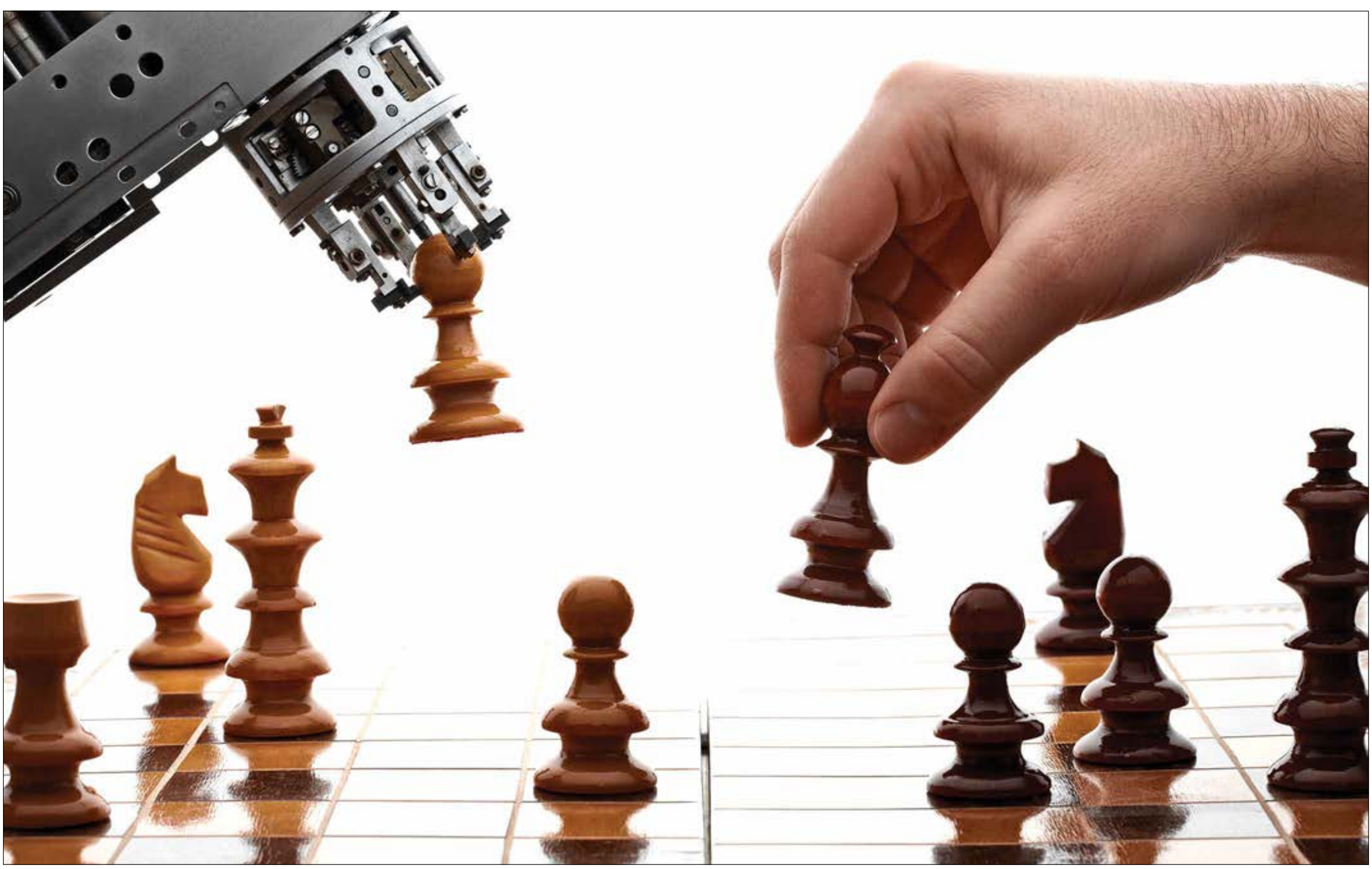
The second major challenge facing autonomy at sea is the problem of bad actors. In the past three years, our society has had to take a sober look at the problem of bad actors in the cybersphere. In that time, the city of Baltimore suffered from multiple ransomware attacks that brought the public school system to a halt for weeks.[17] And it was only last summer that Americans' lives were negatively impacted because of ongoing fuel shortages brought about by a cyberattack on an oil pipeline. When questioned about manually restarting the hacked pipeline, the company's CEO admitted that most of the employees who would have the know-how to restart the pipeline manually were either dead or retired.[18]

In June 2021, Energy Secretary Jennifer Granholm sounded the alarm on the possibility of losing the power grid in the event of a cyberattack. At this point in time, the fragility of the American power grid is common knowledge to most of its operators and engineers. In the context of complex systems, efficiency is basically a euphemism for fragility. The American power grid has been designed with efficiency in mind and lacks sufficient redundancy at the level of transmission and distribution. The use of intermittent energy sources with little or no inertia—solar or wind—is likely to extend this fragility into the realm of electricity generation as well. All of this serves to remind us of the threat that cyberattacks and other forms of informational attacks can pose on autonomous systems.

The simplest and best way to protect a system from cyberattack is to merely isolate it from electromagnetic-based communications of any sort. A perfect example of how isolation, whether intentional or not, can be the most robust defense against cyberattack is the example of the 378-foot cutter mentioned earlier. That cutter was simply too low tech to have its propulsion or ship's service power system connected in any way to a network or communications channel. This lack of technological sophistication ironically made the cutter extremely resistant to any cyberattack.

Isolation from outside communications channels will be impossible for autonomous vessels that require remote monitoring and supervision. This will give any vessels that rely on onboard supervision and monitoring a cybersecurity advantage. The shipping industry and the Coast Guard have been directing a considerable amount of focus on cybersecurity and information assurance lately, but the threat is there and autonomous vessels will be prime targets for attack.

Cybersecurity cannot be an afterthought or a



Machine learning and artificial intelligence have excelled in games such as chess, but challenges still exist when confronted with unknown or black swan events. Daniel Schweinert | Shutterstock

Autonomous vessels will need to be designed and manufactured with a strong emphasis on robust fail safes to reduce risks.

consideration, but must be front and center with any discussion on autonomous vessels. Even on vessels where supervision and override are available remotely, provision for manual override on board the vessel will likely be needed. The risks of unknown unknowns and bad actors dictates that autonomous vessels will need to be built with robustness, not just efficiency, in mind.

The fact that autonomy is not an all-or-nothing proposition, and will likely gradate from smart to autonomous with different levels of onboard and remote human supervision, should help mitigate these pressing challenges. Robust fail safes and protocols will need to be incorporated into these vessels in order to further reduce risk. Classification societies are already developing cybersecurity requirements and protocols for standalone, federated, and integrated computer-based information technology systems installed on vessels.[19]

Despite the complexities of the technologies used, the future of autonomy in the shipping industry can be easily understood as a movement in the direction of increasing use of machines and computers for monitoring, analyzing, decision making, and acting on those decisions. This increasing use of machines and computers is likely to come in the form of smart and semi-autonomous vessels in the near future, with the prospect of more fully autonomous vessels coming later.

It's clear there are large economic and technological forces leading the push for autonomous vessels and other autonomous systems. Autonomous vessels have clear benefits to the shipping industry in the form of decreased labor costs and improved safety for workers. However, autonomous vessels also face many challenges in the form of unknown unknowns and black swan events on top of a susceptibility to cyberattacks and other forms of manipulation. A robust and secure

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approach to autonomous vessels, where threats and dangers are properly accounted for, is the best path forward for this new technology.

About the author:

LT Boone Swanberg graduated from the U.S. Coast Guard Academy in 2014 and received his M.S. in electrical engineering from Virginia Tech in 2018. He currently resides in Alexandria, Virginia, with his family.

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Why Autonomous Vessels?

Factors driving the trend towards autonomous ships

by R. Glenn Wright, Ph.D.
President
GMATEK, Inc.

Across various modes of sea transportation, from local ferries, law enforcement and rescue services, to scientific research and the regional and international transport of goods and materials, progress toward achieving partial or full autonomy is ongoing. Commonly referred to as maritime autonomous surface ships (MASS), some aspects of this path leading to autonomous ships are evolutionary in that well-known and defined processes, such as autopilot and stabilization, are mechanized through automation. However, revolutionary advances are also taking place in navigation, propulsion, and operation of commercial and naval vessels resulting in new and disruptive processes throughout the industry. Underlying factors driving these changes are many and varied and include attaining greater efficiency and economies in vessel design and operation, reducing environmental risk, and enhancing safety of navigation and crew members.

A Broad Seascape

There is no overall general model by which vessel autonomy will be achieved, nor the extent to which it will be implemented. Experiments are underway exploring the feasibility of unmanned vessels crossing entire oceans. Commemorating the 400th anniversary of the 1620 *Mayflower* voyage, the autonomous scientific research vessel *Mayflower*'s crossing from Plymouth, England, to Plymouth, Massachusetts, is just one example.[1] Militaries, governments, and private industry are all exploring the possibilities of this technology.

The U.S. Navy has also demonstrated several autonomous voyages of different vessel types across the Pacific Ocean and from the Atlantic to the Pacific via the Panama Canal, where the only human intervention occurred during transit of the canal.[2]

Yara Birkeland is envisioned as the world's first fully electric and autonomous 120 TEU container ship with zero emissions for use between Herøya, Brevik, and Larvik in Norway.[3] This project represents a fully autonomous logistics concept from industrial site operations, to port and vessel operations. Additionally, the city of Trondheim, Norway, has an autonomous passenger and bicycle ferry crossing its harbor.

The Sharktech line of autonomous vessels developed by Metal Shark of Jeanerette, Louisiana, provides examples of unmanned surface vessels ranging from 15 to 300 feet, including one in use at the U.S. Coast Guard Research and Development Center.[4]

All of these vessels have a wide range of applications for commercial and government markets and their designs share many common features in their quest to fulfill their particular market and service areas.

Economic Factors Driving Vessel Autonomy

Different sources place the estimated global market for autonomous ships between $14.3 billion to $134.9 billion by 2030, with compound annual growth rates between 6.8 percent and 9.3 percent from 2020 to 2030.[5,6] Such

The *Mayflower Autonomous Ship* (MAS400) attempts to cross the Atlantic Ocean in 2021 from Plymouth, England, to Plymouth, Massachusetts, commemorating the 400th anniversary of the 1620 Mayflower voyage. Photo courtesy of IBM/Promare

The *Yara Birkeland*, left, sails through Brevik, Greenland Harbour, Norway, on its way to Norwegian shipyard Vard Brattvåg on its first autonomous voyage in 2020. Upon delivery, the vessel will be tested for container loading and stability before undergoing further preparations for complete autonomous shipping. Photo courtesy of Knut Brevik Andersen of Wilhelmsen Ship Service

Below, Norwegian University of Science and Technology researchers collect data while testing the autoferry prototype on Norway's Trondheim Canal in 2018. Photo courtesy of Norwegian University of Science and Technology

diversity of opinion resulting in an order-of-magnitude difference in projections can, in part, be attributed to variances in market research methods used in obtaining projections. However, it is also a reflection of uncertainty in a new market for which there remain many great unknowns.

The COVID-19 pandemic has also changed many basic assumptions as to how shipping and staffing of ships is accomplished, thus altering the dynamics upon which such predictions are based. Contributing factors include hardships for seafarers stranded on board ships well beyond contract expiration, havoc across the entire passenger ship industry, significant shortages of shipping containers and disrupted logistical supply lines worldwide.[7–11] Events have also revealed opportunities to enhance processes and operations to help overcome such challenges.

Vessel automation eliminates many of the costs associated with crew members residing on board including wages, training, food, supplies, medicine, travel and repatriation, crew safety (e.g., International Convention for the Safety of Life at Sea), and other associated administrative and management costs. Also eliminated are costs associated with the design, development, installation, operation, test, and maintenance of onboard facilities and other support systems typically afforded to human activity. Gains in efficiency may be achieved by dedicating space formerly associated with onboard facilities to carrying additional cargo. Additionally, the elimination of windows and portals, allows for more efficient designs with less wind resistance than would otherwise be possible, which results in fuel and energy savings.

Attempts have been made to estimate the amount of savings that may be achieved based upon different types of ships and the roles they perform. One study suggested the cost of owning and operating an autonomous bulker over a 25-year period is $4.3 million less than a conventionally manned ship, representing a reduction of 3.4 percent over the required freight rate of the conventional vessel.[12] Another determined the introduction of autonomous ships in short-sea shipping can reduce total operational cost by an average of 11 percent, with 94 percent of these savings coming from reduced time charter costs and 6 percent from fuel cost reduction.[13]

These savings are somewhat offset by costs incurred for land-based labor located at remote control centers and other facility locations needed to support and maintain vessel operations.

Further offsetting these savings are the costs of new and additional sensors, computers, communications equipment, and associated infrastructure needed to support and implement autonomy. Insurance costs have been much more difficult to estimate as the Shipowners' Property and Indemnity Club of London and others are now developing policies to meet the liability insurance needs of owners and operators of many types of autonomous and remotely operated vessels.[14] Life cycle costs associated with critical cybersecurity and artificial intelligence-based systems establishing the brains of autonomous ships that have yet to be proven are still very subjective due to the present lack of maturity of these technologies.

The ability to monetize ship-acquired data gathered via the vast interconnected sensor networks inherent to the function of autonomous ships may provide a means to significant gains in efficiency, additional income streams, and other resources for owners and operators. Such opportunities are only now beginning to dawn with the advent of autonomy, autonomous ships, and port digitalization. This pertains to both traditional and non-traditional logistics in terms of the physical products they carry, as well as data products created throughout the voyage process. From source, through transport to destination, immense amounts of information can be acquired including, but not limited to:

- ship operations
- physical environment in close vicinity to the vessel
- cargos carried
- other vessel traffic along routes of transit
- quality of aids to navigation
- detection and identification of hazards
- inter-ship exchange of data and information

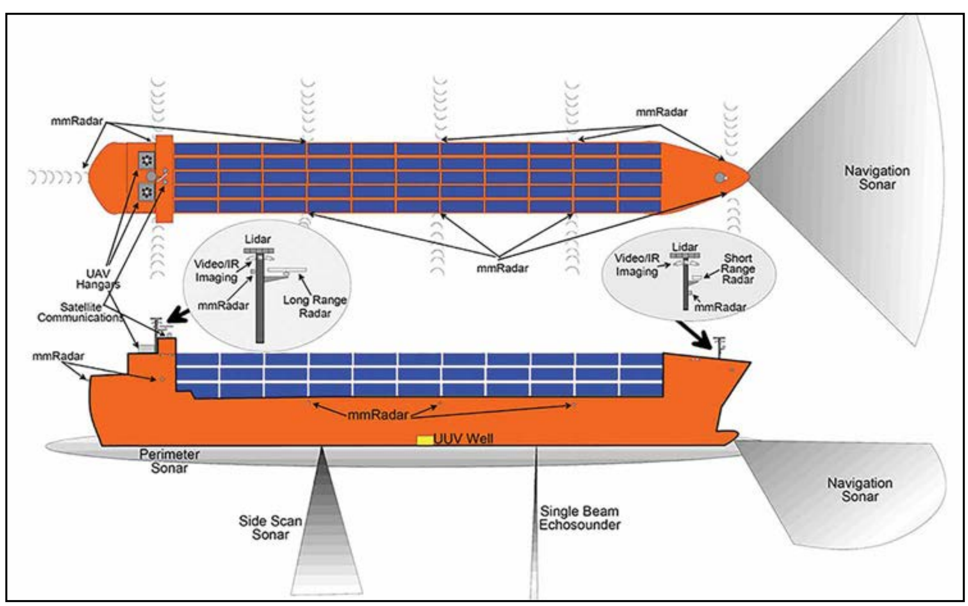
Implications of the successful pursuit of data monetization apply to enhanced hydrography, meteorology, failure prognostics, ship maintenance, law enforcement, search and rescue, and environmental protection.

Safety

The ability to sharply reduce human error as a cause for loss within the shipping industry is a key driving force towards the implementation of autonomous vessels. This position is bolstered by estimates that 75 percent to 96 percent of marine accidents can involve human error.[15] Results of Allianz Global Corporate & Specialty's analysis of almost 15,000 marine liability insurance claims between 2011 and 2016 show human error to be a primary factor in 75 percent of the value of those claims analyzed.

World headlines are rife with accidents where seafarers were caught unaware or used poor judgement that led to catastrophic loss of life, property, and environmental damage, the *Exxon Valdez*, *Costa Concordia*, *El Faro*, and USS *John S. McCain* among them. Case studies of the events associated with these vessels, and many others, indicate instances of distraction and failure to comprehend the significance of changes in their environments that would otherwise have led to action and possibly have prevented these accidents. These include lack of appreciation of differences between echosounder depth indications and charted depths, inability to properly discern the true nature and behavior of radar contacts, inappropriate interpretation of weather data and failure to correlate sensor display content with their actual physical surroundings.

Significant differences exist in the design of autonomous and conventional ships in the expansion of existing and new sensors and sensor types and the use of artificial intelligence to interpret and act upon sensor indications. Such technology promises greater insight into ships' surroundings and improved understanding to enhance overall situational awareness. Human senses are extended beyond traditional physical and conceptual



Autonomous vessel sensor suite placements allow different perspectives based on their locations. Graphic courtesy of R. Glenn Wright

An autonomous test vessel is put through its paces in September 2020. Developed by shipbuilder Metal Shark and autonomous technology developer Sea Machines, the vessel was provided to the Coast Guard Research and Development Center in New London, Connecticut. Photo courtesy of Metal Shark

barriers through expanded subsea, surface, and even space-based sensors to complement the conventional bridge sensor suite and navigation instruments. These include forward-looking navigation sonars to gain insight into the underwater environment ahead of the bow. Additionally, there are visible and infrared cameras for real-time observation; laser and millimeter radars for precise close-in hazard detection and maneuvering; and satellite-based weather, optical imaging, and automated identification system (AIS) observations for real-time voyage planning and execution.

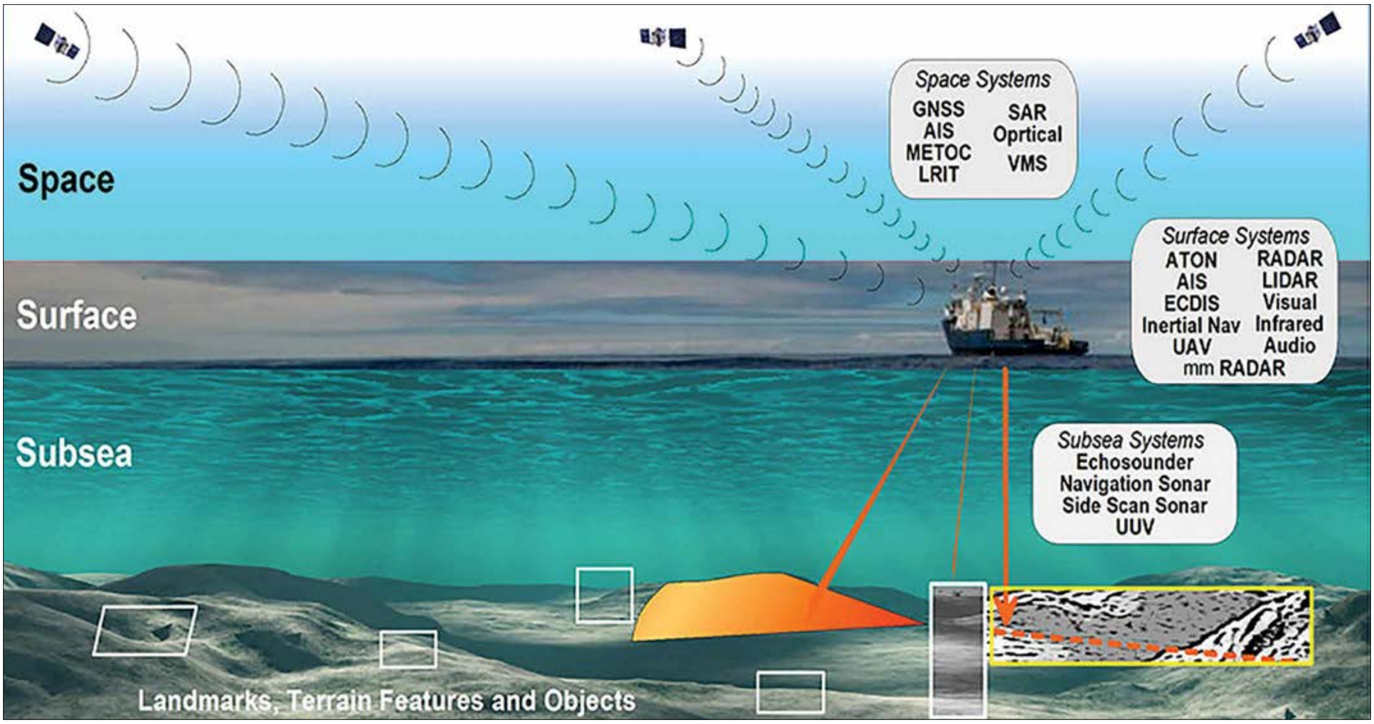
Greater capability to fuse and comprehend the meaning of many different sensor inputs used in onboard decision-making is planned through the use of artificial intelligence-based processes. There is hope these processes will perform at least as well as humans under similar conditions, while promising greater and more consistent performance. This approach should overcome many human limitations problems associated with distraction and sensory overload while attempting to perform complex operations. This is especially true in the presence of many warnings and alarms that routinely sound on the bridge and become ineffective once watchstanders become accustomed to reflexively silencing them through the course of a voyage. Such systems will also possess an ability for continuous learning to enhance capabilities that can be shared amongst other vessels, remote control centers, and technology developers.

Environment

In much of the relevant literature, there is an impression given that autonomous ships are synonymous with environmentally friendly ship designs and operations. Such claims are not necessarily without merit as opportunities are taken to create these vessels using sustainable new designs and technologies that can project minimal ecological impact. This includes eliminating human sources of waste and garbage as well as ballast water, engine cooling, and grey water discharges while at sea. Also being considered are new fuels and forms of propulsion that produce little to no carbon dioxide or particulate emissions.

All such efforts are indeed praiseworthy and essential to continuing to reduce the ecological footprint of shipping, and autonomous ships can lead the way in implementing such technologies. However, these principles apply to all forms of shipping, conventional and autonomous, and are not ends unto themselves. Further, eliminating one environmental hazard and replacing it with another, possibly greater, hazard is neither sustainable nor desirable in the long run.

For example, lithium-ion batteries are touted for their high energy density and are being used to supplement



Marine environment sensor systems provide layers of awareness awareness of a ship's surroundings. Graphic courtesy of R. Glenn Wright

conventional fuels in hybrid vessels and provide the main source of energy in many electric vessels. Their weight enables installation low in the hull eliminating the need for other forms of ballast. However, many Tesla automobiles and the Norwegian battery-hybrid ferry *Ytterøyningen* are examples of battery fires and explosions that have been difficult or impossible to extinguish and have emitted gasses hazardous to firefighters.[16,17]

Charging batteries with an electric grid where power is generated using coal or fossil fuels merely displaces pollution from the point of use to the point of origin, and the disposal of all kind of spent batteries also has significant environmental implications. Kinetic charging of batteries from wave action and vessel deceleration, hydrogen fuel cells, and green ammonia produced using renewable fuels are examples of alternative energy sources being considered.

The most significant contribution automated ships can make to reduce the overall environmental impact of shipping is through the creation and use of technologies that can eliminate and/or reduce the severity of accidents. Groundings, collisions, and allisions, regardless of whether they are caused by a conventional or autonomous ship, can have extreme consequences to the environment. Without human supervision and a capacity to rapidly intervene when problems occur, it is essential that autonomous ships have dependable capabilities to respond to all foreseeable events, and even to improvise to behave appropriately for unanticipated circumstances.

In an era where GPS jamming, denial of service attacks, and AIS spoofing are commonplace, reliance upon single-point-of-failure technologies for positioning, navigation, and timing can no longer be endured. This is especially true when operating in congested and sensitive areas and near marine sanctuaries.

Redundant systems using multiple global navigation satellite systems and sensors and newer navigation techniques, such as virtual aids to navigation that do not require physical infrastructure, must be considered. Consequently, even ancient techniques including sea bed feature and contour following using modern artificial intelligence-based pattern recognition should be studied.[18,19]

Infrastructure

Not solely a driving factor, but also an enabling factor, the current worldwide effort for port digitalization will facilitate seamless integration of autonomous ships into the port environment. The previously described attempt to establish a fully autonomous logistics concept from industrial site operations to port and vessel operations with *Yara Birkeland* is an early example. Smart ports use automation and technologies such as artificial intelligence, big data, the Internet of Things, and blockchain to improve performance.[20] The digital economy and transition to a platform economy are creating new opportunities for value creation through data-based services and data-driven business models.[21] New business models can result with information about infrastructure use becoming more valuable than the goods and materials that exist within the infrastructure itself.

One example is hydrographic and geospatial data and imagery acquired by highly sensored autonomous ships that can be used by the ports to monitor channel depths, buoy placement, and shore-based equipment for dredging, maintenance, and performance measurement. Technology frameworks supporting innovation platforms tailored to autonomous ship operators and service providers will form the basis for data monetization to take place.

Autonomous vessels can also take advantage of physical enhancements to port and harbor facilities and approaches currently being developed, as well as drive new technologies that benefit all shipping endeavors. Processes and facilities for the automated loading and unloading of cargo from conventional vessels should be interoperable across all vessels regardless of type. Absent able-bodied seafarers on board the vessel, automated ships will require new methods for automatic berthing and unberthing that eliminates the need for lines and ropes when securing to the wharf. At present there exist systems that use electromagnets, as well as vacuum pods that cling to the sides of the vessel, for this purpose.

Bunkering is another area where autonomous and conventional vessels can share newly developed technology. However, it is likely that this task will require some level of manual effort to connect between the vessel and bunker source. One exception is the recharging of electric batteries where contactless connection is made through inductive coupling for wireless power transfer. This process can be fully automated, and charging can begin even before the vessel is secured to the wharf, as partial connectivity can be achieved while in close proximity—several feet—to the power source. This can also result in better use of docking time for charging the batteries.[22]

The approaches to harbors, as well as areas within the harbors, provide another opportunity for infrastructure enhancement that takes advantage of autonomous ships'

Icebreaker *Urho* and M/T *Tellus*, both operating with a crew, sail on a collision course off the coast of Oulu, Finland, in April 2020. Autonomous vessels will need to meet high safety standards to minimize the maritime accidents that adversely affect health and safety, nations' economies, and the environment. Valokuva24 | Shutterstock unique capabilities in terms of computer vision and electronic sensing. Conventional aid to navigation and buoy design is based upon human vision, hearing, and radar reflectivity to guide vessels within secure channels. Neither the International Maritime Organization, nor national regulations, recognize machine vision as a viable watchstanding tool in the absence of qualified seafarers. Autonomous ships can provide testbeds for entirely new designs and classes of aids to navigation optimized for enhanced sensing capabilities that will benefit all future shipping needs.

Conclusion

The consequences of failure in the maritime industry that can adversely affect the lives of so many in terms of health and safety, nations' economies, and the environment are unparalleled. The March 2021 grounding of one container ship, *Ever Given*, in Egypt's Suez Canal interrupted world trade for a period of six days, creating a backlog of over 400 ships waiting to pass through this critical choke point.[23] Initial financial claims greater than $900 million were made by the Suez Canal Authority, with hundreds or thousands of additional claims likely to be made by other ship owners for losses incurred while waiting for the canal to be cleared.[24,25] All this happened without significant damage to the vessel itself, nor the environment or the canal, except for some dredging needed to free the ship, and without injuries to crew members or other personnel in the area.

The driving factors associated with progress in maritime vessel and port technology have led to the advent of autonomous ships. However, without humans to intervene under adverse conditions, unprecedented diligence must be given to ensure accidents of all kinds involving autonomous ships are prevented to a much greater degree than for maritime shipping as a whole. The consequences of an event similar to *Ever Given*, or even a collision with a small pleasure craft involving an autonomous vessel, would be grossly magnified in terms of scrutiny based upon the perception of unproven and immature technology. To gain acceptance of the maritime industry and the public in general, all issues associated with autonomous ship operations and how they are handled in a responsible manner will determine the degree to which success of this new innovation will be judged.

About the author:

For more than 40 years, R. Glenn Wright has led numerous projects associated with aerospace, maritime, and medical sensor-based systems. He is currently performing research in sensor analytics for remotely operated and autonomous vessels and vehicles. A master mariner, his newest book, Unmanned and Autonomous Ships*, was published in March 2020.*

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Autonomous Vessel Policy Work Requires Proactive Measures and Measurements

by Camilla Beth Bosanquet
Public Policy Ph.D. Student
Schar School of Policy and Government
George Mason University

Global innovation in autonomous vessel technology is, at present, accelerating. U.S. government leaders and professional staffers, particularly those working within the executive departments, would do well to learn about vessel autonomy now. Attending briefings, making field visits, and reading relevant publications should enable a baseline understanding of vessel autonomy. Yet, adept policymakers ought to go further in anticipating foreseeable developments requiring policy intervention.

As is commonly done 'inside the Beltway,' such policymakers must consider these emerging technologies, as well as any commercial and military applications, in light of their own policy responsibilities. Less obvious is an imperative for database development, construction, and management. Yet, given that vessel autonomy promises to bring about substantial technological and economic changes, early data collection will prove critical to best inform policy analyses and decision-making as vessel autonomy evolves and proliferates.

An Acceleration in Vessel Autonomy

In the three years since the International Maritime Organization's Maritime Safety Committee commenced its *Regulatory Scoping Exercise for Maritime Autonomous Surface Ships*, many successful sea-trial evaluations of numerous autonomous vessels have made for splashy headlines. While industry actors have partnered with government officials and international organizations to contemplate apropos navigation safety and other regulatory modifications, their primary efforts have understandably focused on developing requisite vessel automation technologies. These technologies include sensors, artificial intelligence, machine learning, remote command and control capabilities, communications software and hardware, cyber security, and navigation systems. The resultant first-generation autonomous surface vessels[1] have been designed to ferry passengers, carry vehicles, explore the ocean, provide coastal defense, and transport containers.

Assuming Moore's Law conceptually holds in this instance, advancements in autonomous vessel technology should accelerate in the coming years. By all accounts, the commercial maritime transport industry is poised to undergo a technological transformation driven by projected cost savings. Ancillary motivations include pro-social rationale—seafarer work-life balance, protection of marine life, renewable energy, climate repair, environmental sustainability, and so on. Suffice it to say, vessel autonomy will contribute to *economic* transformation of a major transport sector and, in all likelihood, significant *socioeconomic* change. Policy discussions will therefore quickly transcend evident regulatory revisions of the Convention on the International Regulations for Preventing Collisions at Sea, the International Convention for the Safety of Life at Sea, and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers.

Moore's law: The observation that the number of transistors in a dense integrated circuit doubles about every two years.

Broad Policy Implications

Identifying and prioritizing relevant policy conversations presents opportunities for policymakers at all levels to employ their imaginations as to how emerging technologies might relate to the responsibilities of their position, office, directorate, agency, or department.[2] Moreover, proactive consideration of the interests of other potential stakeholders from across the U.S. government goes far to mitigate myopic or parochial thinking. While vessel autonomy is, at present, on the radar of the Defense,[3] Homeland Security,[4] and Transportation departments, interest among other departments certainly will grow in the immediate future. Interagency conversations must and will expand beyond the U.S. Coast Guard, U.S. Navy, U.S. Space Force, and the Maritime Administration. Proactive engagement across the government will prime the pump, so to speak, to engender future collaboration.

Contemplating the interests of U.S. presidential cabinet advisors provides an initial glimpse into the range of probable intra- and interagency policy work on autonomous vessels. Even a cursory consideration of departmental concerns and responsibilities yields a robust list:

The Secretary of Agriculture will look for efficiencies in the movement of hinterland farm products, feed, and fertilizers to and from both ports and markets.

The Secretary of Commerce will seek to boost the economy by stimulating autonomous shipbuilding, encouraging jobs in the autonomous technology sector, and finding cost savings in transporting American-made goods to overseas markets.

The Secretary of Education and **Secretary of Labor** will want to ensure sufficient education and training pathways and resources to prepare a future workforce of skilled technicians should job opportunities for longshoremen, able seamen, firemen/oilers, and mates weaken.

The Secretary of Energy will be keen to understand new energy requirements for modern vessels increasingly built to zero-emissions standards and powered by electricity.

The Secretary of Health and Human Services, in cooperation with the Secretary of Homeland Security, the Federal Emergency Management Agency director, and the Secretary of the Navy, will envision autonomous hospital ships always ready for immediate and crewless dispatch to coastal disasters.

The Secretary of Housing and Urban Development will reimagine urban waterways replete with autonomous public transportation ferries and goods delivery vessels, plus the requisite pier facilities to accommodate them.

The Secretary of the Interior will encourage and track the development of clean energy technologies in the maritime sector. Simultaneously, the department's Environmental Protection Agency will plan to prevent, respond to, and mitigate toxic spills and other environmental damage resultant from autonomous vessel collisions, allisions, groundings, and natural disaster events. The Secretary of the Interior will also consider the application of autonomous vessels to break ice and deliver food, medicine, supplies, and energy to indigenous communities in remote locations, e.g., along the Alaskan shoreline.

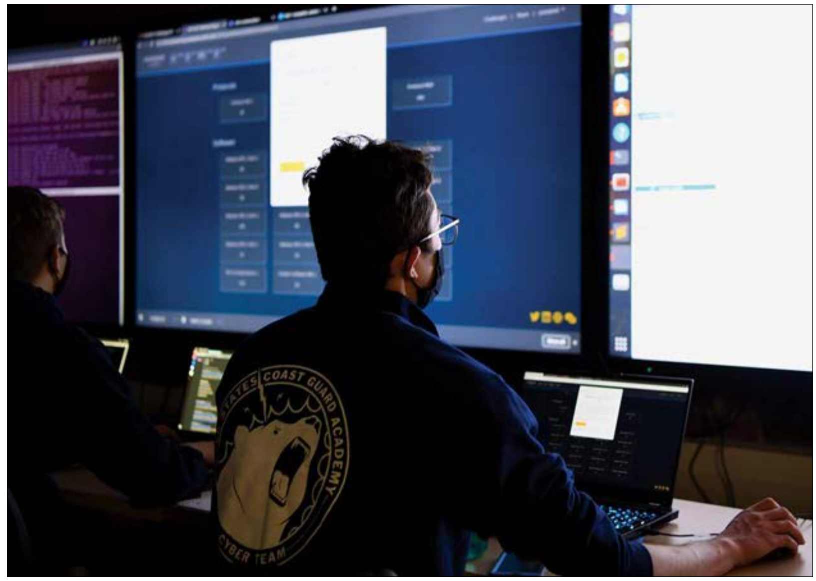
The Secretary of Labor, beyond promoting advanced technical training to meet autonomous vessel workforce requirements, might reconsider new employment classifications to capture an evolving maritime workforce.[5] Doing so would enable policymakers and other researchers to identify gaps and propose solutions.

The Secretary of the Treasury and the **Attorney General** (i.e., the Justice Department) will wish cooperatively to address the many ways in which commercial vessel autonomy could exacerbate already-existing problems of trade-in-value money laundering, corruption within the maritime industry and at ports, and other financial crimes perpetrated across the maritime sector.

The Secretary of Veterans Affairs will seek to improve support to veterans transitioning from military

Developed by Thales UK and AVS, *Halcyon* undergoes unmanned trial runs in Plymouth Sound, United Kingdom, under the supervision of Royal Navy HMS *Argyll* personnel in October 2019. Billy Watkins | Shutterstock service to U.S. Merchant Marine employment. This could include implementing new training and pathways for veterans to work on sophisticated autonomous technology or perform remote command and control functions.

Not to be overlooked, the **Secretary of State** will wish to evaluate how autonomous vessel innovation, technology, and proliferation will impact U.S. foreign policy. State Department personnel must consider a remarkably wide range of issues. Cybersecurity of autonomous or remotely operated maritime vessels will undoubtably constitute a top priority across the whole of government, given threats posed by adversarial states and nonstate actors. The prospects of automated identification system and GPS spoofing, satellite communications hacking, technological vessel hijacking, high-seas piracy, ransomware, denial of service attacks, etc., oftentimes present unique diplomatic challenges requiring State Department intervention. International sales of autonomous vessel technologies, particularly when adapted for defense applications, and the transfer of aging or technologically obsolete warships to developing nations both fall squarely in the department's lane. In terms of its long-standing foreign policy imperative to nurture democratic republics throughout the world, the department will also wish to monitor any potential economic and political ramifications of maritime job losses for small, democratically constituted countries that produce large numbers of qualified seafarers, e.g., Philippines, Indonesia, and Ukraine.


Coast Guard Academy students participate in the National Security Agency's 20th annual National Cyber Exercise in April 2021. The academy recently instituted a Cyber Systems degree to meet the needs of defending cyberspace, enabling operations, and protecting infrastructure. Coast Guard photo by Petty Officer 2nd Class Hunter Medley

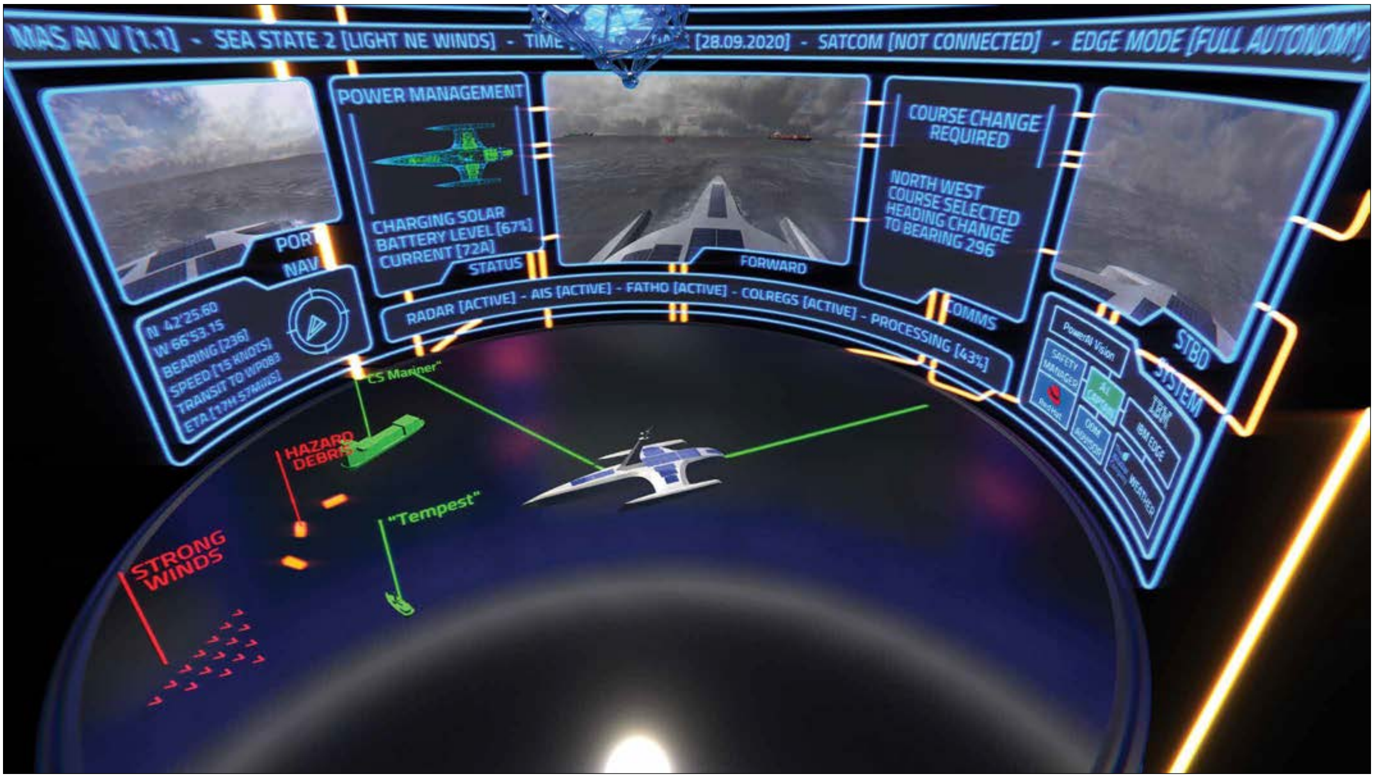
Suffice it to say that other critical players in the U.S. government will similarly hold stakes in the vessel autonomy game. Certainly, the Director of National Intelligence and the U.S. Trade Representative will each remain attuned to autonomous vessel technology developments both here and abroad. Aforementioned, the secretaries of Defense, Homeland Security, and Transportation, are already developing autonomous vessel technology, policy, and strategy. These departments will continue to expand their use of, and involvement in, vessel autonomy in the foreseeable future.

A Call for Data

Policy practitioners and academics alike frequently search for quality data when analyzing real-world phenomena. Far too often, data insufficiency hinders such analyses and precludes well-supported policy recommendations. Such unfortunate outcomes are avoidable insofar as policy executives can call for and direct the measurement of "what matters." Consultation with subject matter experts and professional researchers aids in the identification of what is practicable and worthy of measurement. As with early consideration of what portfolio responsibilities might relate to vessel autonomy, engaging in preliminary thought exercises concerning what data would be helpful in future policy analyses is worth doing now.

That U.S. government databases are decentralized follows from the fact that the federal government is, itself, somewhat decentralized. Researchers understand this and frequently work around the inconvenience of visiting multiple websites to mine data. Certainly, the Census Bureau, Bureau of Economic Analysis, Bureau of Labor Statistics (BLS), and Bureau of Transportation Statistics (BTS) collect and provide a great deal of data, much of which is required by Congressional legislators and their oversight committees. Yet the underlying questions answered by these data are typically proposed by the agencies and departments themselves.

In conjunction with considering what new policy challenges might emerge from the proliferation of autonomous vessel technologies, policymakers ought to determine what data may be necessary to answer future questions and pursue their collection, if not already collected. As one example, questions concerning the displacement of credentialed American urban ferry operators by fully autonomous ferries might send a researcher to BTS, BLS, and the U.S. Coast Guard's National Maritime Center, which handles U.S. Merchant Marine credentialing. Data do exist concerning individuals who maintain active merchant licenses, but more



Mayflower 400 researchers are currently collecting quality data with future regulations and policies in mind. Photo courtesy of IBM/Promare

subtle differentiations—those actually employed on their license, in what capacity or role, on variously sized vessels, etc.—prove challenging when navigating public data void of critical distinctions. More detailed data sets could be had from union halls or shipping companies' HR departments, but such information is almost always propriety and not necessarily available to policy staffers, academics, and other researchers.

It is true that the list of questions that might require supporting data calls could be lengthy, if not endless. It is also true that data collection and database construction and management can be costly. Nevertheless, present evaluations of existing data and prioritizations of anticipated data needs, assuming future implementation of new data collection, could prove prescient. In the coming decade, major questions will emerge in the policy realms of trade, commerce, energy, environmental protection, labor and employment, training and education, technology, cybersecurity, national security, homeland defense, and others that necessitate corresponding data. Creating collection frameworks now and making resultant governmental data available to academics, researchers, journalists, and the general public has great potential to accrue significant follow-on benefits to policymakers.

About the author:

Retired Coast Guard CDR Camilla Beth Bosanquet is a third-year Public Policy Ph.D. student at the Schar School of Policy and Government, George Mason University, in Arlington, Virginia. Her doctoral research encompasses transnational criminal organizations, counterfeiting, global corruption, illicit trafficking, and maritime transportation economics. She welcomes email correspondence via cbosanqu@gmu.edu.

Endnotes:

1. The author acknowledges the term "autonomous vessels" encompasses a variety of vessel types. While this piece largely references surface vessels, semi-submersible and submersible technologies are contemporaneously under development. Likewise, subtle differences between "manned" and "unmanned" autonomous vessels technically matter, however, this article principally contemplates future commercial shipping employing unmanned autonomous surface ships.

2. Emerging technology is a veritable treasure mine for young professional staffers and junior military officers. Their initial research, analyses, and recommendations could well provide a foundation upon which their organizations can build both policy and strategy.

3. Already, the Department of Defense has been conducting operational testing and evaluation of, while simultaneously developing the tactics, techniques, and procedures for operating, four prototype autonomous naval vessels, with more ships on order.

4. The Secretary of Homeland Security will no doubt maintain an interest in autonomous ships for their potential use in counterterrorism and counter-trafficking applications. An argument could be made, however, that investment in autonomous vessel technology could significantly improve outcomes for the U.S. Coast Guard in executing its search and rescue mission coastal and near-coastal environments—particularly resultant from heavy weather events—without risk to Coast Guard equipment or personnel.

5. Distinguishing between those mates, engineers, and captains who are employed in the operation of *unlimited* tonnage vessels and those who are not would be of great help to researchers. Such clarity is not currently present in publicly available BLS data. Improving the identification of various types of mariners would be particularly helpful in cases where national security and education policy scholars seek to comment on military sealift capability, maritime academy curricula, and the benefits of the Jones Act. While such data undoubtedly exist they typically are not readily accessible to the public, not classified in such a way as to be useful, and/or propriety to a private entity.

Current MASS Projects and Technologies

Autonomous Vessels

The *Mayflower 400* and minimizing risk to improve technology

by LCDR Mason Wilcox
Chief of Inspections and Investigations
First Coast Guard District

In the fall of 2020, the owners of the *Mayflower 400 (MAS400)* approached U.S. Coast Guard District 1 with a plan to operate their fully autonomous vessel within U.S. waters. Mr. Brett Phaneuf, president of Submergence Group, LLC, had just completed construction of the *MAS400* in Plymouth, England, and was making plans for its journey across the Atlantic Ocean in commemoration of the original *Mayflower*'s 1620 sailing from England to Plymouth, Massachusetts. At the time, the vessel was undergoing sea trials off the coast of England, allowing the team to fine-tune the computers that would eventually allow it to sail without human intervention. The research company Promoting Marine Research and Exploration (ProMare) was responsible for design, fabrication, and testing under the management of Mr. Phaneuf. The ProMare team also worked with several other partners, like IBM, to ensure the most powerful and technologically advanced equipment was being used to ensure a successful mission.

The objective of the *MAS400* project was to demonstrate that autonomous vessels can operate safely in the open ocean and arrive at a predetermined port. Additionally, ProMare intends to conduct bathymetric and oceanographic data collection for use in studies of the oceans and our environment. This electric propelled trimaran has battery systems and a backup generator that gives her a 10-knot speed and a capability of several thousand nautical miles.

The *Mayflower Autonomous Ship 400* conducts sea trials off the coast of Plymouth, England, in March 2021 before making an attempt at crossing the Atlantic Ocean. Photo courtesy of IBM/Promare

IBM researchers Rosie Lickorish and James Sutton work on the *Mayflower Autonomous Ship 400* before the ship attempts to cross the Atlantic Ocean. The Coast Guard worked with all stakeholders to address maritime law compliance prior to the transatlantic crossing. Photo courtesy of IBM/Promare

During the initial contact with Mr. Phaneuf, District 1 identified gaps in policy and regulation that needed to be resolved to ensure a safe waterway, while at the same time making allowances for the expansion of new technology and the learning that takes place with innovation. Determining how this vessel would comply with the International Regulations for Preventing Collisions at Sea (COLREGS), specifically Rule 5, lookouts, was a central issue. In the spirit of the rule, the technology on board allows someone at a command center to maintain a proper lookout, but the *MAS400* does not meet the prescriptive requirement. There is no human on board to maintain a proper lookout by sight and hearing. With that in mind, several questions needed to be addressed:

- Is the vessel technically under command?
- Should the vessel be marked in accordance with Rule 27?[1]
- Can we even call the *MAS400* a vessel?
- Does Rule 5 even require a human to be the lookout, after all it does not mention "people or persons" having to maintain situational awareness, it only says "every vessel."[2]

These were the questions that challenged the prevention professionals at District 1. The goal was to support industry, technological development, and project success, while preventing a collision at sea and protecting the safety of the waterways for the many commercial and recreational users.

Through consultation with the National Vessel Documentation Center and Coast Guard Headquarters offices, the decision was made to classify the *Mayflower 400* as a recreational vessel. This limited the regulatory scheme to that of other recreational vessels of similar size and greatly eased the compliance burden of meeting commercial vessel rules.

Laws and regulations typically lag behind new technology. We have seen this in autonomous vessels as well as other areas like cybersecurity and alternative fuels. As a regulatory agency, the Coast Guard must ensure compliance with its maritime laws, regulations, and policy and has limited ability for exemptions and equivalencies, depending on the situation.

The Coast Guard had to keep its number one goal—safety—in mind while allowing for innovation and giving the service time to learn more about the regulatory and policy gaps, and how to overcome them. Smartly interpreting existing standards for these new technologies, and developing localized policy and solutions tailored to individual situations, while waiting for the rulemaking and policy process to catch up is a continual challenge for the Coast Guard.

The proposed journey for the *MAS400* was to cross the Atlantic Ocean from Plymouth to Provincetown, Massachusetts, and then shortly thereafter transit to Plymouth, Massachusetts, with later port calls along the eastern seaboard. As planning progressed, it became apparent to the district office that all of the District 1 areas of responsibility in which the *MAS400* was intending to operate needed to be on the same page.

Many of the Captains of the Port (COTP) within District 1 had significant concerns with a fully autonomous vessel operating within their waterways. The district instituted a process to ensure all the concerns from the field were addressed and the *MAS400* could operate in multiple COTP zones under the same rules.

The Operations Order's Objectives

(a) Though not manned, the vessel is expected to abide by all the same navigational rules and regulations as prescribed in the Coast Guard Navigation Rules.

(b) The IBM artificial intelligence system is capable of learning/decision making, and programmed to act in accordance with the International Regulations of Preventing Collisions at sea without outside intervention.

(c) The owner/operator will provide an escort boat when the *MAS400* is within U.S. territorial waters.

(d) The *MAS400* position, course, speed, and other relevant information will be continually monitored and have various remote checks and software updates through the control center which is manned 24/7.

(e) Continual *MAS400* position, course, and speed can be tracked and is available at: www.mas400.com and via the mobile device app "Marine Traffic."

(f) Broadcast Notice to Mariners will be prepared as necessary to notify the public regarding the *MAS400* movements.

Autonomous vessel hulls are increasingly being marked with the word "UNMANNED" offering another measure of safety to port operators and traditional waterways users. Photo courtesy of IBM/Promare

District 1 decided to create an operations order (OpOrder) to ensure consistency of regulations, safe procedures, and tactical controls for the journey. This brought together all the stakeholders under one umbrella and helped to create good information flow. Most importantly, it still allowed the Captains of the Port's autonomy in decision making if they felt something was not right with the operation. This was coordinated with the assistance of Coast Guard Headquarters Waterways Management office as well as Deputy Commandant for Operations.

About the *Mayflower 400*

The *Mayflower 400*, a 50-foot-long solar-powered trimaran, is capable of speeds of up to 10 knots and is navigated by onboard artificial intelligence with information from six cameras and 50 sensors. In addition to its lithium ion batteries, it has a diesel powered generator to provide electricity when solar energy is not available to the 20 KW electric propulsion motor. https://mas400.com/

A working group was set up from District 1, Waterways Management and Vessel Inspections to create this OpOrder. Input was received from the five COTPs, District 5, Coast Guard Waterways Management, and the *MAS400*'s owners. The signed OpOrder included six common objectives agreed to by all parties. If the *MAS400* operated outside of these objectives, an expectation to use a Captain of the Port Order existed to stop or modify operations

In addition to the common objectives, Mr. Phaneuf provided the Coast Guard with a company operations plan, intended voyage plan, and risk assessment, including a portion on cybersecurity. The risk assessment, similar to a failure mode and effects analysis, was considered one of the most important documents and provided reviewers a level of comfort that the autonomous systems were well-designed with contingencies in place should problems occur. In addition, Mr. Phaneuf also had Lloyds Register UK[3] involved for automation and vessel construction oversight.

District 1 had a few additional requests which were addressed without any hesitation, including adding a flashing yellow light to the mast of the *MAS400*, as well as marking the side of the hull with "UNMANNED." The ProMare webpage also allowed for 24/7 live viewing from four web cams and its automated identifications system tracking. With no humans aboard, there was no justification to enforce other requirements, like lifesaving or firefighting equipment.

The most discussed safety issue was the use of an escort vessel within 12NM. Both the Coast Guard and ProMare agreed that the distance of the escort to the *MAS400* would vary depending on the density of marine traffic in the area. Once again, the goal was to allow the technology to prove itself without causing undo risk to the boating public. After multiple meetings between the Coast Guard, ProMare staff, and Lloyds, it was agreed that the planning process had sufficiently mitigated risks and that the *MAS400* voyage would be allowed to commence as a test of the new technology on a recreational vessel.

On June 15, 2021, the *MAS400* left Plymouth, England, for Cape Cod, Massachusetts. Unfortunately, three days into the voyage, an exhaust leak started in the generator, filling the vessel's hull. This limited the generator's ability to produce the needed power for propulsion, especially during the cloudy days it was experiencing. The owners decided to direct the vessel to return to home for repairs and attempt the crossing in 2022.

What has been learned from this project? Though the *MAS400* has yet to complete its Atlantic crossing, early engagement with the Coast Guard, and working across the team of stakeholders, is key to evaluating and mitigating risk at the Captain of the Port level. Efforts led at the district and headquarters levels help improve communication of information and ensure a consistent approach across all zones, particularly for a project like this, which spans several COTP zones.

The goal from the start has been to let the technology prove itself, while preserving the safety of the waterway for all users. Through the Coast Guard's OpOrder and the District 1/District 5 working group, we have proven that the Coast Guard can work with industry to find ways to accept this new technology.

For more information

The OpOrder is available for Coast Guard units, please contact LCDR Mason Wilcox at mason.c.wilcox@uscg.mil

About the author:

LCDR Mason Wilcox has served in the U.S. Coast Guard for 16 years. Since direct commission into the MARGRAD program in 2005, he has spent his career as a marine inspector and investigator.

Endnotes:

1. Rule 27—International Regulations for Preventing Collisions at Sea (COLREGS) Vessels Not Under Command or Restricted in Their Ability to Maneuver
2. Rule 5—International Regulations for Preventing Collisions at Sea (COLREGS) Conduct of Vessels in Any Condition of Visibility, *Look-out.*
3. Lloyds Register is one of 12 members of the International Association of Classification Societies that oversees vessel construction, standards, and ensures compliance with US and International shipping laws. www.lr.org

Marine Autonomy Today and Tomorrow

by Michael G. Johnson
Founder and CEO
Sea Machines Robotics

Lauren Lamm
Vessel Test Lead
Sea Machines Robotics

It is no secret that the global maritime industry is responsible for billions in economic output and is a major driver of jobs and commerce. Despite the sector's success and endurance, it faces significant challenges that can negatively impact the industry's performance and profitability. Developers of autonomous marine technologies are solving many of these challenges by developing systems that are helping the marine industry transition into a new era of task-driven, sensor-computer-guided vessel operations.

Before exploring this concept further, it is necessary to explain marine autonomy in clear terms. Autonomous control of a vessel is a highly practical technology that aids the navigation of vessels and improves the productivity and safety of mariners on the water today.

Lloyd's Register defines autonomy for commercial marine operations across six categories, ranging from low automation to unmanned operations.

By this definition, understand that today's autonomous systems are commonly designed as human-on-the-loop systems. Most current use cases involve supervised autonomy in both local and remote unmanned missions, with unmanned configurations primarily being conducted in controlled domains.

If autonomy does not equal unmanned, what then is the basis for the need for this type of technology? The truth lies in the fact that myriad modern-day challenges, such as a high on-water accident rates and dangerous work environments, provide entree for revolutionary solutions based upon best-available technology. Further, as the marine industry workforce ages, modern technology will play a role in drawing in younger recruits. In this day and age of smart phones, TVs, and self-parking cars, the next generation of mariners will not only appreciate and respect the capabilities of modern smart ships, but will also expect them.

Defining Autonomy for Commercial Marine Operations

0: Manual Operation
No autonomous function. All decision-making made by a human operator.

1: Low Automation
All actions taken by human operators, but decision support tool can present options or influence decision-making. Data is provided by systems on board.

2: Partial Automation
All actions taken by human operators, but decision support tool can present options or influence decision-making. Data is provided by systems on or off the vessel.

3: Conditional Automation
Decisions and actions are performed autonomously with human supervision and authorization.

4: High Automation
Decisions and actions are performed autonomously with human supervision. High-impact decisions allow human operators to intervene and override.

5: Full Automation
Rarely supervised operation where decisions are entirely made and actioned by the system.

6: Unmanned
Unsupervised operation where decisions are entirely made and actioned by the system during the mission.

—Lloyd's Register

Solving Some of the Industry's Greatest Challenges

Perhaps the greatest challenge facing our industry is the inherent risk that comes with "dull, dirty, and dangerous" jobs on the water. According to the National Institute for Occupational Safety & Health,[1] commercial marine and maritime workers face a higher risk of fatality, injury, and illness than the average American worker. The reason for this is obvious—on top of some of the hazards seen in other industries, including fatigue and use of heavy equipment, mariners face additional risks of vessel collisions, allisions, groundings, severe weather, and more.

Autonomous-command and remote-helm control systems offer several solutions. For on-water incidents caused by fatigue, a known major factor in marine incidents, today's technologies offer obstacle detection and collision avoidance capabilities. Commercially available systems use continuous data from sensors such as computer vision, radar, AIS, IMU, and GPS, and offer mariners 24/7 watch redundancy. These advanced technologies can be more reliable and accurate than the human eye, especially in times of low light or in poor sea conditions. All of this combined can reduce operator fatigue and the risk of operational incidents.

Another serious risk includes crew exposure to challenging sea states and toxic conditions. For sectors like marine spill response, firefighting, search-and-rescue, and patrol, crews often execute missions in poor conditions and may encounter smoke, heat, fumes, and other hazards. Autonomous and remote-helm control systems enable minimally manned or unmanned methods of handling these situations, thereby increasing safety by reducing or eliminating the need for humans to be on board vessels during missions. Today's autonomous systems also uniquely execute with human-like behavior, intelligently factoring in environmental and sea conditions—including wave height, pitch, heave and roll—and make controlled speed changes between waypoints

Sea Machines successfully deployed the world's first autonomous spill response vessel in August 2019. The Marine Spill Response Corporation and U.S. Department of Transportation Maritime Administration worked with Sea Machines to demonstrate the latest capabilities of autonomous vessel technology. Photo courtesy of Sea Machines for added crew comfort.

One example of this is Boston-based Sea Machines Robotics' successful 2019 deployment of the world's first autonomous spill response vessel, a Kvichak Marco skimmer boat owned by Marine Spill Response Corp. (MSRC). The company executed the project alongside MSRC and the U.S. Department of Transportation Maritime Administration (MARAD) to demonstrate the capabilities of autonomous vessel technology in increasing the safety, productivity, and predictability of marine spill response operations. With the ability to operate in unmanned modes, the autonomous vessel could be commanded by shoreside crews, no longer needing to be exposed to fumes and chemicals during clean-ups. Autonomy also meant time-sensitive missions could be executed faster, without waiting on the arrival of crew to manually operate the boat. Dangerous and time-consuming crew changes were also reduced or eliminated, allowing onshore mariners to focus on collecting spilled product from a safe shoreside position.

The Sea Machines SM200 system enables wireless helm and propulsion control, as well as remote control of auxiliaries and payload equipment. The Coast Guard and the American Bureau of Shipping approved the SM200 in early 2020 for installation aboard a class of U.S.-flag tugboats that support articulated tug-barge sets. Photo courtesy of Sea Machines

"Response timing is critical. The sooner we can get to a spill, the sooner we can contain it and control it, the less damage it will do. The technology we saw is a clear example of how remote systems can help us be more efficient with that and respond quicker," MARAD's Deputy Administrator Richard Balzano said, following the event. "This is the future of our industry. If our industry is going to be competitive and safer and evolve, it has to look at remote technologies."

Sea Machines' on-going partnership with Hike Metal, a world-class manufacturer of workboats based in Ontario, Canada, is an additional example of autonomous systems supporting crews conducting hazardous jobs on the water. For this project, Hike Metal will integrate an autonomous vessel control system aboard a rigid hull inflatable boat (RHIB) tasked with search and rescue (SAR) missions to develop and demonstrate the capabilities of autonomous marine technology in increasing the productivity and safety of SAR operations.

"We have seen the need to increase response capabilities and also reduce the risk to first responders. We feel this technology and platform will be a valuable tool to all Coast Guard Societies around the world," said Hike Metal's senior project manager, Roger Stanton. "We are very excited to be working with Sea Machines, a leader in autonomous technology for the marine environment."

One of the many significant challenges the marine industry faces is the obstruction of vision by vessel structure or cargo. In traditional operations, crews are confined to a wheelhouse to operate the vessel and on-board payloads. This fixed location does not always offer the best vantage point for operators and, in some cases, requires signals to be relayed from a mariner to the wheelhouse. Wireless and remote-helm control technologies that free crew from the wheelhouse to conduct operations from any location that offers the greatest visibility and safety are replacing this conventional system. Systems like Sea Machines' SM200 enable wireless helm and propulsion control, as well as remote control of auxiliaries and payload equipment. Earlier this year, the Coast Guard and American Bureau of Shipping approved the SM200 for installation aboard a class of U.S.-flag tugboats that support articulated tug-barge (ATB) sets.

Another major challenge we face is that of manual operations. Across all industries, autonomy automates tedious, redundant, dangerous tasks, allowing workers to focus on higher-level operations. In the commercial marine industry, this means that operators can program vessels to autonomously navigate pre-established routes and workboats can be remotely commanded to follow paths in an unmanned or autonomous mode. Offering greater predictability and higher performance than a human operator can, these autonomous missions can be saved and reused for future efficiency.

An often overlooked, but critical, challenge of our industry involves the massive size of our oceans and waterways contrasted with our limited resources available for managing them. Whether the missions be search and rescue, patrol, or hydrographic survey, today's autonomous systems enable autonomous vessels to collaborate as they follow pre-established grid patterns and perform other coordinated tasks. To create a force-multiplier effect, operators can coordinate multiple autonomous boats to follow the same paths at set distances apart. Minimally manned vessels can autonomously collaborate to cover more surface area with fewer resources required. A single shoreside operator can also command multiple autonomous boats with full situational awareness.

As an example of how collaborative autonomy can be used, consider Sea Machines' recent installation of its SM300 autonomous-command and remote-helm control system aboard Amsterdam-based DEEP BV's survey vessel *Loeve.* This system enables remote command of the vessel, including navigation and positioning; control of on-board auxiliaries and sensors; and ship-to-shore data flow. As a result, DEEP's crew now can remotely monitor and command multiple autonomous vessels from a shipboard or shore-based center located anywhere with network connectivity. This remote capability increases operational health and safety by reducing or removing high-risk activities generally associated with crew working aboard small survey craft in dynamic marine environments. By breaking the 1:1 crew-to-vessel relationship, companies can better use their technical experts across multiple concurrent projects. A shoreside crew also alleviates the difficulty of finding in-demand surveyors for multiple boats, as a single surveyor can now manage several remote missions simultaneously.

Sea Machines collaborated with First Harvest Navigation of Connecticut in April 2019 to launch the first autonomous hybrid cargo vessel in the United States. The electric-powered *Captain Ben Moore* became the first U.S. hybrid cargo vessel to feature remote crew-assist technology and generate zero emissions. Photo courtesy of Sea Machines

"Besides unparalleled flexibility advantages, it offers a time-saving option to increase efficiency and control costs towards a more sustainable future. With Sea Machines integrated on our vessel, we will soon begin to transfer tasks from the vessel to the safe working environment of the office," said DEEP's CCO Jurgen. "As well as improving safety, we will gain flexibility, continuity and quality."

Yet another challenge that can be solved by today's autonomous marine systems is the limited shoreside visibility personnel currently have into at-sea vessel operations. To solve this, some commercially available autonomous systems enable crews to monitor the operations of working vessels in real time anywhere there is a network connection from a shoreside location or second vessel. This "on-watch redundancy" can help to prevent operational incidents and keep crews and cargos safer. Further, human operators can command and control fleets of unmanned vessels with greater efficiency and reduced operational cost.

An important final topic involves roadway congestion, which may seem like an odd topic for a marine industry-focused article. However, the maritime sector has the tremendous opportunity to expand its marine highway system by shifting cargo from overburdened highways to underused marine corridors. Shifting freight from trucks to autonomous cargo vessels reduces roadway congestion. In many cases, autonomous ships can help to increase supply chain performance.

An example of this is Sea Machines' collaboration with First Harvest Navigation of Connecticut to launch the first autonomous hybrid cargo vessel in the United States. Powered by the SM300 autonomous command and remote-helm control system, the electric-powered *Captain Ben Moore* is now the first American hybrid cargo vessel to feature remote crew-assist technology and to generate zero emissions. Offering First Harvest Navigation redundancy and flexibility for crew shifts, as well as the capability to autonomously command *Captain Ben Moore* from the company's land-based control station, the vessel can deliver cargo from terminal to terminal in less than 45 minutes. By contrast this same trip takes nine hours by truck.

"Part of our transportation goals are to develop autonomous, hybrid catamarans to move farm products across Long Island Sound. The SM300 autonomous navigation system will help us achieve many of our goals because it enables shipping movements to be completed very reliably and efficiently in a seamless and sustainable delivery system," said First Harvest Navigation President Bob Kunkel. "Shifting cargo from streets and highways also alleviates the growing congestion, lowers emissions, and reestablishes our waterways as a viable and cost-efficient alternative to land-based transport."

It is clear that today's available autonomous and remote technologies are already starting to solve some of the marine and maritime industries' greatest challenges. This includes mitigating operational risks and hazards to mariners, reducing manual operations, maximizing resources to cover large areas, alleviating crew restrictions, and providing greater shoreside visibility into at-sea operations. Combining these solutions with an expanding marine highway system means improved supply chain performance and greater operational predictability and productivity on the water.

Diverse Autonomy Applications

Thus far, applications for autonomous marine technology have been discussed aboard spill response skimmers, search and rescue RHIBs, survey boats, tugboats supporting ATB units, and cargo vessels. When considering how these intelligent systems can be used now, and in the future, it is important to understand the wider set of applications available to workboats and commercial vessels. Today's available autonomous-command and remote-control technologies have many uses. While not an exhaustive list, the sidebar offers some additional uses.

Again, these are just some of the many use cases for today's available autonomous marine technology. Every day, more and more applications arise, each born out of the need to improve operational safety, productivity, predictability, and on-water capabilities.

Additional Uses for Autonomous Marine Technology

Marine patrol operations benefit from multiple autonomous workboats operating collaboratively along pre-planned routes and repetitive paths. These coordinated efforts create a force-multiplier effect that can cover large surface areas more safely and productively.

Autonomous security boats can match the speed and course of larger ships, making the **escort operations** of vessels carrying high-value cargo safer and more cost-effective.

Ice-breaking tugboats can autonomously zig-zag through harbors and near-shore waterways during freezing conditions to **help keep shipping lanes open**.

Broad network coverage so long transits to offshore sites aboard offshore commercial boats can be executed autonomously, using dynamic waypoint following capabilities. Pairing manned mother vessels with unmanned daughter craft—ideal for offshore surveillance and monitoring, surveying, seismic operations and spill responses—reduces crew expenses and can increase operational periods due to the reduction in stop-work periods related to shift changes.

High-bollard pull tugboats towing out loaded barges can be programmed to operate in collaborative following modes. Such capabilities allow tugboats in complex formations to maintain an exact course and speed from the point of departure to the offshore project site, **eliminating fatigue and increasing operational predictability**.

In marine emergency response scenarios, stationed vessels, like fireboats, can be remotely deployed immediately. Because responses are not delayed waiting for responders to travel in, incidents can be attended to faster and often before they escalate into large-scale situations. Two unmanned boats can autonomously collaborate in highly aggressive sweeping patterns that put out flames faster than more conservative, manned boats could.

For government operators, unmanned vessels can be stationed long-term at sea to serve as the vital communication link between aerial and subsea assets. These vessels can also serve as a "floating battery," providing power to connect stand-off vessels to SATCOMs.

For special forces operations, minimally manned and unmanned marine operations allow for removal of military personnel from potential hostage situations. Unmanned drone boats can also serve as diversions, allowing crewed boats to complete missions safely.

Autonomous marine assets can **support maritime rescue operations**, expeditionary logistics and humanitarian relief efforts because they can deliver cargo and personnel faster and more cost-effectively. Minimally manned vessels can also serve as efficient "floating hospitals," allowing more room for medical staff and patients. Following disasters near coastal areas, an unmanned vessel stationed near shore can provide a signal to restore communications and connectivity.

What's Next: Technology for Larger Vessels

The marine industry is on the cusp of even larger changes due to this surge of technological innovation. The next wave of progress will include artificial intelligence-powered perception systems for larger vessels, including ships, tankers, cruise ships, and ferries, that will provide advanced situational awareness for piloting. Such technology will provide mariners aboard with a full picture of a ship's surrounding domain, traffic,

Technological innovation is allowing artificial intelligence to provide advanced situational awareness for piloting larger vessels. Ultimately, mariners will have a full picture of a ship's surrounding domain, traffic, and obstacles. Photo courtesy of Sea Machines

and obstacles. This picture is created using data from conventional marine sensors, like radar and automatic identification system, fused with new technologies, such as real-time image recognition for vessel detection and tracking and Light Detection and Ranging (LiDAR).

The version of this technology under development by Sea Machines will display these situational awareness data feeds in a user-friendly way on wide-angle panoramic screens located in the wheelhouse and other areas of the ship. In this way, the system is "always on watch," and supports navigation 24/7, even in poor visibility and challenging weather conditions.

Along with serving as an advanced situational awareness system, the system will also act as a hub and conduit for shipboard digital data. This system will collect, display, record, and transmit operational telemetry and data like navigation and traffic information, videos of the operating domain, environmental information, and the condition of on-board machinery.

The main advantages of advanced perception and situational awareness technologies is the reduced risk of uncontrolled incidents, accidents, and delays that impact cargo schedules and reduce operators' bottom lines. These incidents are traditionally caused by limitations in conventional shipboard instruments and the perception limitations of human operators.

Sea Machines is now trialing its artificial intelligence-powered perception and situational awareness technology aboard A.P. Moeller-Maersk's vessel, *Vistula Maersk*, an ice-class container ship in Denmark. The installation marked the first time computer vision, LiDAR and perception software have been used aboard a container vessel to augment and upgrade transit operations. This system is expected to become commercially available to maritime operators and naval architecture and marine engineering firms in the near future.

The Future Is Now

In closing, it must be emphasized that autonomous technology is here and being adopted faster than other adjacent industries, like land transportation. Many early adopters in the commercial marine industry have already begun leveraging autonomous and remote-helm control technologies for their vessels to increase capability and improve operational safety, productivity, and predictability. While fully unmanned ships are still on the horizon, the industry will see a rapid uptick of autonomous and unmanned, medium-to-large-sized workboats in the coming months and years. The result will be the start of an unprecedented era of safety, increased efficiencies, and the introduction of myriad new skill sets for mariners.

The maritime industries are a critically significant component of the global economy and it is up to us within the industry to keep it strong and relevant. Along with people, processes, and capital, pressing the bounds of technology is a key driver. The world is being revolutionized by intelligent and autonomous self-piloting technology, and today we find ourselves just beyond the starting line of a busy road to broad adoption through all marine sectors.

About the authors:

Michael G. Johnson, founder of Boston-based tech company, Sea Machines, is also a marine engineer, three-time entrepreneur, and sector leader with a primary goal of building progressive and sustainable innovation for modern society. Sea Machines is a leading provider of autonomous control and intelligent perception systems for marine vessels.

Captain Lauren Lamm is a graduate of the Massachusetts Maritime Academy and holds a 3rd Mate Unlimited Tonnage license. She is the vessel test lead for Sea Machines, a position that allows her to trial the company's autonomy products and provide recommendations that make them easier to use and more intuitive for customers from the mariner's perspective.

Endnote:

1. www.cdc.gov/niosh/topics/maritime/default.html

Marine Autonomy Research in Unstructured Environments

Testing the limits of new technologies on Lake Superior

by Travis White
Research Engineer
Michigan Technological University
Great Lakes Research Center

Autonomous is a word bearing different implications in different contexts. This is especially true in the maritime domain. The Convention on the International Regulations for Preventing Collisions at Sea (COLREGS), colloquially the "Rules of the Road," provide a regulatory framework governing safe navigation. Nowhere in the above rules is the word "autonomous."

Globally, there has been a rapid uptake of new technology across the maritime industry that is changing vessel operations through automation while outpacing the progression of existing maritime regulations. Lacking uniform guidelines on the development, testing, and application of new technologies, a practical interim strategy for many early adopters has been structured testing in unstructured, real-world environments. This strategy has been adopted and embraced in the Great Lakes Region, where there is a strong and growing blue economy, world-leading workforce development programs, and considerable investment in marine technology research, development, manufacturing, and infrastructure.

Great Lakes Research Center at Michigan Technological University

At Michigan Technological University's Great Lakes Research Center (GLRC), we focus on using these opportunities to help solve existing and future challenges in the marine industry using the Great Lakes as a natural testbed. Our campus overlooks the Keweenaw Waterway and is just a few miles from vast and harsh open waters of central Lake Superior. Our unique and challenging environment is an integral component of our academic programs and research portfolio.

GLRC is an early adopter and developer of many new marine technologies and is well-equipped with an arsenal of tools to tackle climate, energy, and mobility challenges surrounding water resources. In addition to several conventional research vessels, Michigan Tech has a growing inventory of remotely operated and unmanned vehicles. This includes a third-generation L3Harris OceanServer Iver 3 autonomous underwater vehicle that is equipped with onboard high resolution interferometric side scan sonar, high resolution cameras, and other sensors. This technology is used to map the lake floor, photograph aquatic habitats, monitor for invasive species, measure currents flowing through the lakes, locate and identify historic shipwrecks, aid in search and recovery missions, and perform structural scans of submerged infrastructure. Michigan Tech researchers recently completed construction of an autonomous surface vehicle that will be employed to autonomously map the bottom of the Great Lakes and contribute to other scientific missions and workforce development.

Smart Ships Coalition

Motivated by the economic significance and vitality of the maritime industry in the Great Lakes and growth in global leadership, stakeholders from across the region have organized around emerging trends, technologies, and opportunities related to smart shipping and automation. Multisector partners, including Michigan

Side-scan vs. Interferometric Side-scan Sonar

Side-scan sonar builds detailed acoustic images of the seafloor allowing for detection of objects and bottom structures, whereas interferometric side-scan sonar also comprises a bathymetric function with sounding points established in three dimensions.

Tech, Michigan's Office of the Great Lakes (OGL), and the Great Lakes-St. Lawrence Governors and Premiers (GSGP), executed two resolutions that would establish what is known today as the Smart Ships Coalition (SSC). in October 2017, GSGP signed a resolution recognizing the Marine Autonomy Coalition, known today as Smart Ships Coalition. The following month, the state of Michigan entered into a memorandum of understanding with the Norwegian Forum for Autonomous Ships (NFAS) calling for the "exchange of information and noncompetitive cooperation on smart ship technology and autonomous ships.

In January 2018, the United States Coast Guard Marine Safety Unit Duluth and Station Portage were briefed on a concept of operations for a Lake Superior autonomous vessel testbed area and received a draft plan from OGL and the GLRC detailing the proposed test area, the types of testing it could support, and strategies for risk mitigation. On August 10, 2018, SSC was officially launched with 18 confirmed members attending a public ceremony. During this ceremony, the Marine Autonomy Research Site (MARS) was formally recognized by the offices of then-Governor Rick Snyder and now-retired Michigan Office of the Great Lakes Director Jon Allan.

Today the Smart Ships Coalition has grown to include more than 50 members, from private and nonprofit industry, government, academia, and international organizations that share a common interest in the advancement and application of technologies operated in marine environments. These members—scientists, policy makers, resource managers, innovators, navigators, and educators—are working collaboratively to develop technology, safety protocols, and policy surrounding the incorporation of autonomous maritime systems into the mobility solutions of tomorrow.

SSC members support cross-functional working groups to allow for quicker and greater adoption of autonomy in marine environment operations. Their goal is to change the state of autonomous technologies and operations in marine applications where the rate of adoption for autonomous technologies lags behind that of air and ground domains. The Coalition seeks to learn from these industries and international partners, like NFAS, to provide quicker advancement in the marine environment in the Great Lakes region and U.S. coastal oceans.

Marine Autonomy Research Site

Autonomous surface vessels (ASVs) and autonomous underwater vehicles technology has matured to the point of these becoming readily available "off-the-shelf" tools in recent years. The number of products and types of vehicles under development continues to grow, as does the size. Testing is needed to verify associated risks and compliance with real-world conditions, including the interaction with commercial and recreational vessels, compliance with existing maritime regulations, and the amount of oversight and control needed for safe and efficient operation. For these reasons, the SSC announced the MARS testbed open to those interested in testing autonomous vehicles and related technologies.

The goal of the MARS testbed is to allow collaboration between technology developers, university researchers, government, and industry to meet the future challenges in marine technology development, application and workforce development. Given the rugged environment, combined with the availability of talent, advanced technologies, and countless other resources, the GLRC is uniquely positioned to house MARS, the area in and adjacent to the Keweenaw Peninsula Waterway. The location is uniquely suited as a test bed for several reasons. MARS is the first freshwater site of its kind in the world and is centered within a 30-mile radius of Michigan Tech's main campus in Houghton. The area is served by the university's high-accuracy, real-time kinematic global positioning system which covers the Keweenaw Peninsula's Portage Canal, Lily Pond, and Torch Lake. These locations can best be described as urban-industrial areas having very moderate and highly seasonal marine traffic.

Great Lakes Research Center staff deploy a third generation L3 OceanServer Iver 3 autonomous underwater vehicle at the Marine Autonomy Research Site in Michigan's Upper Peninsula. Photo courtesy of Michigan Technological University

Coast Guard Chief Petty Officer Damian Meyer pilots an experimental vessel at the Marine Autonomy Research Site in Michigan's Upper Peninsula helping researchers collect maneuvering data. Photo courtesy of Michigan Technological University

The MARS area also includes significant Lake Superior shoreline and coastal waters along the peninsula's east and west coasts. The coasts exhibit features ranging from rocky shorelines with steep slopes reaching continental shelf depth within a few miles of shore to sand and sandstone shorelines that are rapidly shifting. Also worth noting is the extremely dynamic seasonality offered by this test environment. This portion of the Upper Peninsula experiences severe winters and arctic-like conditions, including gale force winds, persistent precipitation, heavy fog and snow, and highly variable ice conditions ranging from shore-fast ice to transient "sea ice."

At 31,700 square miles, Lake Superior has the largest surface area of any freshwater lake in the world and experiences ice coverage exceeding 90 percent during many winters. Its long-term average peak ice concentration (1973–2019) is 62.3 percent. The wave state climate is severe with waves approaching 30 feet observed periodically and waves exceeding 10–15 feet occurring relatively often during the spring and fall transition periods.

Testing at MARS over the past several years has largely focused on smaller research and survey vessels, typically less than 10 meters, as well as other standalone technologies. This category of vessels includes those with the greatest near-term commercial potential in the Great Lakes and U.S. coastal areas. Gaining experience with these types of vessels will enable stakeholders to test operation and safety on navigable waters in a structured manner but using an unstructured, real-world environment where subjects can interact with other vessels in a tractable capacity.

Per interim operating guidelines, the operation of such vessels is still subject to United States Coast Guard regulations. As such, all testing will be conducted under the supervision of a licensed mariner with support staff and standby vessels prepared to take action should intervention be necessary. Looking toward the future, the MARS testbed location is also well-suited to handle testing of much larger vessels, with existing facilities and new investments being made to further develop the waterway infrastructure.

Working With the Coast Guard

Michigan Tech's model of collaboration with industry and government has resulted in a strong working relationship with Coast Guard District 9 at all levels across the Great Lakes. At the local level, GLRC researchers have a long history of working with Station Portage, a small boat station located directly across the Keweenaw Waterway from Michigan Tech's campus. Station Portage has two 47-foot motor life boats and one 29-foot response boat small and provides the only heavy weather search and rescue coverage on Lake Superior. Many of the station's former and current officers have volunteered their time to support Michigan Tech with outreach, training, and science and research projects.

GLRC was fortunate to hire retired Station Portage Executive Petty Officer Jason Swain in 2020 to serve as a research vessel captain and marine logistics coordinator. His involvement in planning and executing missions within the MARS testbed has been invaluable.

At the regional level, GLRC has also found a strong ally in Duluth's Marine Safety Unit, which provided much guidance on setting up the MARS site, and coordinates many of its activities with Sector Sault Sainte Marie. This working relationship has been paramount to the success and safety of GLRC's work on the Great Lakes. In return, we hope to share our knowledge and insights, specifically those pertaining to autonomous and unmanned vessels, with the Coast Guard to help inform future waterway management, policies, and safety. As such, we were pleased to respond to the recent *Request for Information on Integration of Automated and Autonomous Commercial Vessels and Vessel Technologies Into the Maritime Transportation System* the Coast Guard issued August 2020.

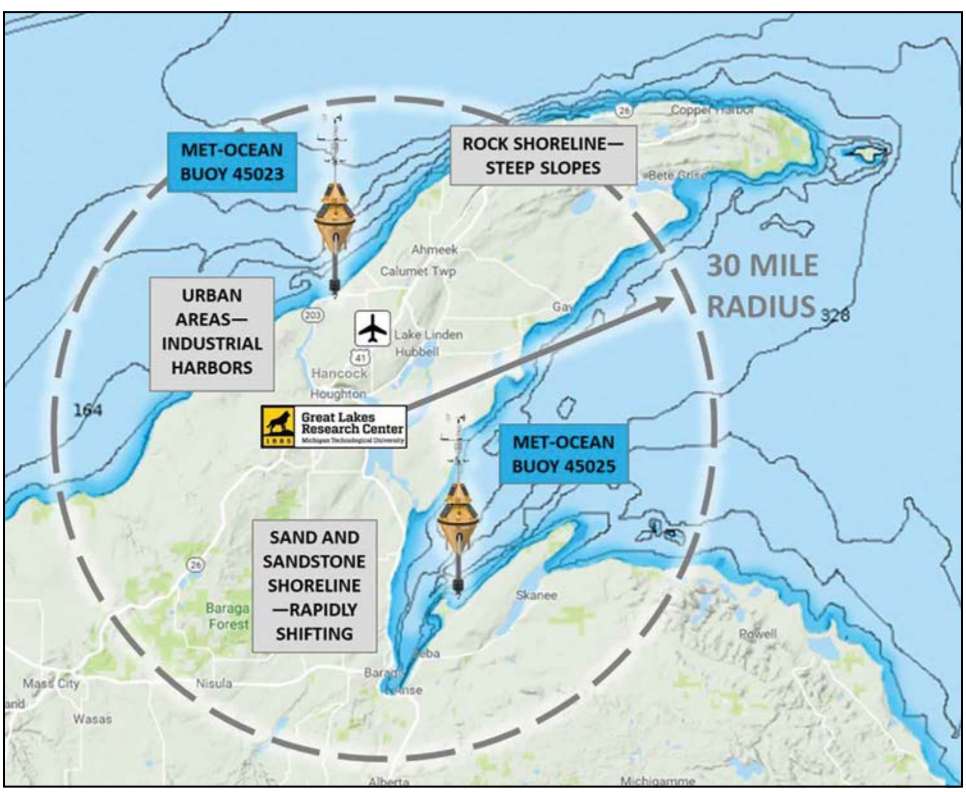
Michigan Tech will be participating in upcoming regional National Preparedness for Response events with the Coast Guard in summer 2022. There will be demonstrations of remotely operated, autonomous, and unmanned assets to aid in these events.

Ongoing Research

The goals for much of the research done at MARS are to develop new technologies, experiment with new applications for current technologies, demonstrate technology readiness, train developers and operators, and facilitate technology commercialization.

The first research project conducted in the testbed was an experiment designed to investigate one of the foremost limiting factors pertaining to autonomous surface vessel use by the United States Navy—the inability of ASV's to negotiate and survive large sea states and extreme weather conditions. The goal of this experiment was to capture vessel motion data and record an expert navigator's prescribed maneuvering strategies used to maximize vessel stability in rough seas. This data is helping to develop a next generation autonomous control system capable of making navigation decisions that replicate those used by an experienced navigator. Similarly, data was collected representing current autonomous maneuvering strategies for comparison.

Baseline runs were done implementing straight line—nonoptimized—trajectories about the course. This was immediately followed by an optimized wave dodging technique that is commonly employed by the Coast Guard



Map courtesy of Great Lakes Research Center

Engineering students deploy an autonomous surface vehicle built upon a stock Yamaha WaveRunner personal watercraft at the Marine Autonomy Research Site in Michigan's Upper Peninsula. Photo courtesy of Michigan Technological University

when negotiating challenging sea conditions in order to maximize crew and vessel survival. Preliminary observations based on the data collected from this experiment shed new light on Coast Guard vessel control strategies used to maximize vessel environmental survivability in high surf and extreme weather navigation scenarios.

Wave dodging optimized contact between the vessel hull and water to maintain control and reduce slam. This was accomplished by allowing the vessel to roll in order to minimize vessel pitch when encountering a significant wave front. The result of this strategy reduced accelerations in the heave and surge directions and also prevented loss of propulsion and loss of control. These findings have implications for future vessel design and next-generation autonomous control systems. Personnel from Coast Guard Station Portage were instrumental in supporting this test by providing subject matter expertise, as well as safety planning guidance.

During the 2021 field season, personnel from the GLRC constructed an autonomous surface vehicle, built on a stock Yamaha WaveRunner personal watercraft using off-the-shelf components. The autonomy components and mission planning software are products of the unmanned aerial vehicle domain. The researchers have been adapting this commercially available technology to the existing vessel controls in order to develop fully autonomous operation capabilities, including waypoint navigation, station keeping, and mothership tracking. Beginning in 2022, it will be employed to autonomously map the bottom of the Great Lakes and contribute to other scientific missions and workforce development.

This project is a "platform build," meaning it is intended to be configured and reconfigured to meet the needs of current and future research and training. One of its first configurations will include a portable multibeam sonar system allowing for high-resolution mapping and environmental assessment tasks. The vessel is easily transportable, has a cruising range of approximately 140 miles at 3 knots, and is capable of efficiently performing shallow water surveys in depths up to 200m.

A related project is currently underway that aims to create a waterway "digital twin" of the MARS testbed,

A remotely operated underwater vehicle is deployed through several feet of Lake Superior ice to evaluate future Arctic capability. Photo courtesy of Michigan Technological University or in other words a high-resolution bathymetric dataset collected by means of GPS and sonar from multiple vessels that operate within the testbed area. Multiple vessels will be equipped with a simple "black box" device that records GPS and sonar readings and data will be wirelessly transferred to a third party for rapid processing. An Israeli startup, DockTech, is a member of the SSC and provides maritime data insights to facilitate safer and faster shipping. The company is contributing its proprietary hardware and providing the data processing to facilitate this project, which will improve the safety of navigation and help increase commercial use

within the mapped areas. This digital twin model is a product that can be interpreted by autonomous vehicles in order to inform navigation decisions.

There were numerous other autonomous, unmanned vehicle deployments facilitated in the Great Lakes during the 2021 season by the GLRC team, including multiple Saildrone missions in collaboration with the United States Geological Survey office. These missions will assess how radiated noise from large vessels impacts fisheries assessment methods by comparing fish population assessments gathered by traditional survey vessels to those obtained from the solar- and wind-powered Saildrone platforms. GLRC and MARS provided logistical support for deployment of these vehicles in lakes Huron and Michigan during summer 2021. Similar types of vehicles, including a Liquid Robotics SV2 Wave Glider, were deployed in Lake Superior around the same time to conduct other types of scientific research.

During the winter months, GLRC researchers shift gears from testing vehicles in open water to testing vehicles and technologies above and below ice. Winter 2020 through spring 2021, saw testing of remotely operated vehicles to develop and prove out navigation and imaging capabilities for explorations under ice. Other recent winter experiments demonstrated target sensing and tracking using acoustic sensors with machine learning and artificial intelligence to improve tracking capabilities of vehicles like snowmobiles operating on frozen bodies of water.

Workforce Development

In addition to technology development and scientific research, Michigan Tech also brings strong workforce development to the Great Lakes. The GLRC develops undergraduate- and graduate-level scientists and engineers ready to tackle upcoming challenges with a growing emphasis on a cyber-ready workforce with skills in data science, machine learning, artificial intelligence, cybersecurity, and autonomous marine systems. These skills will position Michigan's future mobility workforce as the world's premiere mobility workforce. In partnership with Michigan Economic Development Corporation, the GLRC and SSC will host the inaugural Cyber Boat Challenge, a hackathon challenge for college students focusing on maritime cybersecurity, taking place May 23–25, 2022.

Development of new engineers and scientists in STEM fields is of critical long-term importance to the Navy, and Navy supported industries, in maintaining technological superiority. This superiority directly influences the capability and safety of the warfighter. Unfortunately, many STEM graduates are either unaware of naval-related careers or are unprepared for problems facing the Navy STEM workforce. An Office of Naval Research-supported program at Michigan Tech aims to send into the nation's future workforce a steady flow of highly motivated and trained civilian engineers and scientists capable of supporting naval related industries on day one. Focus areas include underwater acoustics, noise control and vibration, autonomy and control, unmanned vehicle design, and sensors and sensing platforms. Each of these fields are critical to the Science and Technology Strategic Plan of the Navy and the Navy's Force of the Future. With the growing need and interest in maritime career paths, Michigan Tech aims to continue to increase its offerings and programs in this area.

Thanks to the ever-expanding network in the SSC, other academic institutions and training facilities have begun collaborating to identify gaps in current curriculums and develop new programs that include new and emerging technologies. Michigan Tech has a close relationship with Northwestern Michigan College, home of the Great Lakes Maritime Academy and Great Lakes Water Studies Institute, which offers a bachelor of science degree in Marine Technology. These programs are highly complementary to the engineering and science programs offered by Michigan Tech and contribute to the state of Michigan's leading role in preparing the future workforce for the maritime industry.

Conclusion

At the unveiling and launch of the MARS and SSC, U.S. Rep. Jack Bergman (R-MI) said, "This center puts us on the cutting edge. And if you're not on the cutting edge, you're behind." That's really what these strategic investments of time and resources represent to the Great Lakes maritime sector. The work being done here is also of national importance, as shipping will undoubtedly look different in the future. Research and multisector collaboration are critical elements for a successful transition to the future.

About the author:

Mr. Travis White has more than 14 years of experience as a licensed master on the Great Lakes and holds a Bachelor of Science in mechanical engineering from Michigan Technological University. In his role as a research engineer at the Great Lakes Research Center, he oversees the Marine Autonomy Research Site and Smart Ships Coalition.

For more information

New members are welcome to join the Smart Ships Coalition. For more information go to www.smartshipscoalition.org/members.

Regulating MASS

Maritime Autonomous Surface Ships and the IMO

Addressing the regulatory challenge at the international level

by Mr. Lee Franklin
Electrical Engineer
Office of Design & Engineering Standards
U.S. Coast Guard

Over the past several years, advances in data collection, analysis, and communications have enabled advancements in remote capabilities and decision-making support. These technologies continue to develop and there are currently several projects around the world and within the United States that are establishing unmanned vessel operations. In response, the Coast Guard is working closely with interagency, domestic, and international partners to begin addressing how these technologies will safely integrate into the existing marine transportation system.

The United States has been a leader in the ongoing discussions on autonomy at the International Maritime Organization (IMO), where the Coast Guard heads U.S. delegations representing the United States' position on numerous regulatory issues within the international commercial maritime industry. Members of the Assistant Commandant for Prevention Policy's staff facilitate the development of United States' positions and discussions on autonomy at IMO's Maritime Safety Committee (MSC).

United States Participation on MASS at IMO

In June 2017, at the 98th session of the MSC, the United States co-sponsored a technical proposal highlighting the need for a regulatory scoping exercise on maritime autonomous surface ships (MASS). The goal of this exercise was to assess the degree to which the existing regulatory framework under its purview may be affected to address MASS operations. Following in-depth discussion of the proposal, the committee agreed to include the regulatory scoping exercise for MASS in its 2018–2019 biennial agenda with a target completion date of 2020.

Post-MSC 98, the United States worked with other IMO member states to develop a technical proposal outlining an approach to the regulatory scoping exercise. Recognizing the scope of work, and potential challenges in a 2020 completion, the United States began preparing its own proposal, which built upon the approaches being developed and included terms and descriptions for use in connection with the regulatory scoping exercise.

The group proposal and the U.S. proposal were submitted to the 99th session of the MSC in May 2018. After their consideration, along with other proposals, the committee began developing a framework for the exercise. This included preliminary definitions, as well as a methodology for conducting the exercise. After the session, the United States and other volunteering IMO member states formed a correspondence group to test the proposed methodology and identify areas for improvement ahead of finalizing the framework.

During the 98th session of the Marine Safety Committee, member states agreed to include a regulatory scoping exercise on maritime autonomous surface ships in its 2018–2019 agenda. The exercise was finalized during the 103rd session in May 2021. Photo courtesy of the International Maritime Organization

The need to highlight several areas for improvement raised by the correspondence group was recognized, and the United States provided a technical submission to the 100th session of the MSC that proposed approaches for process improvement. After consideration, the committee approved the final framework for the regulatory scoping exercise and invited interested IMO member states and international organizations to participate. The final methodology consisted of a two-step approach and a plan of work and procedures.

Royal Navy Minehunting Boat *Harrier* undergoes unmanned trial runs at Her Majesty's Naval Base Clyde, United Kingdom, in August 2020. The International Maritime Organization has been working with member states to ease regulatory challenges and pave the way for global autonomous shipping. Photo courtesy of LPhot Stevie Burke

Regulatory Scoping Exercise of MASS

First Step

During the first step in the exercise, IMO member states volunteered, either individually or in groups, to conduct an initial review of IMO conventions and mandatory codes under the purview of the MSC. These conventions included the Safety of Life at Sea; Standards for Training, Certification, and Watchkeeping (STCW); Maritime Search and Rescue; and Load Line. The mandatory codes established under each parent convention were reviewed to establish how they would be affected by MASS operations. These mandatory codes included the Ships Operating in Polar Waters and the Safety for Ships Using Gases or Other Low-flashpoint Fuels.

In order to facilitate the process of the regulatory exercise four degrees of autonomy were developed:

- Degree one: A ship with automated processes and decision support
- Degree two: A remotely controlled ship with seafarers on board
- Degree three: A remotely controlled ship without seafarers on board
- Degree four: A fully autonomous ship

The initial reviews were conducted to determine whether each regulation or rule, with respect to each of the four degrees of autonomy, in the conventions and mandatory codes:

- prevents MASS operations
- does not prevent MASS operations and requires no actions
- does not prevent MASS operations but may need amendment or clarification
- has no application to MASS operations

The United States volunteered to lead the initial review of STCW supported by other volunteering IMO member states. With issues surrounding autonomous navigation being a major concern, the United States also volunteered to support the initial review of the Regulations for Preventing Collisions at Sea. Correspondence groups were formed to facilitate each initial review.

Given the complexities and challenges surrounding MASS related issues, the United States' positions for each regulation or rule were developed in consultation with subject matter experts from the Coast Guard and interested interagency stakeholders. The Department of State, the U.S. Navy, and the National Oceanic and Atmospheric Administration, were among these stakeholders. The United States' and other IMO member states' positions were debated via correspondence groups until a consensus was reached. The initial reviews for the remaining conventions and mandatory codes under the MSC's purview were directed by various IMO member states.

Among the many challenges the initial review groups faced was ensuring that all reviewers approached the process with the same assumptions. With each IMO member state having its own geographical, political, and infrastructure interests to consider, it was difficult to ensure all views and concerns were addressed when establishing these assumptions. Ensuring reviewers avoided any presumptions of how advances in MASS-related technologies will or will not progress in the future was another challenge; for example, the presumption that a ship carrying passengers will never operate without a crew on board. Reviewers had to set aside any preconceived notions on the development and acceptance of MASS-related technologies in order to preserve the results of the regulatory scoping exercise.

After the initial reviews were completed, IMO member states and international organizations were invited to comment on each regulation or rule in the respective conventions and mandatory codes. Commenters were tasked with providing agreement or disagreement with the initial reviews and submit additional comments as needed. Given the reality of an aggressive timeline, the numerous regulations or rules requiring review, and the complexity of issues faced, preliminary U.S. positions were developed ahead of the comment periods for the remaining conventions and mandatory codes under review. These positions, too, were developed in consultation with subject matter experts from the Coast Guard and interested interagency partners.

Once the comment period concluded, the volunteer IMO member states that conducted the initial reviews considered all the comments received and modified the initial reviews as appropriate. A summary of results was developed for each review and submitted to the committee for consideration.

In September 2019, an intersessional working group for MASS was established, the results from the first step of the regulatory scoping exercise were considered, and the commencement of the second step was authorized.

Second Step

The IMO member states that volunteered to conduct the initial reviews during the first step also retained those roles for the initial review during the second step. Considering the results of the first step, the initial reviews for the second yielded recommendations for the most appropriate way of addressing MASS operations. As provided for by the respective documents, these recommendations included equivalencies for developing interpretations of, and/or amendments to, existing conventions and mandatory codes. Additionally, they were provided with respect to the four degrees of autonomy developed to facilitate the process of the regulatory scoping exercise and allowed for the potential development of new mandatory codes, guidelines, and a "none of the above" option.

After the initial reviews were completed, IMO member states and international organizations were again invited to provide agreement or disagreement with initial recommendations and additional comment as needed. At the conclusion of the comment period, all comments received were reviewed and the initial review was modified as appropriate. A summary of results and recommendations was developed for each review to be submitted to the committee for consideration at the 102nd session of the MSC in May 2020.

Concluding the Scoping Exercise

Due to the global COVID-19 pandemic, the 102nd session was held virtually in October 2020. With the recent shift to virtual meetings, the committee determined that, due to the importance of the issues surrounding MASS, the results of the scoping exercise were best addressed at the 103rd session of the MSC in May 2021 to allow for improvements in the facilitation of virtual meetings. With the postponement, the committee invited additional submissions on the results of the second step and other MASS-related topics, including MASS trials.

A report summarizing the results was drafted, and the exercise finalized at MSC 103 noting the preferred way forward being the development of a new goal-based MASS code. Recommendations for priorities for further work were provided, including the need for agreement on terminology and definitions, as well as addressing common gaps and themes identified during the regulatory scoping exercise. Among those common gaps and themes is the question of whether a remote operator should be designated as a seafarer.

Interim Guidelines for MASS Trials

In 2018, the committee recognized that interim guidelines for MASS trials were necessary to gain more experience with the technology and its unique operational issues. The information and practical experience gained during trials can be applied to the efforts to address MASS operations at IMO beyond the conclusion of the regulatory scoping exercise. After MSC 100, the United States and other IMO member states drafted proposed interim guidelines. The aim of the guidelines was to ensure trials of MASS-related systems and infrastructure are conducted safely, securely, and with due regard for the environment. The guidelines, which also encourage information sharing with the IMO and other stakeholders, were finalized at the 101st session of the MSC in June 2019.

Current safety regulations were developed with the underlying assumption that a human crew would be on board. As a result, the transition to remote and unmanned operations may have a tremendous impact on the effectiveness and relevance of regulations/standards around the world. With the long-term goal being the development of effective safety standards, the United States will continue to be a leader in the ongoing discussions at IMO to allow the safe integration of MASS in the existing marine transportation system.

About the author:

Lee Franklin has been a civilian employee with the U.S. Coast Guard for the last 12 years, and currently serves as an electrical staff engineer in the Coast Guard Headquarters Systems Engineering Division.

COLREGS and Autonomous Surface Vessels

by LT James Meyers
Electrical Staff Engineer, Marine Safety Center
U.S. Coast Guard

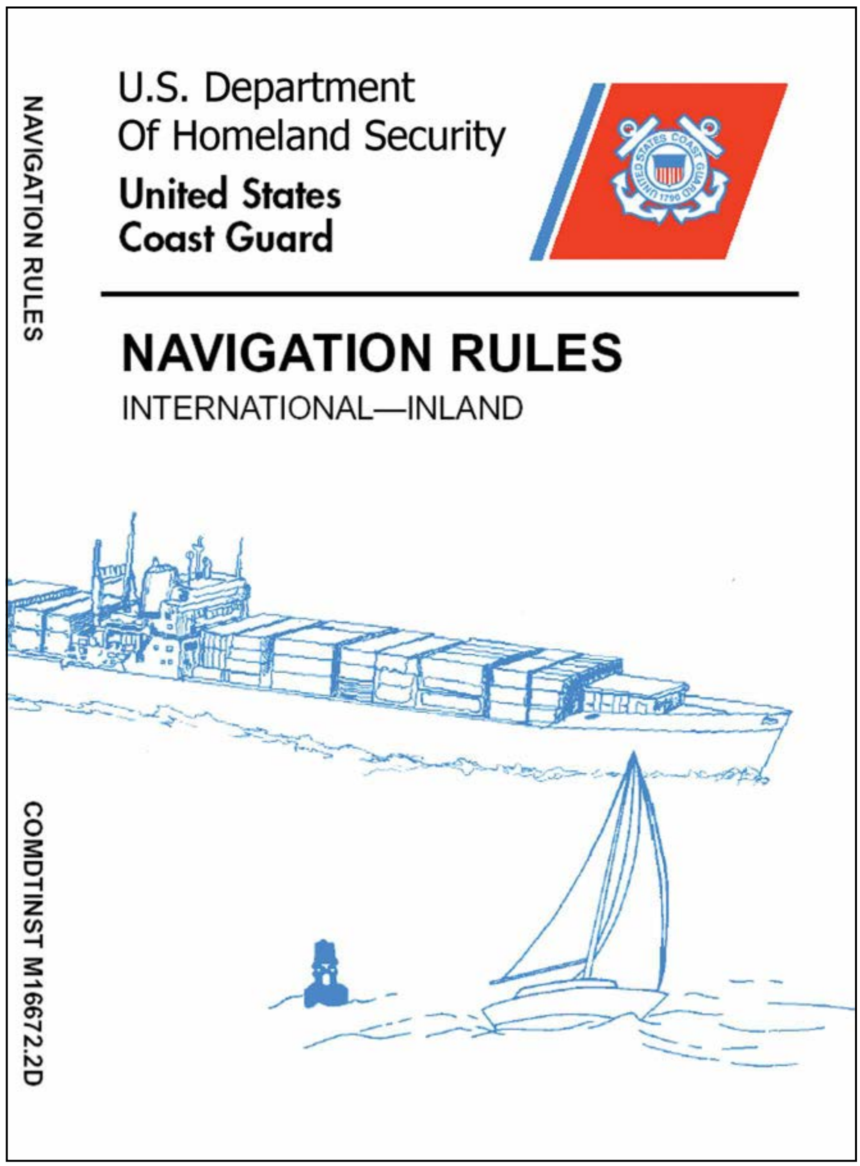
The emergence of new technology in autonomous navigation raises questions with regard to how the rules of the road (COLREGS)[1] are written and how autonomous surface vessels (ASV) will fit into the current framework. We can attempt to create ASVs that mimic human behavior according to COLREGS, but as the rules are currently written, and until further guidance is promulgated, it is not possible for an autonomous vessel to navigate waters in accordance with COLREGS. In order for ASVs to operate legally and safely, we must start by asking the right questions predicated on the following COLREGS rules:

- Rule 3—Definitions (How do we define autonomous vessels?)
- Rule 5—Look-out (How do vessels without people on board meet look-out requirements?)
- Rule 18—Responsibilities Between Vessels (What are the responsibilities between an ASV and other vessels? Who has right of way?)

Formalized in 1972, and made effective in 1977, COLREGS was developed by what is now known as the International Maritime Organization (IMO). These rules have mostly remained unaltered, with the exception of some minor amendments, and all U.S. flag vessels must adhere to them where applicable.

Why Do We Care About ASVs and COLREGS?

Indications are that this segment of the industry will continue growing in coming years and is here to stay. If the United States is going to maintain a globally prominent role in artificial intelligence (AI), specifically with respect to autonomous vessel operation, it is time to consider how ASVs fit into the overall framework of relevant regulatory instruments.



The body now known as the International Maritime Organization formalized the Convention on the International Regulations for Preventing Collisions at Sea in 1972. It went into effect in 1977. Coast Guard graphic

There are currently limited U.S. regulations and guidance addressing ASVs with the Navigation Safety Advisory Council (NAVSAC) Resolution 16-01[2] serving as some of the only domestic guidance available. This resolution, while serving to mitigate risk and a step in the right direction, offers little formal guidance and can be roughly summed up as "operate ASVs safely."

Similarly, IMO has issued interim guidelines for Maritime Autonomous Surface Ships (MASS) trials[3] while it assesses existing IMO instruments as part of its 2018–2023 Strategic Plan.[4] As part of this effort, they will be evaluating various requirements and guidelines for vessel design and construction loading and stability, tonnage measurement, seafarer training, search and rescue, safe container loading and, of course, the COLREGs.

From the August 2020 Request for Information

The transportation industry is currently undergoing a major transformation related to automated and autonomous technologies.… Highly automated and autonomous vessels have the potential to improve safety in the maritime system, where it is estimated that 75% of accidents are caused, at least in part, by human error. However, the introduction of automation and autonomous technology into commercial vessel operations brings a new set of challenges that need to be addressed, affecting design, operations, safety, security, training, and the workforce.

Though ASV is typically used to describe smaller vessels, while MASS is used to describe larger vessels, the acronyms can be used interchangeably.

Regardless of the area being evaluated, we must start by asking the right questions which will pave the way to ensuring ASVs are operated legally, safely, and with a low barrier to entry. With regards to ASVs, does each COLREGS rule prevent or allow the operation of ASVs? If the regulation doesn't allow the operation of ASVs, what needs to change? How will a change impact other COLREGS rules or regulations outside of COLREGS?

The scope of these questions can and should comprehensively address all aspects of automation and autonomous vessels, including cyber security, levels of automation, potential accident scenarios, and the nature of the vessel's operation. For our purposes here, we will focus on the navigational safety aspect, and primarily how ASVs may fit into the existing COLREGS framework. While there is room for debate on which rules are most impacted by ASVs, Rules 3, 5, and 18 are those most applicable to this discussion, with some ancillary discussion on other pertinent rules.

The Right Questions

Rule 3: Definitions

How do we define autonomous vessels? The definitions in Rule 3 of COLREGS have required little modification over the years, and the introduction of ASVs to the marine operating environment poses some important questions regarding these definitions. Rule 1, Applicability and Rule 2, Responsibility, directly tie into this discussion.

Rule 1 addresses the applicability of the rules. As individual countries attempt to create rules for ASV operation, and until COLREGS is updated to consider ASVs, any rules created for ASVs must not interfere with the rules or be confused for anything within the rules. This leaves a window for new rules or guidelines regarding ASV operation so long as they do not interfere with COLREGS. No change to Rule 1 is likely needed, assuming definitions for remotely operated vessels and fully autonomous vessels are added, considerations are made for responsibility of these vessels, and the lights, sound signals, and day shapes they should display.

Rule 2 outlines the responsibility of vessels, owners, masters, and crew. With autonomous vessels, there is a potential legal issue in determining who is responsible at any given time—the owner, master, or crew. If the vessel is operated remotely, who bears the blame if the vessel causes a collision or neglects to comply with the rules? How can an autonomous vessel or vessel operator/software designer ensure there is no "neglect of any precaution which may be required by the ordinary practice of seamen or by the special circumstance of the case," as specified in Rule 2. This rule when applied to ASVs could become a bit of a Turing Test. For example, will an ASV make decisions that would be indistinguishable from the decisions a human might make?

Additionally, Rule 2(b) leaves room for "emergency" procedures in programming to ensure that in a worst-case scenario, an ASV may take extreme actions to prevent collision, even if it violates another navigation safety rule. Regulating this and requiring consideration for decision boundaries and risk assessments becomes as complicated as attempting to model the mind of a vessel operator. Similar to Rule 1, this rule may not need to be changed to address ASVs, but application to autonomous

An Expeditionary Warfare Unmanned Surface Vessel autonomously navigates a predetermined course during the Advanced Naval Technology Exercise at Camp Lejeune, North Carolina, in 2019. Marine Corps photo by Lance Corporal Nicholas Guevara

vessel operations may become challenging from a legal standpoint. Future case law will likely be integral in shaping the interpretations of COLREGS as applied to ASVs. This leads us to the legal definitions outlined in Rule 3. How are they impacted by the introduction of ASVs?

The definition of **vessel** requires that water craft be used, or be capable of being used, for transportation. This likely still applies to ASVs if the broader interpretation of transportation is taken. ASVs may be designed to never transport human passengers, reducing some of the requirements for human safety on the vessel, but if we consider that they are transporting goods, equipment, or are performing surveys, the term "vessel" would likely still encompass ASVs. The broader implications of where we draw the line on what constitutes a vessel and what does not will need to be considered.

A **power-driven vessel** is defined as any vessel propelled by machinery. This applies to many ASVs, but not all, such as sailing drones. This definition is used frequently throughout COLREGS in determining actions to avoid collision, hierarchy, and responsibility between vessels. Should this definition stand and be applied to ASVs, we would require machinery propelled ASVs to operate in the same manner as manned, power-driven vessels, but give way to sail operated ASVs. This opens a host of issues, including how ASVs determine the type of other vessels. Something simple like determining the type of vessel is easily done by a look-out or with an automated identification system (AIS), but these systems are not universal, and in practicality it is a nearly impossible for ASVs to accurately and reliably determine vessel types in all scenarios. A better alternative would likely be to add an additional definition for ASVs, or possibly multiple definitions, to distinguish between levels of automation such as remotely operated vessels versus fully autonomous surface vessels. An argument could be made that remotely operated vehicles must maintain the same level of monitoring as fully manned vessels with due consideration for system security, redundancies, and operating profile.

Do sailing ASVs fall into the category of **sailing**

vessels? As discussed above, the mere fact that their propulsion is via sails does not holistically consider how the vessel is operated and would likely be better defined under either a remotely operated vessel or a fully autonomous surface vessel accordingly.

Since they don't have the same capacity to avoid collision or assess the navigational pictures as humans, it is possible that at least some ASVs best fall under the category of **a vessel restricted in its ability to maneuver (RAM)**. Illustrating a potential worst-case scenario; if ASVs are considered RAM, it lowers the barrier to entry so they no longer need sophisticated detection software as they would have the right of way over power-driven vessels in many situations. This would require any vessel not operating as an ASV to constantly determine if other vessels are ASVs and avoid them. This would be far from an ideal scenario, and more likely ASVs operating in restricted waters should bear the burden of avoiding collision with other vessels.

Defining **remotely operated vessel**—any vessel operated remotely without seafarers on board—and **fully autonomous vessel**—any vessel operating without human intervention—are possible starting points for determining how we define autonomous vessels.

Adding these terms to the definition could align with IMO's current scale detailing degrees of autonomy for Degree Three and Degree Four. For Degree One and Degree Two, having seafarers on board allows a vessel to remain defined under COLREGS in accordance with its vessel type and many of the COLREGS and ASV-related problems resolve, so no additional definitions should be required.

IMO's Degrees of Autonomy

- Degree One: a crewed vessel with automated processes and decision support
- Degree Two: a remotely controlled ship with crew
- Degree Three: a remotely controlled ship without seafarers on board
- Degree Four: a fully autonomous ship

The first stage of a Falcon 9 Full Thrust rocket lands on the autonomous spaceport drone ship *Of Course I Still Love You* in 2016. The Coast Guard is currently negotiating a design basis agreement that will use autonomous technology to facilitate rocket-recovery missions on board a Subchapter I vessel. Photo courtesy of SpaceX

A Saildrone Explorer unmanned surface vessel sails in the Gulf of Aqaba off of Jordan's coast, December 12, 2021, during exercise Digital Horizon. U.S. Naval Forces Central Command (NAVCENT) began operationally testing the USV as part of an initiative to integrate new unmanned systems and artificial intelligence into U.S. 5th Fleet operations. NAVCENT is one of the many commercial and military entities exploring the use of unmanned autonomous vessels in various environments. Army photo by Corporal Deandre Dawkins

Rule 5: Lookout

How do vessels without people on board meet look-out requirements? COLREGS explicitly says a lookout by "sight and hearing" is required, which must be a person for vessels currently operating under COLREGS. For ASVs not intending to have people on board, this poses a whole new set of questions. Does that mean that all ASVs must have a visual component such as a camera? Does a Light Detection and Ranging (LIDAR) sensor or radar replace that? Also, do all ASVs need to have a microphone or the capability to determine sound signals? Additionally, are any of these adequate to replace the human component of a look out. This rule will either need to be updated to include "look-out" requirements for ASVs or the potential inclusion of an exemption for ASVs.

The question of what determines "lookout" is unique for ASVs as even an inexperienced seafarer has decidedly higher-level classification capabilities than even the most sophisticated environmental mapping systems. For example, most humans will easily be able to distinguish a vessel or group of vessels as fishing, sailing, or power-driven vessels. Without that information directly provided to an ASV by something like AIS, it would require a highly reliable and sophisticated system to accurately determine vessel types in its vicinity.

The calculus by which an ASV makes lookout decisions versus a human may differ based on the scarcity of information available to many ASVs as compared to human operators. ASVs are often operating using radar or LIDAR as a main means of sensing and interpreting their environments, essentially making them operate in "restricted visibility" at all times.

Rule 6 covers "Safe Speed," and much like Rule 5, the question of what determines safe speed for ASVs is heavily influenced by the discrepancy between a computer-based decision system versus a human seafarer's capabilities. Rule 6 may not need to be changed, however the calculus by which an ASV determines safe speed versus a human-operated vessel may differ based on the scarcity of information many ASVs have compared to human operators.

Defining risk of collision, Rule 7 also ties directly into Rule 5. It will likely not be impacted by the introduction of ASVs to the rules, however its application to ASVs becomes interesting when considering how each ASV is, or isn't, performing contact detection and avoidance. Are they using radar, LIDAR, or some other system? Is the information high quality or is it "scanty?" Can the ASV make a determination if this information is good or bad? What is the ASV's action if sensors break, or weather deteriorates so as to prevent sensors from functioning properly? As with many of these other rules, additional caution and conservative assumptions in ASV decision-making models may mitigate some of the risk of collision.

Rule 11 covers vessels in sight, and similar to Rule 5 on lookouts, this prompts the question of what defines "sight" for ASVs? Does it imply that a vessel "would" be in sight if a look-out were on board? What about if the ASV is using a camera? What if it is not? What if we consider vessels that operate only using radar or equivalent navigation systems to always operate under a "restricted visibility" operating profile? We may need to redefine what "in-sight" means to more broadly include ASVs or make an ASV-specific provision.

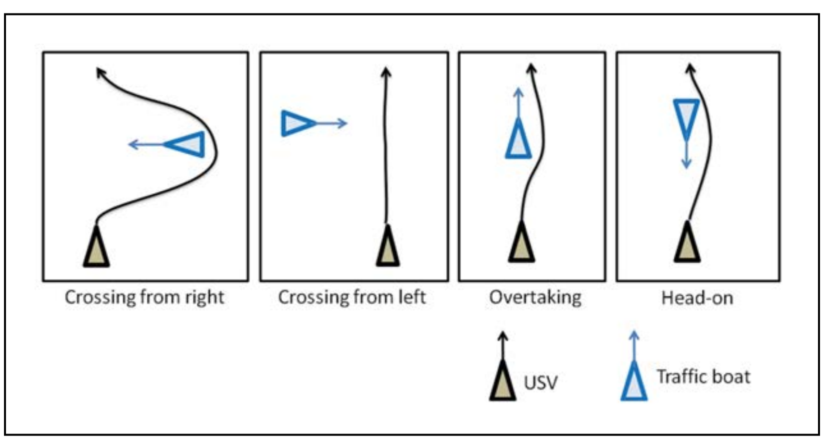
Rule 19 regarding restricted visibility is interesting as many ASVs operate using radar as the primary method to detect other vessels and assess whether risk of collision exists during restricted visibility, similar to a manned vessel. The main difference is that a manned vessel has—and must use—other tools available such as sound signals and lookouts that ASVs don't typically use. The question then is whether ASVs should ALWAYS operate as though restricted visibility applies. This could potentially be done by always flying appropriate day shapes, displaying appropriate lights, and sounding a unique sound signal to indicate a vessel is an ASV. This may be overkill though and not take into consideration that manned vessels will still interact with ASVs in "unrestricted visibility." What is considered restricted visibility for ASVs or remotely operated vehicles is likely one of the most difficult questions to address as sensing and visibility are fundamentally different between manned vessels, ASVs, and even remotely operated vessels.

Parts C and D, Lights and Shapes and Sound and Light Signals respectively, are another set of rules requiring consideration for the difference between human and computer sensing. If ASV and remotely operated vessel definitions are added to the regulations, it would make sense to include unique day shapes and lights to make them easily identified. Additionally, if we provide definitions for ASVs or remotely operated vessels, sound signals would be a useful tool for alerting mariners that a vessel is operating autonomously. In the event that ASVs become more commonplace in congested harbors, there are potential issues with excessive noise. Regardless of whether the vessel is an ASV or not, there must be a way for vessels to identify the status of other vessels. One way is to require ASVs to have lights, shapes, and sound signals that alert non-ASVs of their status. This still begs the question of how ASVs will determine the operating status of other vessels.

Rule 18: Responsibilities Between Vessels

What are the responsibilities between an ASV and other vessels? Who has the right of way? Depending on whether ASVs and remotely operated vehicles are provided their own definitions or exemptions will determine how they are incorporated into Rule 18. The main question is whether ASVs will have the right of way, or like the seaplanes and wing-in-ground craft, will have to keep well clear of all other vessels and avoid impeding their navigation. Conservatively this makes the most sense as it should be the responsibility of those operating ASVs to keep clear of other vessels, but there may be some complications and unique scenarios to consider. These complications arise in Rules 9, 10, and 13 regarding narrow channels, vessel traffic separation schemes, and overtaking, respectively. The main questions here are what defines an autonomous surface vessel and how must it interact with other vessels, namely where does it sit in the hierarchy?

Rule 8 discussing action to avoid collision, is another rule not likely impacted by the introduction of ASVs into COLREGS. However, from the design and regulation aspect of ASVs, it will be important to use overly conservative safety assumptions, possibly at the price of efficiency. ASVs, and robots in general, are well-suited for path optimization exceeding the capabilities of humans.



Obstacle avoidance maneuvers required for various Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) situations. NASA graphic

Eight unmanned high-speed maneuvering surface targets, upper right, lead the way as five unmanned autonomous vehicles escort a high-value asset during an Office of Naval Research-sponsored demonstration of autonomous swarmboat technology on the James River in Newport News, Virginia, in 2014. U.S. Navy photo

However, as has often been said, "Navigation is a non-contact sport." The highest priority must remain avoiding collisions by ASVs. If that means taking early and effective action and making alterations of course and speed large enough to be readily apparent to other vessels, ASV navigation decisions should prioritize these actions over path planning optimization.

Rule 10 regarding traffic separation schemes opens the door for discussions about ASVs operating in different conditions. An ASV operating on open ocean is very different from an ASV operating in congested waterways. With regard to vessel traffic separation, a provision to consider what responsibilities exist between ASVs and other vessels should likely be added.

Part E: Exemptions is one final rule to consider which would impact most, if not all, of the rules discussed here. Depending on how the rest of the rules are either modified or revised to address ASVs, there may still be some gray area or items that need special consideration and clarification. Section E would be the perfect opportunity to include any exemptions that ASVs might have.

Conclusion

As it currently stands, ASVs cannot, by definition, meet COLREGS. If the U.S. is going to safely integrate autonomous vessels into our existing maritime operating environment, it is time to consider how ASVs fit into the greater framework of COLREGS and other regulatory instruments. We can start by asking the right questions. How do we define autonomous vessels? How do vessels without people on board meet look-out requirements? What are the responsibilities between an ASV and other vessels? Asking, then answering, these questions is a step in the right direction.

About the Author:

LT James Meyers graduated from the Coast Guard Academy in 2015 with a bachelor's degree in electrical engineering and served as a deck watch officer on Coast Guard Cutter Elm. *At Northeastern University, he completed his thesis on COLREGS compliant ASVs and received a master's degree in electrical engineering. He currently serves in the electrical branch of the Marine Safety Center at Coast Guard Headquarters.*

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Captain of the Port Authority and the Technology Revolution

by CDR Laura Springer
Chief, Office of Waterways Policy and Activities
U.S. Coast Guard

LCDR Urdley Smith
Staff Officer, Office of Waterways Policy and Activities
U.S. Coast Guard

The United States is a maritime nation with heavy reliance on the maritime sector, which contributes $5.4 trillion dollars annually to our economy. Further, U.S. ports account for 90 percent of all import and export activity in this nation, linking farms to markets, and ensuring Americans have the goods they need for daily life and access to the services on which they rely.

The maritime sector also remains the most efficient and economical way to transport goods over long distances and is an integral component of the global supply chain. The use of deep ocean ports and inlands waterways keeps transportation and logistics costs down for consumers and reduces traffic on congested highways and railways.

The United States Coast Guard plays a vital role in protecting the nation's waterways and port complexes from threats ranging from oil pollution to terrorism. The nation relies on Coast Guard sector commanders to execute Coast Guard authorities to protect the marine transportation system (MTS). A sector commander's duties include captain of the port (COTP), officer in charge of marine inspection (OCMI), federal on-scene coordinator, and federal maritime security coordinator. Though not a regulatory role, the sector commander is also delegated the responsibility of search and rescue mission coordinator by the district commander. Furthermore, the sector commander is engaged with local industry stakeholders through harbor safety committees and area maritime security committees.

Captain of the Port Authority is perhaps the most encompassing duty assigned to a sector commander. Title 33 of the Code of Federal Regulations (CFR) part 6 and 33 CFR Part 160 outline the above responsibilities. On a daily basis, COTP authority can include anything from issuing a marine event permit for a triathlon, detaining a foreign flagged vessel, or reopening a port after a hurricane. This authority can be traced to the Espionage Act passed by Congress in June 1917. The act was passed with the objective of controlling the anchorage and navigation of ships in U.S. waters, preventing sabotage during wartime.

In 1950, the Magnuson Act made captain of the port a permanent role and Coast Guard authorities grew from safeguarding ships to the protection of harbors, ports, and waterfront facilities. The Coast Guard relies upon these authorities to promote safety and security on U.S. waterways.

Innovation

The Coast Guard has been addressing challenges related to MTS innovation since 1790. It has promoted safety and security during the transition from sail to steam and again during the transition from steam to diesel. America is currently in the throes of the next major technological transition. Big data and the Internet of Things have made the transition to automated shipboard operations possible. Self-driving ships are no longer science fiction.

The successful implementation of new technologies requires a shift in regulatory frameworks and operating paradigms. This is challenging work. In the early stages

USCG Waterways Activities

- COTP Orders
- Safety & Security Zones
- Broadcast Notice to Mariners
- Marine Event Permits
- Large Scale Marine Events
- Marine Events of National Significance
- USACE Permit Reviews
- USACE Project Coordination
- Outreach
- ATON Verifications
- Deadship Tows
- Lightering Ops
- Anchorage Management
- MTS Disruption & MTSRU
- Obstructions to Navigation
- Hurricane Preparation
- Ice Operations Management
- Bridges
- WAMS
- Vessel Traffic Service (VTS)
- Other LAAs

of technological transformations, regulations often cannot keep pace with innovation. In the absence of regulations, communication and risk management are the primary tools available to address the risks associated with the implementation of innovation.

Autonomous Vessels

Data and technology have changed maritime operations and unmanned vessels are now a reality. Autonomous ferries currently operate in Northern Europe and there are a multitude of projects operating throughout the United States. Innovation is an opportunity to increase the public's knowledge of the marine transportation system and expand access to our nation's waterways.

In spring 2021, the autonomous vessel *Mayflower 400* attempted to sail from England to Massachusetts without human operators on board. *Mayflower 400*'s journey across the Atlantic was postponed until the spring of 2022 due to mechanical issues that necessitated a return to Plymouth, England. This was compounded by supply chain delays for replacement parts and the Atlantic hurricane season. The *Mayflower 400*, which can be operated remotely, relied on artificial intelligence and machine learning to cross the Atlantic. This will be the first of many vessels that challenge our traditional models for evaluating risk to the marine transportation system.

Autonomous technologies pose new risks to the MTS, as well as command and control concerns for a COTP. Through its existing authorities, the Coast Guard has the ability to ensure that commercial vessels of novel design can demonstrate a level of safety equivalent to existing standards and regulations. New platforms and technologies remain subject to existing COTP and OCMI authorities and approvals.

Coast Guard Sector Hampton Roads Commander CAPT Rick Wester addresses media after closing the Port of Hampton Roads in response to an August 2017 tropical storm. Coast Guard Auxiliary photo by Trey Clifton

An unmanned rigid-hull inflatable boat operates autonomously during an Office of Naval Research-sponsored demonstration of swarmboat technology at Joint Expeditionary Base Little Creek-Fort Story, Virginia, in September 2016. Navy photo by John F. Williams

Regulations

A long-term regulatory solution for autonomous vessels has yet to be developed. Regulators are working to address this gap internationally, and the International Maritime Organization meets regularly to discuss the regulatory framework surrounding this technology and implement recommendations. Meanwhile, the Coast Guard works diligently with international partners to ensure new risks, such as the changing human role, trust and system reliance, training and qualification, and cybersecurity, posed by these technologies are managed, while existing standards do not hamper innovation. The Convention on the International Regulations for Preventing Collisions at Sea, 1972, has not yet been modified to address autonomous or automated ships. In the absence of these regulations, the Coast Guard coordinates with project sponsors operating in this space to evaluate these projects on a case-by-case basis.

Captain of the Port Role

Captains of the Port and waterways managers have dual objectives when considering maritime stakeholders' use of American waterways. Foremost, they must ensure the safety and security of those using our waterways. Simultaneously, because American innovation and economic advancement are matters of national security and core objectives for other federal agencies, COTPs must balance the use of innovative technology with mitigations that can reduce the associated risks to the public.

As these technologies become mainstream, autonomous vessel operators should engage districts/COTPs very early in the project development process. Operators should be prepared to provide information about how vessels will achieve levels of safety equivalent to existing standards; and detailed project information, such as areas of operation and detailed information on vessel operating systems.

Currently, COTPs conduct navigation safety risk assessments for each automated project. They will often consider operator-provided escort vessel requirements, broadcast notices to mariners, marine safety information bulletins, remote vessel operation standards, limited access areas, and operator-provided vessel operation plans during autonomous vessel operations. Additional low-tech solutions to reduce risk to traditional waterways users include hulls being marked with the word "UNMANNED" and the display of flashing yellow lights as prescribed in Rule 23 of the Inland Navigation Rules. These measures ensure operators are aware of projects and mitigate the risks to the public associated with them. They also ensure equitable access to the nation's waterways while providing the public with information related to navigation safety.

Preparing the workforce

The Coast Guard's prevention staff is responsible for executing the responsibilities related to Coast Guard authorities in the MTS. At the operational level this workload is executed by waterways management staff. This cadre of professionals is charged with facilitating safe and lawful trade and travel on secure waterways. This is accomplished through the mitigation of risk to critical maritime infrastructure, building resiliency in the MTS, and enhancing unity of effort. This work also centers on aids to navigation, mariner information systems, and stakeholder engagement in forums such as harbor safety committees.

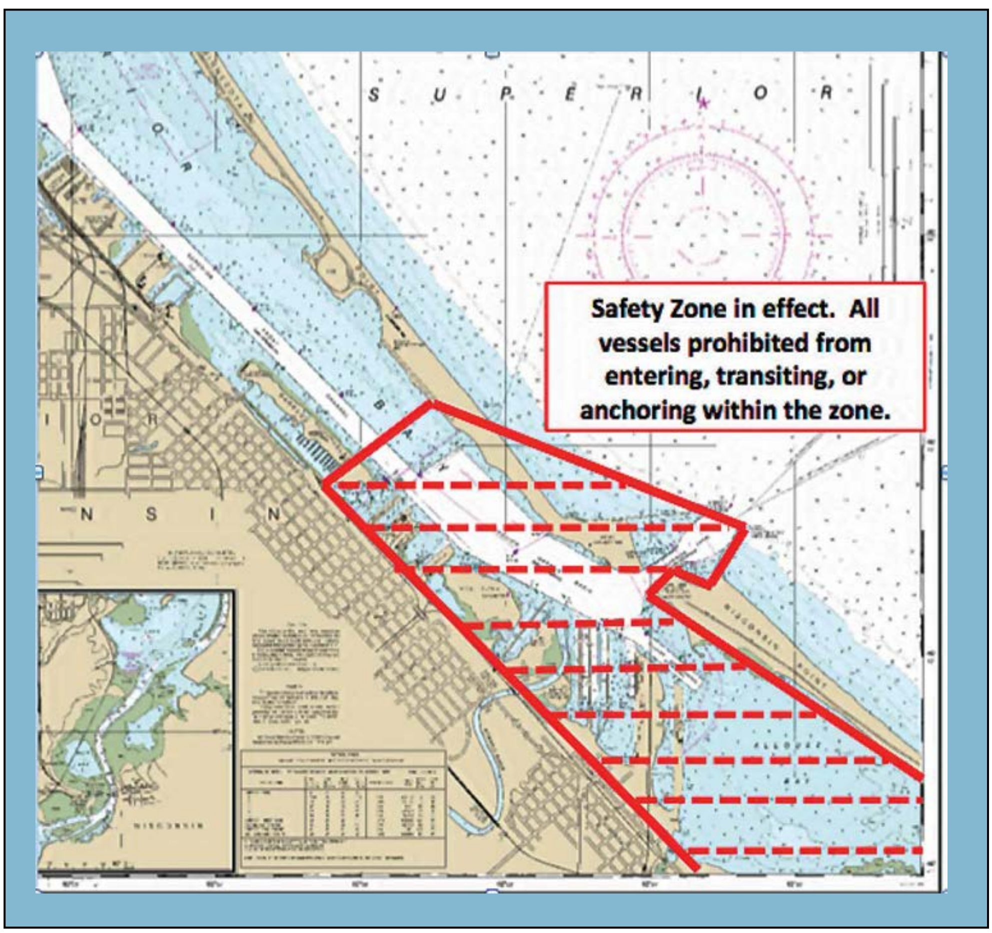
In order to address the challenges associated with MTS management, the Prevention Readiness Initiative (PRI) was established in early 2021. This work focuses on the presentation of a concise and cogent narrative that illustrates the challenges the prevention program faces and provides lines of effort to improve readiness and mission focus.

This initiative consists of four elements. The first element focuses on developing the workforce of the future by restoring the workforce. This includes optimizing skills required for billets, modernizing training, and retaining talent. The program must ensure its personnel have the necessary knowledge, skill, and actionable information to do their job. Further, it must develop a sustainable process to build and retain an experienced cadre of technically savvy professionals who can achieve mission excellence and meet public expectations.

The second line of effort is related to risk management strategies to address challenges associated with compliance, cyber securities, and innovation within the MTS. Increased waterway congestion, advanced technologies, and "just-in-time" delivery expectations for goods and services create increased risks and challenges to current workforce capabilities. Effective operational readiness and mission execution is contingent upon proper risk-based decision making ability and the flexibility to shift resources as needed to mitigate the largest vulnerabilities.

The third element is related to knowledge management and seeks to enhance governance and strengthen program accountability while also leveraging data and knowledge management technology. Effective governance and accountability improves quality control and consistency, both in training and mission execution, and drives excellence. When all employees have access to the available program reference and resources, it facilitates a smarter workforce capable of making timely, informed decisions for efficient mission execution.

The final line of effort is related to strengthening



The Coast Guard Captain of the Port established a safety zone in the Port of Duluth-Superior, Minnesota, in April 2018 in response to the Husky Refinery explosion. The safety zone protected personnel and vessels from possible air quality hazards. Coast Guard graphic

The MS *Prinsendam* sinks in the Gulf of Alaska after an engine room fire broke out in October 1980. The Coast Guard leverages its authorities to respond to all types of maritime hazards and incidents. Coast Guard photo

partnerships. This area of the PRI focuses on the modernization of customer service exchanges, strengthening relationships in the MTS, increasing unity of effort, and enhancing third party oversight. Using these partnerships across federal, state, local, and tribal governments is vital to mission success. Furthermore, engagement with port partners, other government agencies, foreign governments, and international organizations is crucial to safe and secure maritime trade.

Conclusion

America relies on our nation's waterways and the marine transportation system, a key component of our nation's economy, to remain the most cost effective, environmentally friendly, and efficient method of transporting cargo. It is imperative that the Coast Guard work to ensure equitable access to all of our waterways while adhering to existing international and national regulations. In order to remain competitive, innovative technologies must be tested and implemented when possible.

The lines of effort illustrated in the PRI lay the foundation for the Coast Guard to address all modern and future challenges in keeping with the Commandant's mantra of a ready, relevant, and responsive Coast Guard. Committed to working with stakeholders to address the challenges associated with the implementation of novel technology in the MTS, the Coast Guard remains "*Semper Paratus*" to address safety and security concerns related to implementing autonomous vessel technology on our nation's waterways.

About the authors:

CDR Laura Springer is a prevention officer and licensed mariner. She has served in the U.S. Coast Guard for 17 years and completed operational assignments in waterways management, inspections, and investigations. She currently serves as the chief of Waterways Policy and Activities at Coast Guard Headquarters.

LCDR Urdley Smith is a prevention officer with 12 years of service as a deck watch officer and marine inspector. A 2009 graduate of the United States Coast Guard Academy, he holds a BS in marine and environmental sciences, and in 2020 earned an MS in international transportation management from SUNY Maritime. He currently serves in the Office of Waterways Policy and Activities at Coast Guard Headquarters.

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Future Direction

Pursuing Small Unmanned Aerial System Cybersecurity

Employing a reference architecture for SUAS cybersecurity assessment

by LT Melissa Barrett
Technical Engineer
Marine Safety Center
U.S. Coast Guard

Autonomous seagoing vessels, both operated and regulated by the U.S. Coast Guard, present cybersecurity concerns. For the Coast Guard, one challenge is mastering small unmanned aerial systems (SUASs) and autonomous seagoing vessel technology for its own use, as well as maintaining preparedness for defending against adversarial use.

The following article presents a potential solution to mitigate cybersecurity risks in SUASs by employing a reference architecture (RA). An RA, herein referred to as an architecture, is used to design digital models of SUASs, and then apply an embedded cybersecurity assessment to evaluate the model prior to a physical build. While such a solution may also be applied to the Coast Guard's autonomous seagoing vessels, this article will discuss the architecture designed for SUASs.

The recent proliferation of SUASs in the defense and commercial sectors has been accompanied by growing cybersecurity concerns due to the sensitive data commonly obtained by or maintained within these systems.[1] The offshore location of many hardware and software production facilities introduces a corresponding vulnerability in our critical missions. A significant proportion of SUASs and their commercial-off-the-shelf (COTS) componentry are built and tested overseas creating a potential for maliciously embedded cyber vulnerabilities that an adversary may exploit at inopportune times and circumstances.[2]

Although well understood by adversaries, many SUAS users are limited in their understanding of cyber vulnerabilities, specifically where they arise within the SUAS' physical architecture and operational environment. Current research is bringing to light the rapid growth of common SUAS exploits and vulnerabilities including GPS spoofing, denial of service (DoS), sniffing, tampering, repudiation, and escalation of privilege attacks.[3,4] These attacks pose risks such as data theft or hijacking of SUASs like the 2011 incident where an RQ-170 Sentinel Unmanned Aerial Vehicle (UAV) was electronically hijacked and

Common SUAS Security Exploits and Vulnerabilities

A **GPS spoofing** attack will cause the vehicle's autopilot to believe it is in an alternate location from where it physically resides. If an intruder is able to enter in the local network of the UAV system, he/she is also able to impersonate the SUAS' ground control station and take control of it, leading to an undesirable maneuver or even a dangerous crash against a building or a person.

A **denial-of-service** attack will cause the operator to lose control of the SUAS because their commands cannot get from the control station to the vehicle, leaving it unresponsive.

A **sniffing** attack occurs when the transmitted data is intercepted by a packet sniffer if not encrypted.

Tampering corrupts the integrity of signals into and out of the UAV.

Non-repudiation is where the sender is provided with proof of delivery and the recipient is provided with proof of the sender's identity so that neither can later deny having processed the data. Therefore, a repudiation attack is any allowed denial by either party.

Finally, an **escalation of privilege** attack allows an adversary to gain control of the vehicle by convincing the device that they are the valid ground control station via a valid signal.

As armed drones, like this U.S. Air Force MQ-9 Reaper armed with an AIM-9X Block 2 missile, are poised to take their place in the nation's defense, USAS cybersecurity takes on even greater importance. The potential consequences of an armed drone being hijacked could be devastating. Air Force photo by Senior Airman Haley Stevens

subsequently captured deep inside Iranian territory using GPS spoofing attacks.[5]

SUASs are routinely outfitted with COTS componentry for low cost and ease-of-build. But these components, or those developed and distributed in open-source communities and available world-wide through internet sales and direct download of software/firmware packages, represent the major components of both the air and ground segments. In 2018, the Defense Department (DoD) issued a ban on the purchase and use of COTS drones from China or other potential adversaries, citing cybersecurity vulnerabilities.[6] To purchase and use UAS with COTS componentry, the DoD is now required to request approval or exemption to the ban, regardless of where, or for what purpose, the system is to be used. The Coast Guard aligns itself with its DoD counterparts regarding guidance on COTS SUASs, including the order to cease all use of the prolific, industry-standard Da-Jiang Innovations (DJI) SUAS products in 2017, because DJI was found to have significant cybersecurity concerns.[7]

In part of an effort to allow for cybersecurity assessment of newly developed systems, the research team at the Air Force Institute of Technology (AFIT) developed the SUAS RA with an embedded cyber-vulnerability assessment function. This architecture can also assist users with analyzing alternative and cyber-secure COTS components.

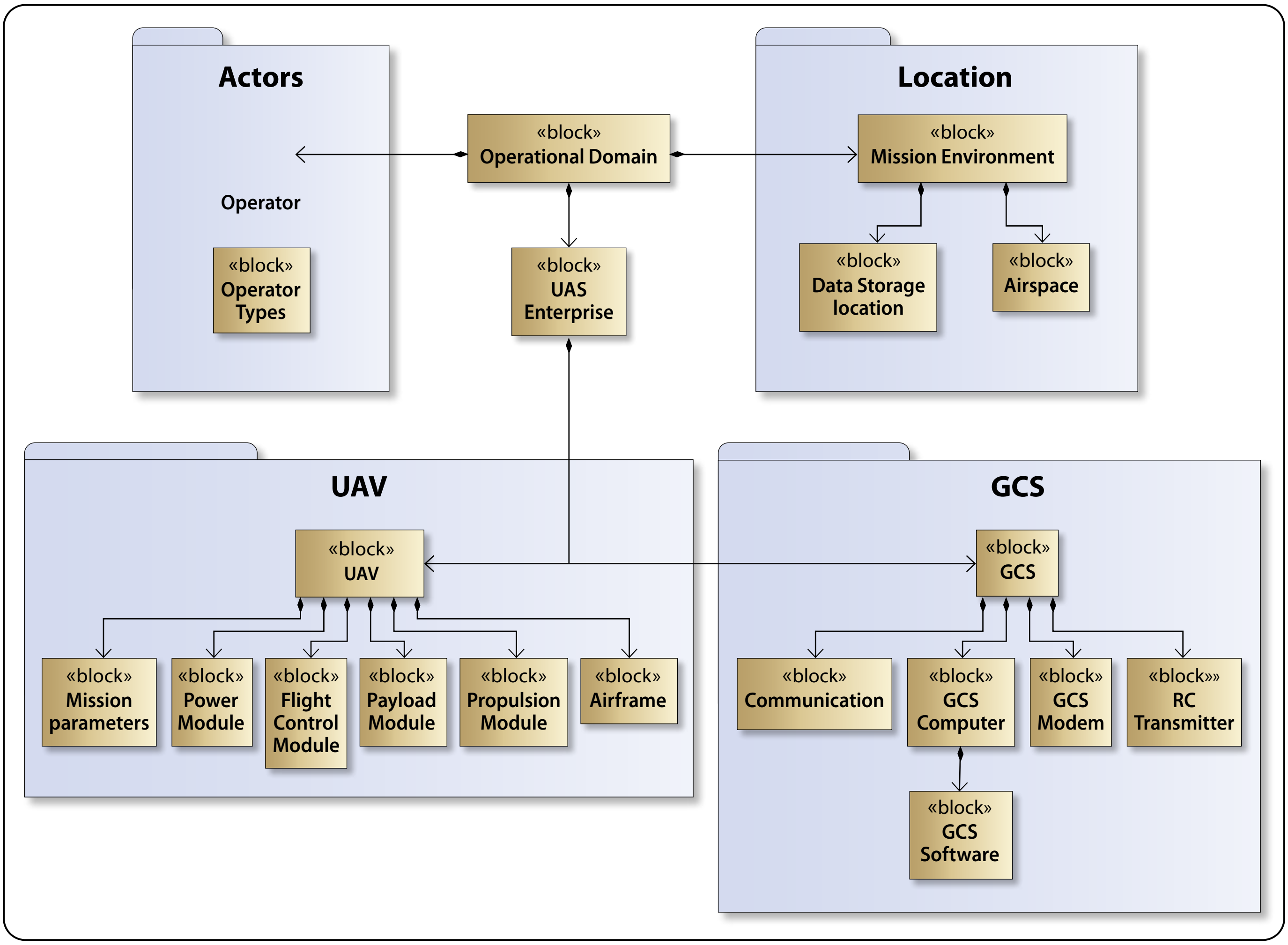
An architecture can be thought of as a template producing a shared understanding across multiple disciplines—engineers, managers, architects, etc.[8] It is "an authoritative source of information about a specific subject area that guides and constrains the instantiations of multiple architectures and solutions."[9] It is a type of knowledge repository based on concepts proven in practice.

AFIT's architecture for SAUS allows interdisciplinary stakeholders to understand cyber vulnerabilities using embedded descriptions of common cyberattacks. It can also allow users to design cyber-secure systems from a template, which includes a library of predefined digital components and example SUAS architectures or digital models. Providing additional value to the user are the cybersecurity-vulnerability assessment tool and model summary document generator. The generated summary contains information necessary for a request to purchase and operate cyber-secure SUASs with COTS components within the Coast Guard and following DoD guidance.[10]

The Reference Architecture

An architecture provides guidance, establishes common vocabularies, presents reusable digital elements, and provides a means for verification and validation of systems-developed architecture.[11] It uses model-based systems engineering (MBSE) to define a candidate system and evaluate it for requirements satisfaction prior to entering the physical system's build phase. The objective of MBSE is to develop a model of a system that carries the project from start to decommission. It is an integration

Figure 1. SUAS Structure Template



Coast Guard graphic

of discipline-specific engineering models and simulations.[12] By ensuring all requirements are satisfied within a digital model, one can build and maintain a physical architecture at a lower cost, as proposed modifications of the physical system may be verified prior to commitment and implementation.[13]

An architecture gets interdisciplinary users on the same page via a common modelling language. It provides consistency of implementation and encourages adherence to common standards by providing example models and templates to allow users to focus on the details of their system, rather than on design portrayal. Finally, it supports validation of models through analysis tools such as the cyber-vulnerability assessment tool. With these elements, an architecture may be easily understood by and deployed across multiple disciplines.[14]

AFIT's Small Unmanned Aerial Systems Reference Architecture

AFIT's architecture captures extensive knowledge of componentry and typical configurations, and is built using the Systems Modeling Language in the Cameo Systems Modeler software tool.[15] While intricate details of the architecture go beyond the scope of this article, the model structure is displayed and explained.

Figure 1 displays the high-level domain model view of an SUAS structure. In addition to the top-level folders, lower-level folders include the UAV and ground control station model views which show their subcomponents, such as the airframe. Within this top-level diagram, embedded lower-level diagrams exist to capture the components within those depicted here in their hierarchical order. This example domain model depiction of a SUAS is the starting block for creating the digital SUAS structure. Not shown are additional embedded diagrams depicting the layout of internal connections, as well as internal-to-external connections.

A feature of AFIT's SUAS architecture is a component library, which houses pre-built blocks for common components that a user can select from to design the architecture. Although not shown here, each component contains predefined connection points or ports, as well as value properties, which a user can fill in or select from a drop-down list. An example of a value property is the country of origin which allows a designer to fill in the country where their component was built and later assess the component for cybersecurity concerns based on the vendor's or producer's location.

With the understanding of an architecture, the following section explains SUAS common cyber vulnerabilities. An architecture can explain these concerns to stakeholders with various levels of cybersecurity expertise and assess the models for risks in the cyber domain.

SUAS Cyber Vulnerabilities

SUASs are particularly susceptible to hacking or interception due to the common lack of attribution and security measures protecting them.[16] These cyber risks may contribute to the consequent likelihood of unauthorized and dangerous use by cyber attackers. As SUASs grow in popularity, and the cost to obtain and operate them drops, they are being implemented in more commercial and defense settings.

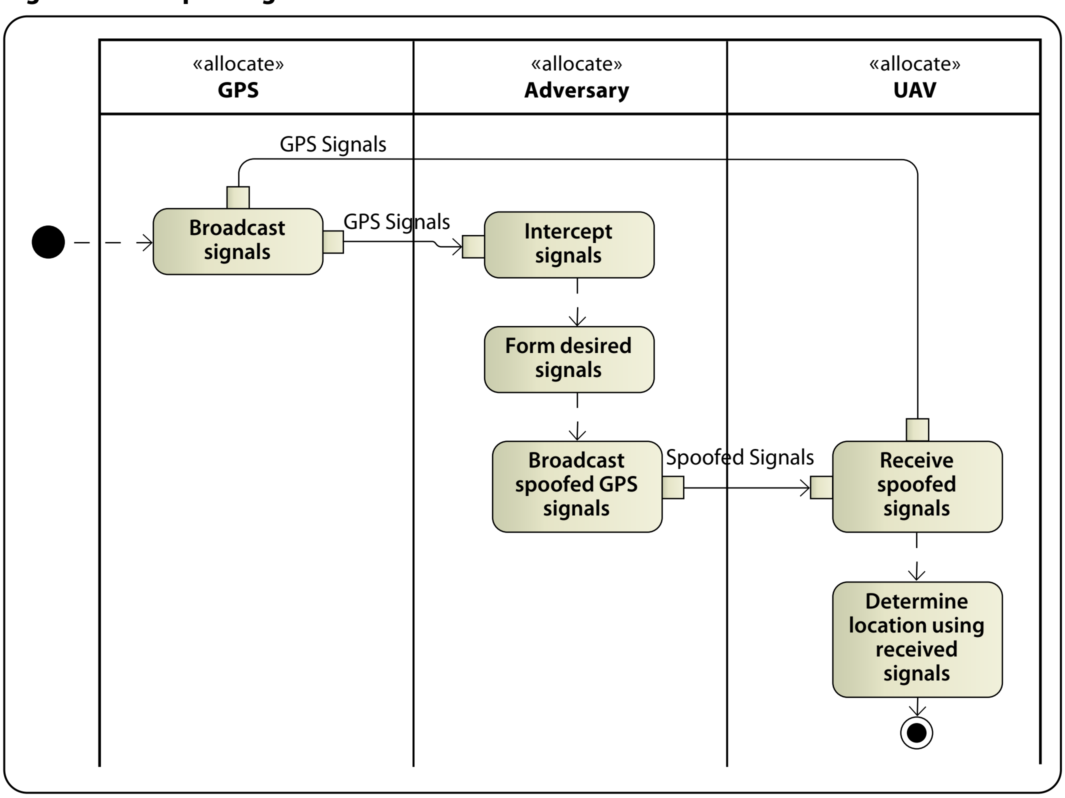
To conduct certain jobs as well as, or better than, a human and to take their place in dangerous settings, SUASs have become autonomous and highly sensor-driven, dependent on functional sensors and receiving correct data from operators and the surrounding environment.[17] However, their small size and low cost limit the ability to incorporate many cybersecurity measures, often resulting in vulnerabilities where input signals to the system may be exploited to cause a malfunction.[18] Malicious actors are exploiting cyber vulnerabilities to infiltrate SUAS local system networks and then using them to facilitate illegal activities, such as stealing confidential data or causing dangerous crashes that harm infrastructure and people.[19]

Due to their lack of intrusion detection or security mechanisms, SUASs can be far more easily hijacked or disrupted. In addition to amateur SUAS data links vulnerable to jamming and other cyberattacks, those data links also tend to broadcast continuous electromagnetic signatures that enable their detection, location, and classification, as well as the location of the operators.[20] Although not of great concern to amateur SUAS users, military personnel are likely opposed to detection.

Common vulnerabilities arise from COTS hardware and software components and the susceptibility of embedded malware within them. They are found at the communication links, consisting of protocol flaws, susceptibility to jamming, and leakage of information. Also common are navigation vulnerabilities which are based on the probability of false signals being accepted and the combination of sensors relied upon to reduce risk. For example, sensors such as the inertial navigation system (INS) are much more difficult to spoof than GPS and may reduce the cyber risk to the system. However, an SUAS's INS quickly loses accuracy over time, and is not typically set up to monitor external aids provided by GPS. It therefore would not alert the operator of potential cyberattacks caused by the vehicle flying slightly off course.[21]

Specific risk lies in cyberattacks including DoS, GPS jamming/spoofing, and control hijacking from an escalation of privilege attack. A DoS attack will cause the operator

Figure 2. GPS Spoofing Mechanics



Coast Guard graphic

to lose control of the SUAS because their commands cannot get from the control station to the vehicle, leaving it unresponsive. A GPS spoofing attack will cause the vehicle's autopilot to believe it is in an alternate location from where it physically resides. If an intruder is able to enter in the local network of the SUAS, they are also able to impersonate the ground control station and take control of it leading to an undesirable maneuver or dangerous crash.[22] Finally, an escalation of privilege attacks allows an adversary to gain control of the vehicle. Operators must be aware of the threat to their SUASs and understand the risks posed by the system and mission when considering the decision to implement more expensive or heavier mitigation features on the aircraft.

How a Spoofing Attack Occurs

Embedded activity diagrams within the architecture explain the basics of common cyberattacks and the components impacted or used in the attack. By intercepting GPS signals and sending false signals in their place, an adversary can cause SUASs to falsely identify their current location and be led to an unintended location or forced to crash. In Figure 2, the target symbol indicates the end of the activity, and the columns dictate the actor performing the actions listed within that lane. Arrows signify an object or signal passing between each action.

For example, GPS signals are passed between the GPS and the external adversary. Once the adversary modifies the original signals, the then-spoofed signals are passed from the adversary to the UAV. An extreme situation of hijacking may result from a spoofing attack where, instead of commanding alternative waypoints or a landing maneuver, the intruder marks an objective where the SUAS crashes.[23]

While the diagram shows the attack carried out at the major component level, a lower-level depiction, not shown here, portrays how the attack involves individual components of the system. An example of a lower-level component for GPS spoofing would show the GPS antenna/receiver as the entry point for the malicious signal, and its connection to the UAV autopilot, responsible for generating navigation commands.

SUAS cyberattacks are common and potentially devastating to personnel or infrastructure.[24] To enable stakeholders' understanding of these risks and produce a cyber-secure architectural model, the architecture assists in providing a minimal education of these threats and associated terminology to employ the cyber-vulnerability assessment and model summary documentation tools discussed below.

The SUAS Cyber-Vulnerability Assessment

AFIT's SUAS architecture cyber-vulnerability analysis tool is referred to as Pettit's Cyber-Security Risk Analysis (PCSRA), and was built based on the Common Vulnerability Scoring System, developed, and maintained by software developer FiRST, for calculating SUAS cybersecurity risk.[25] PCSRA consists of 14 sub-metrics capturing the principal technical characteristics of software, hardware, and firmware vulnerabilities relevant to the system under evaluation.

Figure 3 depicts the user interface to conduct the cyber-vulnerability assessment. It lists all sub-metrics in a single block within the domain model diagram shown in Figure 1. This interface allows the user to select applicable levels for each defined sub-metric based upon their system. The user can access and select from a drop-down list of levels for each to calculate a final PCSRA score. For example, a user has selected the level of the first listed sub-metric, confidentiality impact, as high. The user believes there will be no loss of confidentiality within the impacted UAV or in its communications due to proper security being in place.[26] The levels correspond to numeric values for final score calculation.

A final score falls between 0–10 with 0 representing no cybersecurity risk and 10 representing critical risk.[27] Seen from the bottom of Figure 3, given the subjective inputs to each of the 14 sub-metric entities, this particular SUAS earned a PCSRA score of 1.7, representative of a system with low cybersecurity risk.

Figure 4 shows an example of a defined sub-metric,

Figure 3. Cyber-Vulnerability Assessment Tool

«block»
«physical»
UAS Enterprise

values
CI: Confidentiality Impact = High
AV: Attack Vector = None
DM: Device Modification = Low
PR: Privileges Required = High
UI: User Interaction = Required
II: Integrity Impact = Low
AI: Availability Impact = Low
M: Market = Medium
VS: Vendor Support = High
L: Lifespan= Low
CR: Confidentiality Requirement = Low
IR: Integrity Requirement = Low
S: Scope = Unchanged
AR: Availability Requirement = Low
PCSRA Score = 1.7
Cybersecurity Risk Assessment: High/Med/Low = Low

Coast Guard graphic

attack vector, as it would be shown to the user. This sub-metric represents the connection of the device to potential attackers.[28] Similar to IT networked devices, the location of an attacker directly correlates to the risk of the device being attacked due to size of audience and increased automation of scanning and exploiting.

Another example of a sub-metric is confidentiality requirement, which captures the growing concern regarding brand vulnerabilities created by employing COTS components in SUASs. Confidentiality is defined as "limiting information access and disclosure to only authorized users, as well as preventing access by or disclosure to unauthorized users."[29]

The loss of confidentiality may be more severe in certain missions based upon the data maintained by the SUAS. An example of a high confidentiality risk may be posed by a SUAS capturing video over restricted areas on a COTS camera. A less severe confidentiality risk may be posed by a SUAS conducting public infrastructure surveillance for a safety assessment. In the former example, the data on board the UAV componentry may be rated as confidential.

To capture cybersecurity risk pertaining to component brands and the specific SUAS mission, one can rate confidentiality requirement as high, medium, or low. This is equivalent to noting that the loss of confidentiality is likely to have a catastrophic, serious, or only limited adverse effect on the organization or the mission, respectively.

In addition to the vulnerabilities innate to the system itself, the layout of components requires additional consideration for cybersecurity assessments. Furthermore, adjacent devices and networks, as well as the operational environment, can change throughout a single mission given the mobile nature of SUASs. PCSRA captures these higher-level risks.

Once a score is calculated, an instance table within the architecture may be used to summarize multiple PCSRA scores for a model based on varying selections of sub-metric levels, allowing for comparison of multiple scores. This comparison may assist a user to make educated changes to their model architecture by selecting alternative COTS components or changing the external connectivity of the system to reduce risk.

Figure 4. Defined Sub-Metrics

Attack Vector Values

Base Level	Description
Direct	The UAV is bound to the network directly and the set of possible attackers extends to the entire internet. Such a device is often termed "remotely exploitable" and can be thought of as being exploitable at the protocol level one or more network hops away.
Ground Controller	The UAV is indirectly bound to the entire Internet through the ground controller. An attacker may utilize persistent or live exploitation to the ground controller for persistent or live exploitation of the UAV.
Air-Gapped	The UAV is not bound to the network and the attacker's path is via persistent read/write/execute capabilities on the ground controller. Either the attacker exploits the vulnerability by accessing the ground controller while not connected to the UAV or the attacker relies on persistent code to modify commands live to the UAV.
None	An attack requires the attacker to be physically present to manipulate the vulnerable component. Physical interaction may be brief or persistent.

Coast Guard graphic

Model Summary Document Generator

Following a cyber-vulnerability assessment, the architecture can automatically generate a summary of the digital model in a document for review by those within the Coast Guard and DoD counterparts who may grant authorization to use SUASs with COTS componentry. Military services and component-authorizing officials (CAOs) are delegated authority to approve the procurement and use of COTS UAS, modified COTS UAS, and commercially available UAS or associated equipment.[30] This generation tool demonstrates the desire of the system designer to accurately obtain and display the required data in a transparent, consistent view to the CAOs.

The summary generator includes detailed information required by CAOs, such as a description of the mission environment type, component descriptions, and any Federal Aviation Administration certificates of authorization. It lists the country of origin for each component, as well as additional information, like the autopilot and payload descriptions and version numbers, required for the request. The format of the request displays the hardware and software configurations of the system, data/encryption links between the ground control station and the UAV, and network connections, among other diagrams. The generator builds the document as a user designs the system, reducing their workload. For an SUAS with a complete architectural definition, the user may automatically generate a summary document, rather than tediously compile the necessary information in their own format.

The document generator offers an invaluable benefit to a user looking to compile all necessary information regarding the cybersecurity of their system. This is true whether they are submitting for an SUAS COTS use request or to produce a snapshot summary of the SUAS PCSRA cyber risk for general awareness. This tool and the cyber-vulnerability assessment should assist a SUAS developer to create a more cyber-secure model. That model can then be used to construct a robust physical SUAS and to submit a coherent, complete request to operate it in the high likelihood that it incorporates COTS componentry.

Conclusion

AFIT's SUAS architecture provides a means for SUAS stakeholders to design, develop, and assess their systems for cyber vulnerabilities. Stakeholders may use the architecture to gain knowledge about common cybersecurity attacks on SUASs and to design their own digital model to then be evaluated for cyber risk. This work demonstrated a viable new process to assess digital SUAS models for cybersecurity and may be a feasible solution for autonomous seagoing vessels pending future architectures.

The cybersecurity of SUASs and autonomous systems will need to continue to increase in proportion with the fielding of new fleets across military, commercial, and individual sectors. Improvements to operational autonomous fleets' security will be realized when operational and cyber threats are accurately recognized and weighed. Since the manufacturers of SUASs and autonomous seagoing vessels are slow to respond to this need, consumers must take appropriate actions including assessing the risk of their own systems to protect these most valuable assets.

About the author:

LT Melissa Barrett graduated from the Coast Guard Academy in 2016, followed by an Apprentice and Journeyman Marine Inspector tour at Marine Safety Unit Houma, Louisiana. In 2021, she graduated from the Air Force Institute of Technology with a master's in systems engineering, and is now serving at the Marine Safety Center.

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Creating a Smart Future Through Collaboration and Innovation

Industry partnerships bring smart vessel technology to Maine Maritime Academy

by Emily Baer
Manager of Institutional Communications
Maine Maritime Academy

Maine Maritime Academy's (MMA) waterfront campus sits at the edge of history. For hundreds of years, Castine's beautiful harbor has been witness to change, much of it brought about by the community's rich connection to the sea. Today, the college is helping write the next chapter in maritime history, positioning itself at the forefront of innovation through the practical application of autonomous vessel technology.

In early 2019, Captain Jennifer Norwood, associate professor of marine transportation, introduced members of MMA's Women on the Water Club to technology being developed by the field-leader, Boston-based Sea Machines. With offices around the world, Sea Machines is "pioneering advanced perception and autonomous command and control systems" with the goal of applying "practical AI and machine learning to develop systems that increase the safety, efficiency, and performance" of vessels across industry. After touring the company's New England facilities with her students, Norwood began to imagine a future in which MMA could help train future mariners for leadership in this emerging field.

Norwood helped parlay the visit into a project between MMA and Sea Machines, funded by the U.S. Maritime Administration and the Boston Marine Society. The project, though delayed by the COVID pandemic, introduced autonomous vessel operations to MMA's classroom, fleet, and labs in fall 2021. Sea Machine's SM300 control system was installed on RV *Quickwater*, a 41-foot utility boat. The boat's operational equipment was rigged with controls and sensors that allow it to be autonomously or remotely driven, with collision avoidance capabilities in place.

"Smart vessel technology is emerging in the maritime industry," Norwood said. "And providing our students the opportunity to gain and learn from this technology perfectly fits our mission to provide the best marine-related education of any small college."

MMA's Smart Vessel Project

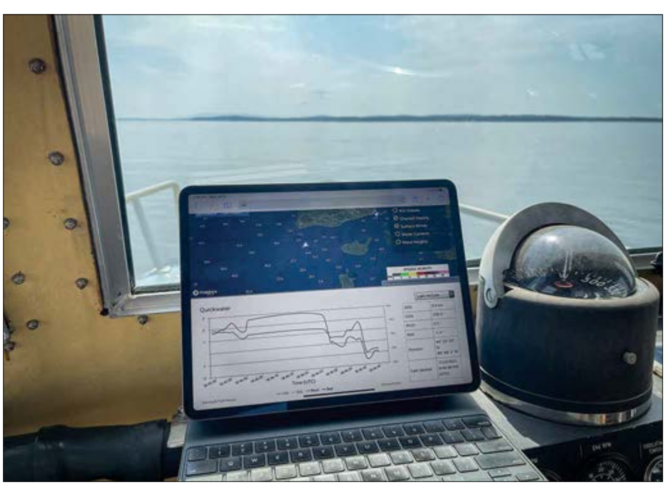
Over several months, what Norwood imagined in Boston, and began with Sea Machines, has expanded and become a reality in Castine. Maine Maritime Academy has partnered with SailPlan, a maritime technology startup based in Reston, Virginia, to accelerate the development of an intelligent vessel's navigation platform and shoreside vessel control.

Docked at the Maine Maritime Academy's waterfront campus, RV *Quickwater* was fitted with SailPlan's remote monitoring systems in early 2021. Photo courtesy of Jacob Ruytenbeek, SailPlan

RV *Addy Rae* conducts her first sea trial with SailPlan in early 2021 off the coast of Castine, Maine, after being fitted with the company's remote monitoring systems. Photo courtesy of Jacob Ruytenbeek, SailPlan

Together with her colleague, Travis Wallace, associate professor of engineering and the project's lead engineer, Norwood has begun installing SailPlan's monitoring systems aboard two of the Academy's vessels—the RV *Quickwater* and the RV *Addy Rae*. Each boat has been equipped with monitoring equipment to provide the vessels' navigation status allowing both to be monitored remotely. This is a critical first step in providing the ability for an autonomous, or uncrewed, vessel to communicate with a traditional crewed vessel. Further development will include monitoring of the vessel's propulsion and steering systems to remotely determine the overall health of the vessel from a shore control center (SCC), and students will be able to monitor the vessels from campus.

In tandem with a professional training curriculum



SailPlan's dashboard module, installed on the RV *Quickwater* in early 2021, allows Maine Maritime Academy deck and engine program students to train on cutting edge technology. Photo courtesy of Jacob Ruytenbeek, SailPlan

to train the modern mariner on this emerging technology, an SCC is being created in Bucksport, at MMA's Center for Professional Mariner Development (CPMD). The center will serve as a control station for both vessels, and emissions and performance will be monitored in the school's Medium Speed Engine Lab in Andrews Hall on MMA's waterfront. For shoreside operators, SailPlan will stream live data feeds from cameras, sensors, and other equipment into the SCC for real-time situational awareness of vessel operations on the water. As a result, unparalleled vessel telemetry will be made available shoreside, and SailPlan's cloud-based route exchange capability will allow autonomous vessels to proactively mitigate collision risks while optimizing routing for efficiency.

"This partnership highlights our strategic focus on faculty research and provides our students with access to the cutting-edge technologies that are transforming our industry," said Dr. Keith Williamson, MMA's vice president for academic affairs. "Bringing real-world experience into the classroom is essential and our progress thus far is truly invigorating."

SailPlan's navigation platform increases safety by capturing and analyzing data on vessel traffic, weather, berth availability, and geographic awareness. This information provides unparalleled situational awareness resulting in the ability to proactively optimize voyage plans, avoid congested waters, and separate from potential collision scenarios to a far greater degree than possible with current market solutions.

Environmental Monitoring and Data Collection

As the project moves into its next phase this fall, a marine systems engineering capstone project student group will test the new systems and assist with maintenance issues. They will also be trained on equipment to monitor each vessel's engine energy efficiency in autonomous and manual modes. Performance data will be sent to equipment in the college's Marine Engine Testing and Emissions Lab (METEL). There, it will model a sea state performance load profile that can be translated into the simulated operation of the lab's 1,020 kW medium-speed Wartsila 6L20 diesel engine, which is closer in magnitude to a merchant vessel.

The vessels are also being equipped to collect data on environmental conditions, such as wind and waves, through sensors, which will also be transferred to the METEL lab. In the following project phase, data from the vessels and METEL lab will be brought together in a shoreside control center where deck and engine students will work side by side to manage the vessel remotely.

Adapting and Evolving Curricula

With two systems now installed, the team plans to continue to outfit MMA's fleet with additional dashboard modules in the coming months. Ultimately, six vessels will be outfitted with smart vessel technology. This will allow students in both deck and engine programs to take advantage of the opportunity to train on cutting edge technology along the campus' working waterfront.

"The advances provided by this new technology allow for significant modernization in our curriculum," Wallace said. "As a result, our undergraduate courses are in the process of undergoing a metamorphosis to adapt to these new and emerging technologies that will be impacting the maritime industry."

Norwood and Wallace are in the process of developing a course that will tie together the navigation and engineering aspects of this technology and start showcasing its abilities to the students in Spring 2022. Meanwhile, smart vessel technology curriculum is also being created for professional development courses as part of the college's offerings through CPMD.

"The implications of this work are massive," Norwood said. "In addition to improving vessel safety, we are providing our students with new opportunities to innovate in cybersecurity, artificial intelligence, and more at all stages of their careers."

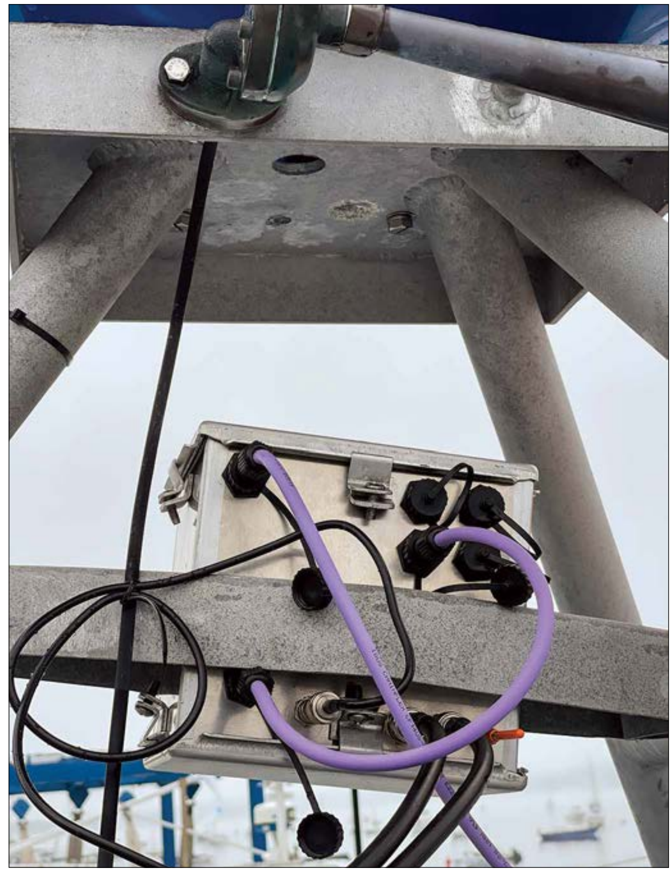
Future-Facing Training Opportunities and Investments

In addition to providing hands-on training opportunities for undergraduate and professional students, MMA's investments in smart vessel technologies have energized partnerships that link the institution with industry leaders that are creating new opportunities within the maritime sector. While some have expressed skepticism about the effect of this technology on real-world maritime activity, Norwood sees the evolution as exciting and unavoidable.

"Smart vessel technology will have the most significant initial impact on small, near coastal, and inland vessels, like the tugboats, ferries, and workboats that many of our graduates work on," she said. "It is imperative that we prepare them for an evolving industry, and we are proud that MMA is actively invested in being a part of that progress."

SailPlan's CEO, Jacob Ruytenbeek echoed that sentiment. "The future of safe navigation rests on digital enablement and vessel connectivity. Our partnership with MMA will accelerate the adoption of these foundational, safety-critical technologies that provide advanced collision avoidance, intelligent vessel routing, and increased insight shoreside."

The work being done at MMA on autonomous vessel technology is providing a pathway to collaborating with the industry directly, creating opportunities to bring new technologies to students, and providing opportunities for them to work directly with partner



Part of SailPlan's SMART, or SailPlan Marine Asset Real Time, System, this box connects remote monitoring controls with shipboard sensors. The addition of this cutting-edge technology is allowing Maine Maritime Academy to modernize its curriculum. Photo courtesy of Jacob Ruytenbeek, SailPlan

companies. The partnerships that Norwood and Wallace are building create a link between all aspects of the industry including the technology companies, vessel operators and logistics, government agencies, and regulatory bodies. This provides Maine Maritime Academy students with a close-up view of how the industry functions as they help write the next chapter in maritime innovation.

About the author:

Emily Baer is the Manager of Institutional Communications at Maine Maritime Academy.

Article contributors:

Captain Jennifer Norwood is an associate professor of marine transportation at Maine Maritime Academy, where she has taught for five years. Prior to her tenure at the Academy, she sailed as master onboard 7th generation dynamic positioned drilling vessels in offshore oil and gas.

Travis Wallace, associate professor of engineering, has been teaching engineering at Maine Maritime Academy for five years and holds a 3rd Assistant Engineer license. Prior to joining the faculty, he worked as a research engineer in the academy's Marine Engine Testing and Emissions Laboratory, and is a Ph.D. candidate in mechanical engineering at the University of Maine.

The “Racing Stripe”

Over 50 years of Coast Guard brand identity

by William H. Thiesen, Ph.D.
Atlantic Area Historian
U.S. Coast Guard

In the modern history of the United States Coast Guard, the shift from mistaken identity to a brand identity has been rapid. As recently as 1956 the Navy was still getting credit for the Coast Guard’s good work.

On ocean station October 19, 1956, Coast Guard Cutter *Pontchartrain* came to the aid of a downed transoceanic passenger aircraft, Pan American’s clipper *Sovereign of the Skies*, which had lost two of its engines en route from Hawaii to California. After the aircraft radioed the cutter and ditched in the ocean, *Pontchartrain* sent out its small boats and gathered up all 31 passengers and crew. One survivor no sooner gained the safety of the cutter’s deck, when he gratefully exclaimed, “Thank goodness for the Navy!”

Formally adopted by the Coast Guard in 1967, the Coast Guard Racing Stripe, with specific colors, size, and angle, was designed by the Loewy-Snaith design firm. Coast Guard photo

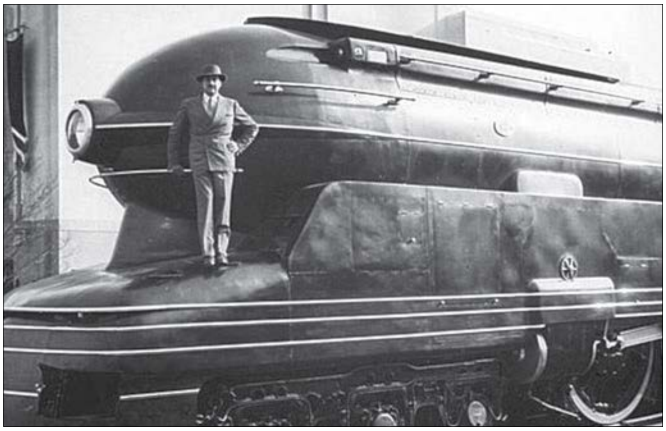
Unfortunately for the Coast Guard, this case was one of many in which the service seemed unrecognizable to the public it assisted.

John F. Kennedy was acutely aware of the importance of image-building, having relied on it during his successful 1960 presidential campaign. When they moved into the White House in 1961, the president and first lady Jackie Kennedy began an effort to remake the image of the presidency. With the aid of professional designers, the first lady completed the redecoration of the White House. They also met with architects to direct the design and renovation of buildings surrounding Lafayette Square located next to the White House.

Kennedy next undertook a redesign of Air Force One, the presidential jet. He believed the Air Force’s initial design was too regal looking and, on the advice of the first lady, he turned to French-born industrial designer Raymond Loewy, whose work had been recognized the world over in the post-war period. Loewy’s Air Force One design won immediate praise from Kennedy and the press, and the aircraft became an important symbol of the president and the United States on official visits at home and overseas.

Delighted by the look of Air Force One, Kennedy granted Loewy’s request for a meeting on May 13, 1963. During that meeting, and a second held a day later, the men discussed improving the visual image of the federal government and Kennedy suggested starting with the Coast Guard. Soon after, the design firm of Raymond Loewy-William Snaith, Incorporated, received a contract for a 90-day feasibility study and, in January 1964, the firm presented its findings to Coast Guard leadership.

With its experience in designing industry trademarks, Loewy-Snaith recommended the Coast Guard adopt an identification device similar to a commercial trademark. The firm believed the symbol should be easily identifiable from a distance, easily differentiated



French-born industrial designer Raymond Loewy, poses with one of his industrial designs—the streamline locomotive. Library of Congress photo

U.S. Coast Guard Cutter *Kimball* and Japan Coast Guard Ship *Akitsushima* operate alongside helicopters and unmanned aerial vehicles to practice interdicting foreign vessels operating illegally in Japanese waters. The Coast Guard "Racing Stripe" has been the inspiration for coast guards around the world. Coast Guard photo

from other government or commercial emblems, and easily adapted to a wide variety of air and sea assets.

The Coast Guard established an ad hoc committee to work with Loewy-Snaith on the project and, on June 19, 1964, the Coast Guard signed a contract to "accomplish studies, prepare design efforts, and make a presentation of a comprehensive and integrated identification plan for the U.S. Coast Guard." On March 21, 1965, during an all-day session, representatives from Loewy-Snaith presented their findings to the service. Later that day, Coast Guard chief of staff, Rear Admiral Paul Trimble, agreed to proceed with the Integrated Visual Identification System.

During the development process, Loewy-Snaith selected a wide red bar to the upper right of a narrow blue bar canted at 64 degrees and running from right to lower left. The Loewy-Snaith team used its own stylized version of the traditional Coast Guard emblem for placement on the center of the red bar. The overall design came to be known as the "Racing Stripe" or "Slash" emblem.


Admiral Edwin Roland, 12th Commandant of the Coast Guard, was instrumental in the adoption of the Coast Guard Racing Stripe. Coast Guard photo

Next, the Racing Stripe design was tested on cutters and facilities in Florida, due to milder weather conditions and the wide variety of sea assets stationed there. The prototype slash was affixed to the cutters *Diligence* and *Androscoggin*, a buoy tender, vehicles, and buildings at Base Miami. At North Carolina's Air Station Elizabeth City, it was affixed to an HH-52 Seaguard helicopter, an HU-16 Albatross amphibian, and an HC-130 Hercules turbo-prop aircraft.

On May 4, 1966, the service's ad hoc committee for testing the Visual Identification System sent the commandant a favorable report regarding service-wide use of the Racing Stripe. During the prototyping process, the Coast Guard's selection committee had decided against the Loewy stylized shield, instead opting for the service's traditional shield. While the plan received the stamp of approval, details had to be ironed out over several months. By early spring 1967, most outstanding issues had been resolved, including the type-font for lettering and specific paint color specifications. Commandant Instruction 5030.5 was issued

U.S. Coast Guard Cutter *Bertholf* (left) moves in formation with Philippine Coast Guard vessels *Batangas* (center) and *Kalanggaman* during a joint exercise. Coast Guard photo by Chief Petty Officer John Masson

on April 6, 1967, ending four years of study and experimentation and making way for the service-wide implementation of the Integrated Visual Identification System.

Initially, the adoption of the Racing Stripe met with resistance from the Coast Guard's service culture. However, over the course of the late 1960s and early 1970s, the symbol spread to every maritime and aviation asset in the service. By 1975, the Coast Guard's sail training ship *Eagle* remained the last asset not sporting the emblem. Traditionalists had long held that the Racing Stripe would destroy her classic lines and opposed application of the emblem to her bow.

The distinctive white hull and racing stripe emblem of the Coast Guard serves to de-escalate tensions during the cutter *Dallas*' delivery of humanitarian goods to Georgia in 2008, during that country's hostilities with neighboring Russia. Coast Guard photo

However, preparations were underway for Operation Sail 1976 to celebrate the nation's bicentennial, and *Eagle* was serving as the host ship. Coast Guard leadership saw an opportunity to present the service's brand identity to the world and distinguish *Eagle* from the other tall ships. The Racing Stripe received a public stamp of approval when CBS news anchor, experienced sailor and OpSail TV commentator, Walter Cronkite, singled out *Eagle* and her Racing Stripe logo with approving remarks.

Over the past 50 years, the service and its missions have been associated with the Racing Stripe symbol and its unique color scheme. During this time, the U.S. Coast Guard has served throughout the world and collaborated on a variety of levels with foreign coast guards and sea

Spain Sweden Germany China

Turkey South Korea India Egypt

Many foreign coast guards use a variant of the racing stripe for their emblem. Some, such as the United Kingdom, France, Russia, among others use blue and red stripes similar to the United States. Stripe colors are based on their country's flag. U.S. Coast Guard *Proceedings of the MSSC* illustration

services. These activities include training, international patrols, liaison personnel, and advisors to foreign sea services. In modern operations, such as Operation Iraqi Freedom and the deployment of Cutter *Dallas* in 2008 during the war between Russia and Georgia, the presence of Coast Guard cutters with the Racing Stripe has proved a de-escalating influence in high-tension maritime missions. This international engagement has spread the service's reputation and brand identity throughout the world.

In various colors and sizes, the Coast Guard Racing Stripe is a common emblem for federal, state, and local law enforcement and sea service vessels. Such is the case with these Customs and Border Protection assets. U.S. Customs and Border Protection photo

The Integrated Visual Identification System stands as the most successful branding program of a federal agency in U.S. history. Since the 1970s, the Coast Guard Racing Stripe design has been applied to assets not commonly associated with the service. With alterations in coloration and angle, it has become a symbol for sea service vessels at the federal, state, county, and municipal levels throughout the United States, as well as for scores of foreign sea services. The iconic Racing Stripe, developed more than 50 years ago to distinguish the service and its assets from other sea services, will live on well into the future.

Since the adoption of the Racing Stripe, no longer does the Navy get the credit for Coast Guards' many missions carried out around the clock, 365 days of the year. Thanks to a visionary president, talented industrial designers, and Coast Guard leaders who saw the importance of a service brand identity, the assets of the Coast Guard are now easily identified by millions worldwide who share a connection to the sea.

The Coast Guard Racing Stripe finds its way onto a variety of Coast Guard assets, from boats to cutters to aircraft. For a short time in 1979, it even made its way onto a diesel locomotive as part of a partnership with the Central Vermont Railroad. Coast Guard photo

About the author:

William H. Thiesen, Ph.D., is the Atlantic Area historian for the United States Coast Guard. He earned an M.A. from East Carolina University's Program in Maritime History, and a Ph.D. from University of Delaware's Hagley Program in the History of Technology. His books include Industrializing American Shipbuilding: The Transformation of Ship Design and Construction, 1820–1920 *and* Cruise of the Dashing Wave: Rounding Cape Horn in 1860. *His articles appear frequently in naval, maritime, and Coast Guard publications and the online history series,* The Long Blue Line, *featured weekly on the* Coast Guard Compass *web site.*

Chemical of the Quarter

Understanding Ammonia

by Cynthia Znati, Ph.D.
Hazardous Materials Division
U.S. Coast Guard Office of Design and Engineering Standards

What is it?

Comprised of one nitrogen and three hydrogen atoms, ammonia is a colorless gas with a pungent odor. It occurs naturally and is a major component for the production of many commercially important compounds. The basic building block for fertilizers, it is the foundation of modern agriculture, providing the nitrogen essential for the growth of plants, and may be applied to the soil as a liquefied gas or as ammonium salts and urea.

Ammonia is used to make commercial explosives and synthetic fibers, serves as a catalyst in many industrial processes, and is used in petroleum refining. It is used in various metallurgical processes and as a source of hydrogen for welding, as well as a coolant in refrigeration equipment. Effective at breaking down household grime or stains, ammonia is found in many household cleaners.

With recent emphasis on reducing the carbon footprint of transportation, there has been increased interest in the use of ammonia as fuel, either in internal combustion engines directly or as a carrier of hydrogen for fuel cells. Recent developments have led to an improved outlook for ammonia's use in fuel cells. Consequently, several fuel system and engine developers are working on direct ammonia combustion, but current technology requires use of another fuel for this to be feasible. The main drawback to ammonia combustion is the creation of NOx which then needs to be scrubbed from the combustion gases.

How is it produced?

Ammonia is one of the top five chemicals manufactured in the United States and is produced using the Haber-Bosch process, which involves use of a catalyst, high pressure, and high temperature to combine elemental hydrogen with elemental nitrogen. The process has a high energy requirement but enables food production worldwide.

How is it shipped?

Ammonia can take the form of solid, liquid, or gas. The specific requirements for shipping depend on the form in which the cargo is shipped—in bulk or as packaged cargo. Bulk cargoes include solid bulk cargoes, such as ammonium nitrate; liquid cargoes, such as aqueous ammonia or ammonium hydroxide solutions; and liquefied gases, such as anhydrous ammonia.

Why should I care?

Ammonia is toxic and may be fatal if inhaled, ingested, or absorbed through the skin. The permissible exposure limit is 50 ppm. The vapors are extremely irritating and corrosive, and repeated exposure lowers sensitivity to the gas' odor.

Anhydrous ammonia is classified as toxic and dangerous for the environment. It has a moderate fire risk, with flammable limits in air of 16 percent to 25 percent, and an autoignition temperature of 651 C. Anhydrous ammonia corrodes some alloys, and liquid ammonia can attack rubber and plastics. It reacts violently with halogens and can form explosive compounds.

What is the Coast Guard doing about it?

Ammonia has many requirements for shipping by vessel. The specific requirements are dependent upon whether it is being shipped as a solid, liquid, or gas. All ammonia shipments must meet the relevant domestic and international requirements. The Coast Guard Office of Design and Engineering Standards maintains the domestic regulations for bulk transport, works with the Department of Transportation on the domestic regulations for packaged hazmat, and participates in the International Maritime Organization for the development of international regulations.

About the author:
Dr. Cynthia Znati Ph.D., has worked for the Coast Guard since 2011. She is the team lead for Liquefied Gases and Vapor Control Systems in the Hazardous Materials Division of the Office of Design and Engineering Standards at U.S. Coast Guard Headquarters. She received her B.S., M.S., and Ph.D., all in chemical engineering, from the University of Illinois at Urbana-Champaign, Michigan State University, and Carnegie Mellon University, respectively.

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Nautical Engineering Queries

Prepared by NMC Engineering Examination Team

Questions

1. The maximum concentration of hydrogen sulfide to which workers may be regularly exposed without adverse effects is ______________ .

A. 10 ppm
B. 20 ppm
C. 40 ppm
D. 80 ppm

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2. The purpose of the mica used in a boiler water gage glass assembly is to prevent ______________ .

A. overheating of the glass
B. light refraction in the glass
C. etching of the glass
D. leakage from the glass

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3. The clamp-on AC ammeter consists essentially of a split-core and a rectifier-type instrument connected to the secondary winding of a particular type of transformer. Which type is used?

A. Potential transformer
B. Control transformer
C. Current transformer
D. Reactance transformer

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4. When 'reset' action is added to proportional action, the proportional action ______________ .

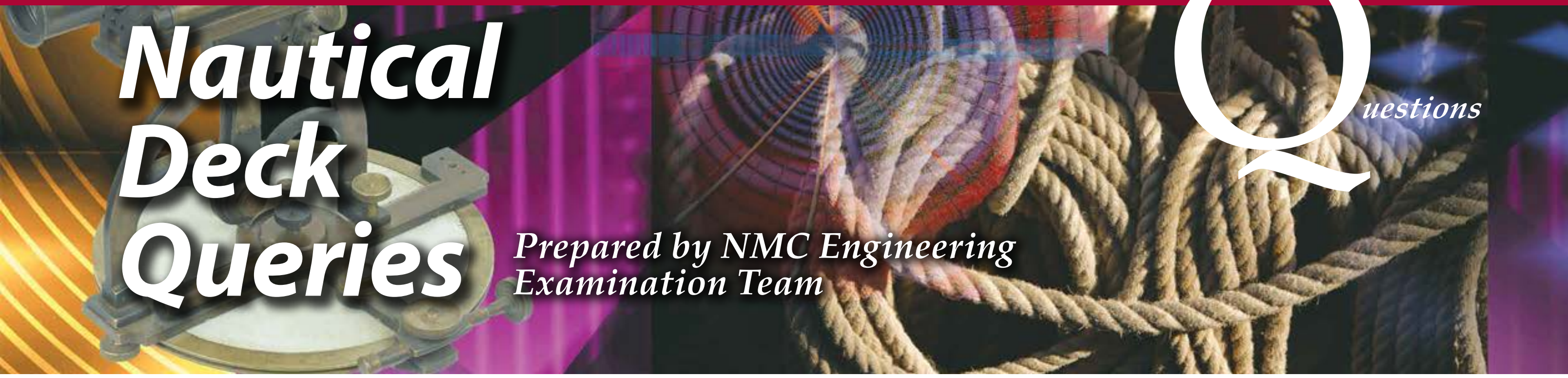
A. aids the reset action during decreasing error transients
B. aids the reset action during increasing error transients
C. opposes the reset action during increasing error transients
D. and reset action are completely independent of one another in the controller operation

1.	A. 10 ppm	Incorrect
	B. 20 ppm	**Correct answer.** "Acceptable ceiling concentrations. An employee's exposure to a substance listed in Table Z-2 shall not exceed at any time during an 8-hour shift the acceptable ceiling concentration limit given for the substance in the table, except for a time period, and up to a concentration not exceeding the maximum duration and concentration allowed in the column under "acceptable maximum peak above the acceptable ceiling concentration for an 8-hour shift."
	C. 40 ppm	Incorrect
	D. 80 ppm	Incorrect

2.	A. overheating of the glass	Incorrect
	B. light refraction in the glass	Incorrect
	C. etching of the glass	**Correct answer.** "A sheet of mica is placed between the glass and the steam and water to prevent glass etching."
	D. leakage from the glass	Incorrect

3.	A. Potential transformer	Incorrect
	B. Control transformer	Incorrect
	C. Current transformer	**Correct answer.** "A current transformer (CT) is used to provide a reduced but proportional current to the ammeter."
	D. Reactance transformer	Incorrect

4.	A. aids the reset action during decreasing error transients	Incorrect
	B. aids the reset action during increasing error transients	**Correct answer.** "Mathematically, the controller output is based on the integration of the error signal over time in addition to the magnitude of the error, hence the term integral. This action is also referred to as reset since the band of proportional action is shifted or reset so that the controlled variable operates about a new base point."
	C. opposes the reset action during increasing error transients	Incorrect
	D. and reset action are completely independent of one another in the controller operation	Incorrect



Nautical Deck Queries

Questions

Prepared by NMC Engineering Examination Team

1. **BOTH INTERNATIONAL & INLAND: Which statement is TRUE concerning a "vessel engaged in fishing?"**

   A. The vessel shows 2 lights in a vertical line, white over red
   B. The vessel may be using nets, lines, or trawls
   C. The vessel may be trolling
   D. The vessel sounds the same fog signal as a vessel underway, making no way

2. **How long are the records of tests and inspections of a cargo vessel's fire extinguishing systems required to be kept on board?**

   A. Until the next Coast Guard inspection
   B. Until the vessel's Certificate of Inspection expires
   C. For 2 years
   D. For 1 year

3. **In the Northern Hemisphere, what do winds veering sharply to the west or northwest with increasing speed indicate?**

   A. A high-pressure center has passed
   B. A stationary front exists
   C. A low-pressure center is approaching
   D. A cold front has passed

4. **The regulations require that inspected vessels on an international voyage, other than small passenger vessels, must carry which of the following distress signals on or near the navigating bridge?**

   A. 12 hand combination flares and orange smoke signals
   B. 6 hand red flares, and 6 hand orange smoke signals
   C. 12 rocket parachute flares
   D. 12 hand red flares

Deck Answers

1. A. The vessel shows 2 lights in a vertical line, white over red	Incorrect
B. The vessel may be using nets, lines, or trawls	**Correct answer.** "The term vessel engaged in fishing means any vessel fishing with nets, lines, trawls, or other fishing apparatus which restricts maneuverability, but does not include a vessel fishing with trolling lines or other fishing apparatus which do not restrict maneuverability."
C. The vessel may be trolling	Incorrect
D. The vessel sounds the same fog signal as a vessel underway, making no way	Incorrect

Reference: International/Inland Rule 3(d)

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2. A. Until the next Coast Guard inspection	Incorrect
B. Until the vessel's Certificate of Inspection expires	**Correct answer.** "Such records shall be made available to the inspector upon request and shall be kept for the period of validity of the vessel's current certificate of inspection."
C. For 2 years	Incorrect
D. For 1 year	Incorrect

Reference: 46 CFR 97.15-60

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3. A. A high-pressure center has passed	Incorrect
B. A stationary front exists	Incorrect
C. A low-pressure center is approaching	Incorrect
D. A cold front has passed	**Correct answer.** "A cold front usually coincides with a well-defined wind-shift line (a line along which the wind shifts abruptly from southerly or southwesterly to northerly or northwesterly in the Northern Hemisphere."

Reference: Bowditch 2002 Ed, Pages 490–492

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4. A. 12 hand combination flares and orange smoke signals	Incorrect
B. 6 hand red flares, and 6 hand orange smoke signals	Incorrect
C. 12 rocket parachute flares	**Correct answer.** "Distress signals. Each vessel must—(1) Carry not less than 12 rocket parachute flares approved under approval series 160.136; and (2) Stow the flares on or near the vessel's navigating bridge."
D. 12 hand red flares	Incorrect

Reference: 46 CFR 199.60(c)(1)(2)

In the News: Coast Guard Rescues Fishing Crew

Members of a Coast Guard Station Bodega Bay boat crew rescue fishermen from a capsized boat near Tomales Bay, California, on November 22, 2021. The Coast Guard was able to reach the three fishermen about 30 minutes after receiving the alert. A GPS verification tool aided in the quick response. None of the fisherman were injured, though they were treated for symptoms of hypothermia. Coast Guard photo

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On September 6, 2021, the *Mayflower 400*, a fully autonomous trimaran, set sail from Plymouth, England a year later than planned due to the COVID pandemic to retrace the steps of its famous namesake in a cross Atlantic voyage. Though the trip was cut short because of mechanical issues, this was the first test of a fully autonomous vessel on open ocean. The next attempt could have wide ranging impacts on the integration of autonomous vessels into the maritime industry and the regulations they operate under. Photo courtesy of IBM/Promare