MSDL | MARINE STRUCTURES DESIGN LABORATORY

Needs Exploration for Long-Term Autonomous Marine Systems: Working Report

ONR Grant N00014-20-1-2044

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MSDL Report Number: 2021-001

Date: August 2022

Abstract: Weeks-to-months long crewless missions in the marine domain present unique challenges for autonomous systems. At these mission lengths, the platform must take on self-assessment and mission planning tasks as well as short-term autonomy tasks such as navigation. The results of a four-prong research program to explore these challenges are reported here. Existing vessels were reviewed and analyzed and a new rating system was constructed. Interviews with human crew members were carried out to identify assessment and planning approaches. A simplified simulation and an STPA-inspired analysis were used to identify areas where research would be beneficial. From these investigations, it is clear that existing planning systems rely heavily on humans to integrate different sources of information. Humans make decisions today based on shared experience and implicit criteria. Automating this process is a significant challenge. Three test cases are proposed to explore the identified research needs, one on fuel management, one on design and operational support of machinery systems, and one on adapting and updating risk criteria in service.

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Contents

List of Figures

List of Tables

1 Executive Summary

Making a marine platform autonomous for long-duration missions of weeks to months at sea has been shown to be a fundamentally different challenge than those faced by crewless air and ground vehicles. Self-health assessment, mission planning and logistics consideration are all heightened for the marine vessel that may be out for weeks to months at a time. However, how such assessments and mission planning is done on crewed vessels today is not well understood, which makes researching algorithms for this area difficult.

This work reports on a broad framework of risk concerns for such long-term missions, and then reviews current marine systems in service. Existing platforms show a clear tradeoff between platform complexity and achievable endurance. Gliders and simple platforms have completed weeks-to-month voyages but with high loss rates. More complex vessels are still in the days-to-low-weeks range of mission lengths, and no vessel currently performs long-term planning autonomously. A new three-component rating system was proposed to track platforms, using the platform's decision-making, endurance, and platform complexity as metrics. Existing platforms were visualized with this system, confirming the capability gap.

A series of interviews with ship and shore crews was used to attempt to determine how such planning is done today. This process revealed that machinery systems comprise the central concern around platform health. The maintenance of machinery is highly structured within the vessel's preventative maintenance system (PMS). However, both integrating the overall health of the platform, and weighing risks for planning were done in a human-center manner. Such planning was not standardized or recorded in a formal procedure, but used extensive human experience and implicit criteria. Shore-side support was also widely used in diagnosing problem, planning repairs, and supporting on-board decisions. Thus, the interviews produced a list of concerns but not a definite planning approach that could be automated.

A high-level simulation-based approach was used to see how accurate planning around platform health had to be to improve operational performance. A fleet of 10 vessels was used to maintain a patrol line at different distances from a support base, with each vessel having a single health parameter that degraded stochastically. Four different planning approaches were compared, and the result showed that even imperfect long-term planning systems may produce large gains in platform effectiveness vs. static rule-based approaches.

Finally, a modified STPA approach was used to try to explore significant risk areas for long-term planning systems. Two STPA formulations were compared, and the approach more narrowly focused on mission planning was able to identify broad areas where existing algorithms may be insufficient. A table of resulting challenge areas was constructed, and three development case studies were proposed to address the gaps in the table. These cases were designed to be tractable for basic research exploration yet involving enough disciplines to be broadly representative of the at-sea mission planning problem. The three case studies included a fuel management study, a machinery design and support case, and an adaptable risk level case. Suggestions for implementing these case studies, and further work, finalize the report.

2 Overview

2.1 Challenges of Moving to a Crewless Platform

Integrating crewless operations into marine platforms is opening up dramatic physical and functional architectural changes not seen in the marine industry since the transition from sail to steam. This transition will be markedly different from crewless platforms in other domains. Aviation and land-based applications of crewless platforms have unsupported mission lengths in hours to days; however, surface and sub-surface maritime assets must operate without crews for weeks to months at a time. The extended time of deployment adds new requirements for a crewless system in terms of mission planning, self-state diagnosis, and reconfiguration. Traditional surface and sub-surface platforms rely on a host of complicated supporting systems to achieve such mission lengths. These systems are, in turn, supported by a human crew, who both operate and maintain the systems. In addition to routine maintenance, the crew also performs extensive high-level mission planning and risk assessment, considering the needs of the mission, capability of the platform, and risks from the operational environment. The presence of the crew, in turn, becomes a primary platform architecture driver, as space, systems, and overall platform motion requirements for the crew drive both the physical and functional architecture of the platform. Thus, unlike a self-driving car, removing the crew from a naval platform involves extensive changes in architecture, function, mission planning, and risk assessment that must be directly addressed if the design is to be successful. This report explores the state-of-the-art in autonomous systems, interviews human crews, conducted an STPA analysis and initial simulation of autonomous systems, and presents recommendations for future research and development of such systems. The focus of the report is only on the long-term autonomy part of the problem, short-term tasks such as autonomous navigation are not addressed as they have been extensively studied elsewhere.

In designing, accepting, and operating future generations of crewless platforms, we currently lack algorithms and frameworks to explore competing architectures for crewless systems. Design approaches, analysis tools, maintenance and sustainment models, and acceptability criteria are all built around both crew-centric design constraints. Buried in many of these approaches is the expectation that a human crew will perform ongoing if informal risk assessment and mission planning onboard. New frameworks able to identify crewless system design drivers, risks, and the acceptability criteria are needed to prevent copying crew-centered platform design and standards. Relying on existing human-centric algorithms, architecture, and approval tools will prevent taking full advantage of crewless systems and result in platforms that will struggle to be competitive internationally. Furthermore, as the commercial industry moves toward optionally crewed solutions, a deeper understanding of the capabilities and vulnerabilities of commercial crewless architectures is vital for naval vessels that must operate in an increasingly crewless ocean.

One high-level framework for thinking about the changes between conventional platforms and optionally crewed platforms is to look at new risks in three different areas:

- Risk of Mission Failure: To complete complex naval missions over a timespan of days to months, optionally crewed platforms must be able to complete high-level mission planning tasks as their own state and the external environment changes. Onboard risk assessment for both the health of the platform and the probability of mission success must be continually updated. Algorithms for such decision-making are currently in their infancy, and conventional design simulation and acceptability criteria used for platform design today are not suited for this task. Most methods employed today use crew safety as the driving concern, coupled with historically based criteria. When the crew safety concern is removed, new algorithms are needed. Additionally, synthesizing a physical and functional solution for a long-duration and optionally crewed platform so that it can understand its capability and perform higher-level planning is a more significant challenge than automating the navigation function (e.g., bridge watch-standing) alone.

- Risk of Sustainment Failure: In addition to much of the high-level mission planning and risk assessment, the crews of current platforms are integral to the platform's maintenance and sustainment. However, optionally crewed systems cannot rely on crews to perform underway preventative and reactionary maintenance. Additionally, such platforms may have vastly different physical layouts than conventional platforms, which can complicate pierside maintenance. Furthermore, in many of the geographic areas of interest, pierside support may be many thousands of nautical miles removed from the operating zone, raising the interest in forward sustainment presence. Algorithms and metrics to track the sustainability of such optionally crewed platforms and determine the best sustainment approach during design are needed. Such approaches do not currently exist, as early-stage design algorithms, today assume traditional sustainment approaches as a constant.

- Risk of Flexibility Failure: Optionally crewed platforms are rapidly evolving, especially the computational side of the platforms. Unlike traditional platforms where both the hardware components and crew training are costly and slow to change in-service, optionally crewed platforms can be rapidly upgraded through software development. Thus, one potential failure mode for such a platform is to have too-tight software and hardware integration, such that software logic upgrades are difficult without making corresponding hardware changes. Additionally, given the higher risk of losing such a platform to another entity via both technical and legal risks, placing much of the platform's capability into difficult-to access code reduces exploitation potential. Thus, exploration of algorithms and metrics to track the complexity and flexibility of the physical and algorithmic composition of the platform is also needed.

When contemplating the three types of failure above, it is tempting to expand this hierarchy in relation to a hardware solution for a crewless platform. However, the change initiated by moving to a crewless construct reaches far beyond the platform itself, involving design and operational decision-making frameworks as well as the hardware solutions on the water. The wider impact of the move to crewless approaches is shown in Figure 1. In this figure, five major areas of operational concern are highlighted in green ovals, building from the three types of failure listed above. In the upper left, "Safe to Operate" addresses concerns around approving a crewless platform for operation, that is, ensuring that the produced platform achieves a sufficient level of safety by design. In rose-colored boxes, new developments that are needed to achieve crewless operation are listed, along with contributing factors in blue boxes. The edges linking the boxes together explain the specific area of R&D interest that were determined in reviewing the state-of-the-art at the time of the proposal. In the design approval stage, concerns that have been highlighted include:

1. Addressing the development of criteria that would allow for explicit but variable risk levels in crewless craft, as some low-cost platforms may be designed to be more attritable than current crewed platforms.

2. Addressing challenges in engineering prediction tools and current criteria when applied to smaller platforms. Many current crewless platforms call for relatively small platforms performing open-ocean deployments. The ability of current engineering tools and criteria to adequately cover this application space is not known.

3. Addressing challenges in variable service lives of crewless platforms, which again may be shorter than the current platforms

4. Addressing challenges in removing crews, which may remove motion, acceleration, and related habitability limits on the design, potentially exposing the remaining equipment and structure to new loads that have not been experienced before.

On the top left, the green oval “Operate Safely” addresses the actions the crew would take on a crewed vessel to ensure that the vessel is operated safely. This involves a complex fusion of the state of the platform, risk thresholds, and operational environment. A human crew is constantly assessing the state of their vessel and adapting to the condition of the machinery, the weather, and their ability to safely execute their tasking. How this is replaced on a crewless platform is not clear, as this type of human analysis is carried out by different crew members blending experience, judgment, and procedures. Little documentation of these procedures was found in the existing literature for these tasks, and as such even the structure of these tasks is not currently clear. In the diagram, the “Mission planning AI” reflect the need to replace this human synthesis with some sort of automated reasoning approach, and the various risk, algorithms, and digital twin techniques needed to handle this process are shown as links into this box. As part of the mission planning, the platform must be able to know its own state, and must be able to make future predictions. This task will require some sort of digital twin, a system that can fuse numerical models and real-world measurements to reason about the state of the platform [60].

Parts of mission planning address mission effectiveness, shown as the green oval “Mission effective” and also the external autonomy problem of safely navigating the craft around other vessels and the bathymetry of the ocean. These areas are significant but are excluded from the current investigation based on the scope of the proposal. The navigation issue is being widely addressed in the marine community, and the military mission simulation piece is difficult to do in a university setting.

The final two high-level concerns address logistics and flexibility and are contained in the bottom two green ovals in Figure 1. Logistics concerns tie together both design and operation. Without crews onboard, maintenance tasks will likely need to be designed out of the platforms or done in batch settings when crews are working on the vessel between missions. This will require the ability to model maintenance in more detail than is currently done during design, as well as the ability to look at new concepts for operations and how sustainment can be carried out. On the operation side, the ability to notify logistic chains of upcoming needs, and modify mission and approaches to account for the platform's current state and the availability of logistics support.

Lack of flexibility was highlighted at proposal time as one of the potential risks associated with crewless platforms, covering concerns around both the increased exposure of these platforms to hostile interference and the rapid evolution of technology in this area which may drive rapid obsolesce. While ideas around upgradability, modularity, and flexibility have been widely explored for conventional, high-value crewed platforms, understanding how these concerns will interact with crewless platform architectures does need exploration.

2.2 Outline of the Current Study

Based on the three areas of concern, mission failure, sustainment failure, and flexibility failures, and Figure 1, the broad areas of need for research on crewless platforms emerge. However, these concerns are at a high enough level that it is difficult to translate them into specific research objectives. To provide a more granular view of the state-of-the-art and current needs in this area, an initial effort to conduct the next level of exploration in these areas was first carried out. The following areas were explored, and each are presented in a chapter in the report that follows:

- A broad survey of the state-of-the-art in autonomous vehicles in the air, ground, and sea domains to look at solutions to the long-term autonomy problem.
- A series of interviews with ship's crew members and shore support staff were carried out to better understand the types of medium and long-term planning needed. This address the "Mission planning AI" box in Figure 1.
- An initial simulation of a small fleet of platforms, looking at the logistics challenges of maintaining an operable fleet with different logistical approaches. This experiment was designed to see how accurate and powerful digital twins would need to be to influence logistics.
- An STPA analysis [28] of the overall process of operating a crewless platform was proposed to identify hazards and control feedback loops that need to be investigated to ensure the safety of the platform.
- Research gaps were identified through an integrated analysis of each of these areas of research and their findings. Three development cases were proposed that would help explore these gaps.

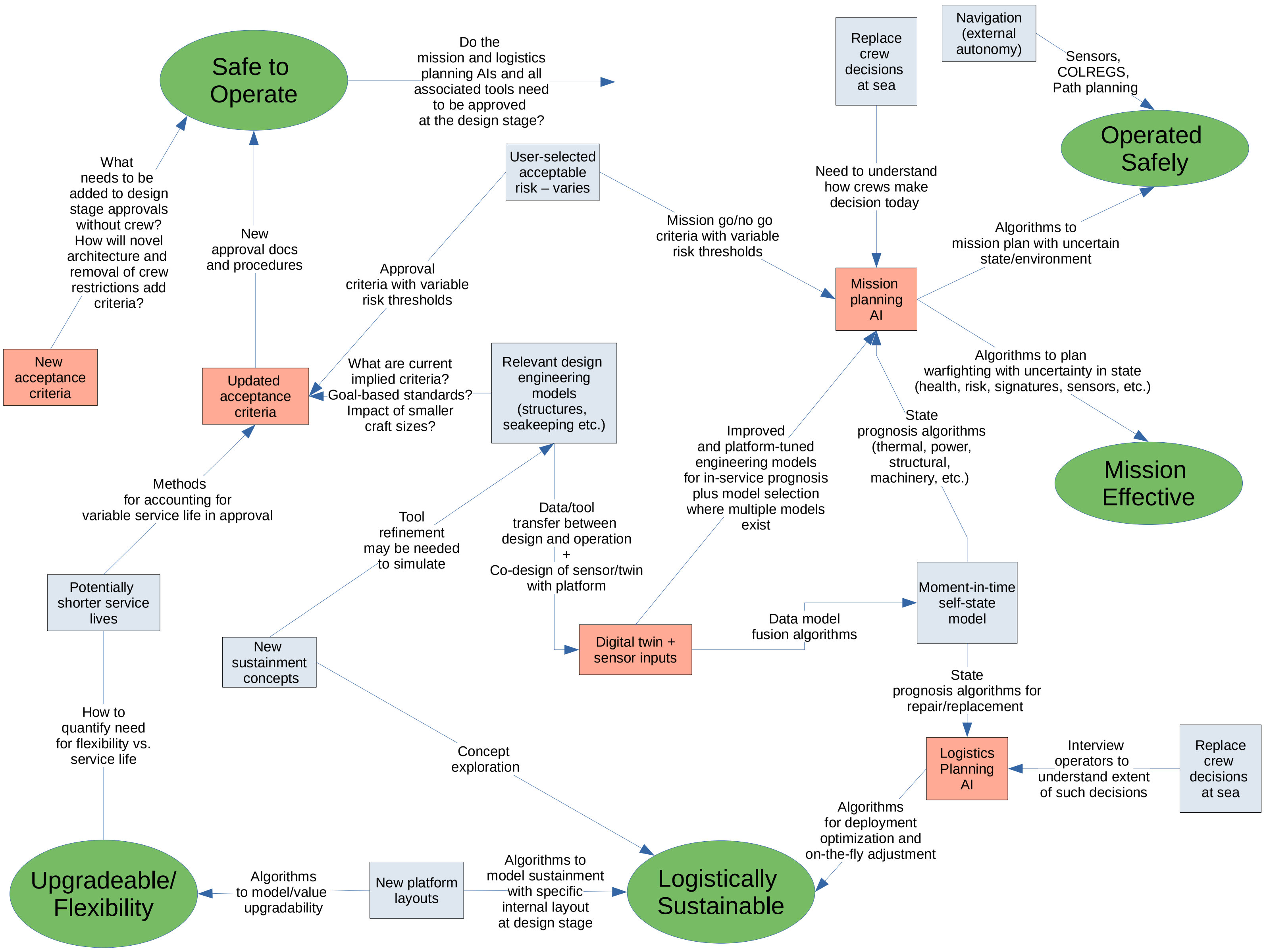


Figure 1: Overview of Broad Impact of Crewless Systems

3 Review of Existing Systems

International interest in autonomous vehicles has grown over the last two decades. However, the extent to which these autonomous vehicles perform long-duration missions is not yet clear, nor are the mission re-planning and logistics approaches required to sustain them. To understand the future demands, a deeper understanding of the present state of autonomous vehicles is critical. This section of the report examines existing air, ground, and marine autonomous platforms to understand what is currently achievable, and where gaps still remain.

3.1 Aerial Systems

Unmanned Aerial Vehicles (UAVs), drones, and similar platforms are among the most well-known crewless platforms today. Such vehicles have been in use for over a century and are being constantly updated and upgraded. They are most commonly found in use by militaries across the world, but as technology advances, commercial and personal drones are becoming more popular and capable.

While the most visible of current crewless systems, most UAVs today function as remote-controlled drones, capable in many instances of translating high-level flight commands into detailed control inputs, and, in the case of some vehicles, executing pre-planned alternate missions in the event of a loss of ground control. Onboard maintenance is very limited, borrowing from crewed planes where redundancy and reliability are used to ensure mission safety over in-flight repairs. Table 1 gives details of some select programs, showing the wide range of options for modern UAVs.

When it comes to endurance, two broad categories emerged from the systems seen to date: Short Range and Long Range. While not an exact breakdown, the list of UAVs could be sorted into those with a range of less than 500 kilometers, and those with a range of greater than 1000 kilometers:

- Short Range UAVs - Both commercial and military UAVs fall into the category of being used for short-range purposes. Commercial drones have a wide variety of uses, including aerial surveillance and capturing footage for product marketing. Militaries use smaller UAVs for reconnaissance and surveillance purposes, especially in areas where sending humans would put lives at risk. Specific examples of short-range UAVs that can be found in Table 1 are the Dragon Eye, RQ-11 Raven, and the Outrider Unmanned Aircraft System.
- Long-Range UAVs - With the need to fly higher, farther, and faster, long-range UAVs are used in the place of manned aircraft. UAVs capable of remote-controlled or autonomous flight are preferred to do surveillance operations or act as hunter-killers in dangerous or hostile environments. Long-range UAVs are mainly found in military use due to their higher costs and require more training than short-range UAVs. Examples that can be found in Table 1 are the MQ-9 Reaper, which acts as a hunter-killer UAV,

Table 1: Selection of Existing UAVs showing Typical Ranges

UAV	**Range(km)**	**Wingspan(m)**
Pointer	2	3
Dragon Eye	5	1
Silver Fox	41	2
Neptune	75	2
Javelin	80	2
Brevel	80	3.5
Luna	80	4
Dragon Warrior	90	3
RPO Midget	100	2
RQ-11 Raven	100	3
Bayraktar TB2	150	12
Shadow	125	4
Outrider	200	4
Seeker	200	7
Shadow 600	200	7
Firescout	400	9
MQ-9 Reaper	1500	20
Heron	3300	17
A 160	4625	11
Global Hawk	22000	35

and the Global Hawk, which is remotely piloted and is used to gather intelligence. The US Air Force uses drones to also accomplish the mission of both combat and non-combat search and rescue. The main objective, as cited by the Air Force, is to minimize the danger to the men and women of the US Air Force. These longer-range platforms often have more complex control systems, using combinations of satellite control as well radio communication. Additionally, some, such as the Heron, are capable of completely crewless operation during the mission, without the need to be in contact with a ground station.

Recent work in the aerospace field is expanding the capability of AUVs and crewed aircraft to conduct mission re-planning based on their current sensed state [27, 46]. While this remains relatively short-duration (e.g. hours), it does begin to address the needs to sense the platform's current health and modify plans based on the remaining capability of the platform. Many of the mathematical approaches taken in this field may be transferable, in part, to the marine domain. However, the smaller spatial scale of the AUVs means that a relatively dense sensor net is possible for AUVs in a way that it is not for marine vessels.

3.2 Ground Systems

An uncrewed ground vehicle (UGV) is a vehicle that operates while in contact with the ground and without an onboard human presence. Similarly, there has been extensive commercial investment in the concept of a "driverless car", where human passengers can be in the vehicle but do not take a role in the driving task. These concepts have been developed since the turn of the twentieth century. Due to technological advances and heightened commercial interest, recent decades have seen a larger wave of growth in the ground systems sector of autonomous vehicles. Unmanned ground vehicles are being used to remove human operators from tasks considered dull, dangerous, or dirty in both the public and private sectors. They can be used to collect information and perform hazardous work that involves no passengers at all, but also carry passengers without the need for an active human driver. The difference in commercial and military interests in UGVs tends to be reflected mainly in the application. The total number of UGV programs across both sectors is too large to enumerate in this report, but most programs fit within certain subcategories based on their general design and capabilities:

- Mobility - In terms of their form of locomotion, the UGV market has been segmented into the common wheeled, tracked, and legged categories, as well as some vehicles that are a hybrid of these methods. Currently, the legged segment of UGVs are best suited for rough and unpredictable terrains, making them useful for critical military operations. Many wheeled UGV programs more closely resemble traditional cars and are an area of increased commercial interest [58].
- Size - UGVs range in size from very small (less than twenty pounds) to large industrial trucks and agricultural tractors. Economic reports that study the growth of the UGV market tend to break up sizes and weights into categories like "light, medium, and heavy" for easier organization, although there is no global standard definition of payload

or tonnage that are associated with these categories. The size of the UGV generally depends on its mission.

- Control Systems - UGVs can also be subdivided based on their decision-making and control systems. Remote-operated UGVs are entirely controlled by a human operator via an interface. The actions of the UGV are entirely up to the operator. An autonomous UGV does not rely on a human controller and can make decisions for itself. However, many UGVs are only partially "autonomous", relying on operator intervention for parts of their mission or when faced with new challenges. This has been seen widely in the commercial car industry, with several proposed systems that require monitoring but are not constantly controlled by a driver. One way of looking at this spectrum comes from a 2005 book "Autonomous Vehicles in Support of Naval Operations", which states autonomous systems can be broken down into 'scripted', 'supervised', and 'intelligent' based on to what extent the vehicle utilizes artificial intelligence technology [13].

Though UGVs vary widely in their size, mission, level of autonomy, and type of mobility, they all generally rely on sensors to provide them information about their environment in lieu of having a human on-board to make observations. Sensors can include compasses, odometers, inclinometers, gyroscopes, cameras for triangulation, laser and ultrasound range finders, and infrared technology [44, 42]. Perhaps the most useful way of examining the current state is to look at commercial and military applications separately.

3.2.1 Commercial Applications

The most mainstream commercial example of unmanned ground vehicles is the driver-less passenger car. Automated driving systems research has been conducted for decades, with the first semi-automated car developed in 1977 by Japan's Tsukuba Mechanical Engineering Laboratory. By 1995 Carnegie Mellon University's NavLab 5 had completed the first partially autonomous coast-to-coast drive across the United States. Of the 2,849 mi (4,585 km) between Pittsburgh, Pennsylvania, and San Diego, California, 2,797 mi (4,501 km) were covered with automated steering (98.2 %), completed with an average speed of 63.8 mph (102.7 km/h). Automated vehicle research in the late twentieth century was primarily funded by government and military institutions throughout the world, but automotive and tech companies have since begun a race to create the most cutting-edge driver-less car technology. Major companies like Volkswagen, Samsung, Ford, and Toyota lead in investment in driver-less cars, with the total global investment reaching over 100 billion dollars by the end of 2019. [58]

Despite millions of miles driven in California and Nevada alone by experimental autonomous vehicles, no fully autonomous vehicle is available to the public today. While many new models of cars include advanced driver assistance technologies (for example, the sensors that detect when a driver is not breaking fast enough to avoid colliding with the car ahead), drivers are still actively engaged in the driving task. This is illustrated by Tesla's "semi-autonomous" cars - the vehicle can keep itself in its current lane and maintain speed in traffic via radar, cameras, and sensors, but the driver is still ultimately in control and must prompt lane changes and pay attention even when the autopilot feature is engaged. Roadways around the globe vary wildly in the density of cars using them and the weather conditions, which pose a challenge for the sensors installed on UGVs. Additionally, if one of the driving factors behind the massive investment of UGVs in commercial use is to reduce the number of accidents and save human lives, the reliability of these vehicles has to be high. Programmers must also consider the ethical and legal dilemmas that arise in incidents involving self-governing cars.

At present, the commercial projects closest to implementing "fully autonomous" UGVs are those that are being utilized in other industrial roles. Mining companies are already deploying autonomous haulers, removing human operators from danger. Caterpillar's MineStar program has developed a hauler without a passenger cab or controls and also a procedure for retrofitting older Cat truck models to autonomous technology.

Autonomous technology is also already proving useful in agriculture, given that farming is typically plotted geometrically. Agriculture company Case IH partnered with CNH Industrial to develop a high-efficiency farming concept trailer. The UGV is based on an existing tractor but without a cab. The vehicle was built for a fully interactive interface to allow for remote monitoring of preprogrammed operations and has an onboard system that automatically accounts for implement widths and plots the most efficient paths depending on the terrain, obstructions, and other machines in use in the same field. The remote operator can supervise and adjust pathways via a desktop computer or portable tablet interface, makes this another example of a UGV with 'supervised' autonomy.

Though the implementation of UGVs in the freight shipping industry is slowed by the same issues facing driverless passenger cars, it is closer to being a reality because these vehicles have fewer and simpler duties they are used for. For an industry struggling with labor shortage and demand for shorter delivery times, UGVs are an attractive solution. The United States Postal Service partnered with the University of Michigan to build a self-driving mail truck - the Autonomous Rural Delivery Vehicle. As early as 2025, it is meant to carry a delivery person on close to 30,000 rural routes, where traffic is less congested, and the path for the vehicle is always the same. Grocery chain Kroger worked with Nuro to deliver groceries to customers' homes using self-driving cars. The first test cases used Toyota Priuses outfitted with autonomous driving technology and a safety driver behind the wheel. As of December 2018, Nuro had two of its custom-built autonomous vehicles delivering groceries in Scottsdale, Arizona. Since that time, smaller autonomous vehicles doing delivery runs have become increasingly commonplace.

3.2.2 Military Programs

UGVs developed for military operations are relatively distinct from those developed for commercial use. There is a demonstrated interest by governments and their military groups around the world for autonomous ground vehicles because of their potential to reduce the number of soldiers in dangerous environments.

In 2016, a UGV called Titan was unveiled. Titan is a multi-mission UGV that can be reconfigured to enhance mission effectiveness. It integrates the battlefield-tested robotic systems and controller from QNA and THeMIS UGV platform and modular mission payload developed by Milrem. The high payload, heavyweight vehicle could be used for the delivery of supplies and humanitarian relief to front lines in war zones. It has manned and unmanned modes, where command and control is handled using a robot controller. Other concept-level UGVs proposed for use in the military act as the heads of convoys to collect intelligence and act as a shield for other manned vehicles. There are also various projects funding smaller robotic combat vehicles to work alongside manned assets in armored formations. Oshkosh TerraMax is an example of a larger vehicle that can be used for both recon and freight transport.

DARPA's Grand Challenge was a competition held in 2004 predominantly focusing on how autonomous technologies could be used for military applications, and despite the boundary-pushing sensor technology that emerged from it, armed forces around the world have been slower to adopt fully self-driving vehicles than other private organizations. Many current semi-autonomous vehicles only have basic capabilities, such as following a manned vehicle or being entirely remotely controlled. Even vehicles that have more advanced sensors and decision-making technology are mainly used on teams with other traditional vehicles. While ground forces are keen to emulate the success of aerial drones in combat and reconnaissance missions, the difficulties of programming a UGV to be able to maintain its health and move in the harsh, unstructured environments of the battlefield have proved sizable. In addition to this, governments tend to be uncomfortable with authorizing an autonomous system to fire weapon systems on their own.

3.3 Marine Systems

In the maritime industry, autonomous vessels fall into three categories: Uncrewed Surface Vehicles (USVs), Uncrewed Underwater Vehicles (UUVs), and Gliders. All three operate at sea without an onboard human presence, though some are also exploring the concept of an optionally crewed vessel. The concept of remote-controlled vessels dates to at least 1898, when Nikola Tesla demonstrated the ability to control a small vessel via radio. Autonomous marine systems have been in development since the middle of the twentieth century, with many projects today being similar to the early projects. However, technological advancements have led to an increase in appeal for autonomous marine systems. Of the programs included in this report, some have been in use since the early twenty-first century, some have been delivered in the past few years, and some are still in the development and testing phase. Figure 2 shows a rough timeline of several recent military and commercial surface programs, with their current status as concept, prototype, or production. The increasing interest in this field is clear from the acceleration of programs shown on the timeline.

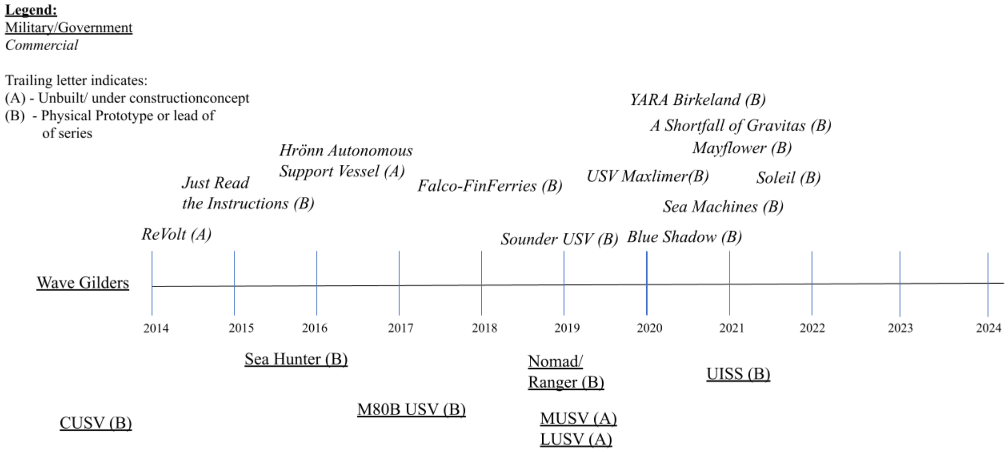


Figure 2: Production Timeline of Recent USVs

3.3.1 Unmanned Surface Vehicles (USVs)

The desire for autonomous surface vessels has grown recently. Removing human lives from possibly hazardous situations is a priority among both the commercial and military sides, so unmanned vessels that can function as effectively as manned vessels are wanted now more than ever before. Additionally, reduced crew costs are a significant driver on the commercial side.

On the commercial side, USVs are wanted that can take the place of ships such as container ships, ferries, and subsea exploration vessels. In the commercial world, moving ships towards partially autonomous operation with extensive shore-based support has been the primary path forward. Additionally, the vessels that are being prioritized tend to either be very close-to-shore, such as harbor ferries or coast-wise shipping, or single-mission, such as underwater survey vessels. Additionally, automating processes on ships already in service to remove work for the crew, or to assist the crew in difficult situations, is also being explored. An example of these efforts includes short-range ferries like Falco from Finferries. In the case of Falco, an in-use car ferry was transformed into an autonomous ferry using technology from Rolls-Royce [20]. It has demonstrated that it can perform fully autonomously and also under remote control, giving several options in how the ship can be operated.

There are also container ships in development which will be both fully autonomous and fully electric. These projects, such as the YARA Birkeland, Asko's freight ferry, and the ReVolt from DNV GL, aim to perform short-range, unmanned trips, alleviating pressure from roadways by moving containers along waterways [26, 12, 52]. While profit margins are smaller with shorter-range ships, having no crew allows for more loading capacity, and a fully electric propulsion drive leads to lower operating and maintenance costs and the potential to be carbon-neutral. So far, all three concepts have originated in Norway, where the combination of topography and a strong desire to be carbon-neutral make this concept especially attractive.

Projects such as Mayflower from PROMARE/IBM and Kongsberg Maritime's Hrönn Autonomous Support Vessel are research and support vessels attempting to remove crew. The Mayflower project is designed for an autonomous ship to self-navigate the Atlantic crossing of its namesake from 400 years ago [7]. Alongside this mission, it will be conducting ocean science and research with other vessels from the University of Plymouth (United Kingdom). While Mayflower's first crossing ended in machinery failure after only a few days, its second journey completed the crossing with two unscheduled stops. The Hrönn Autonomous Support Vessel was a larger, light-service offshore support vessel proposed to support different missions, including remotely operated vehicle (ROV) and UUV operations, cargo transportation to offshore installations, open-water fish farm support, and fire-fighting support. Similar to other USVs, Hrönn was to have the ability to be remotely controlled or fully automated during remotely piloted operations. However, two of three companies involved in Hrönn (Autonomous Ships and Bourbon Offshore) have entered bankruptcy or been dissolved [1], and the project appears to be on indefinite hold.

Developing smaller vessels that primarily do survey and reconnaissance missions has also been an area of active development. The vessel *USV Maxlimer* developed by Sea-Kit is an example of the type of vessel used. Featuring a fairly small length of roughly 12m, and two generators of 18 kW power each [19], the vessel racked up a number of firsts. It won the Shell-sponsored X-prize for ocean exploration by completing a crewless 22-day survey mission [37], and carried cargo across the English Channel [19]. *USV Maxlimer* can deploy and retrieve a towed survey system during these operations. In addition to the *USV Maxlimer*, Kongsberg has a similar vessel class, *Sounder USV* that is being used to support fishing sonar surveys and other survey-related work [34], as can Furgo's *Blue Shadow* class vessel [21]. In China, the People's Liberation Army Navy and Oceanalpha have developed a similar vessel known as M80B [59]. On the large end, Ocean Infinity is reportedly currently constructing 17 survey vessels in the 20m-30m length, capable of performing larger surveys, with aims to grow further and potentially tackle logistics as well as survey [2, 32]. A small option is the USV Bluebottle developed by Ocius [57]. This vessel uses solar sails, passive motion-induced propulsion, and lower-powered sensors to carry out very long-term reconnaissance missions. Existing vessels are between 19 and 22 feet in length and are being used for watching for unreported vessels and potentially submarines [11, 51]. All of these systems operate in human-in-the-loop or human-on-the-loop, with frequent communication between the craft and shore centers. This included CCTV images and other data-rich streams. Most of the larger vessels still have an experienced mariner supervising their operation.

Removing the human from dangerous operations while maintaining direct control over the vessel is another option that is being widely explored. Sea Machines has set up a range of remote-control options for vessels, including advanced sensing to help remote pilots identify other vessels, navigation markings, and similar hazards. Sea machine systems have been reported for use on tugboats, workboats, and cross-sound pallet food vessels between New York and Connecticut [29]. Similarly, towage operator Svitzer is developing a remote-controlled tugboat, building on trials underway since 2017 [50]. Likewise, Robert Allan is developing a line of remote-control fireboats using Sea Machine's systems to allow crew to be removed from the vessel when the vessel will enter dangerous areas while fighting fires [36]. Sea Machines has also demonstrated moving a small workboat, the *Nellie Bly*, through Europe on a 13-day journey with stops[22]. The vessel was remotely controlled from a shore command center, with the AI system providing navigational assistance and collision avoidance. These applications today are largely at the prototype stage.

The U.S. Military is also interested in autonomous surface vessels. Table 2 details several USVs in the United States Military, with range and length included. The U.S. Navy classifies USVs into four categories based on their length [30]. The LUSV is the only ship to fit in the 'Large' or 'Class 4' category, where the ship length is greater than 50 meters. The MUSV, Sea Hunter, and UISS all fit into the 'Medium' or 'Class 3' category, with lengths between 12 and 50 meters. None of the vessels in the table are in the 'Small' or 'Class 2' category, which includes vessels greater than 7 meters long and up to 12 meters long. The GARC Optionally Manned USV is less than 7 meters long, and the ADARO and MUSCL are one and two meters long, respectively, so they fit into the final category: 'Extra Small' or 'Class 1'.

On the military side, autonomous ships are desired for removing humans from the line of danger and reducing daily use cost. Programs such as the Common Unmanned Surface Vessel (CUSV) and Sea Hunter will take on counter-mine and anti-submarine duties, where it is more ethical and practical to send an unmanned vessel into a possibly dangerous situation. Another program, the Large Unmanned Surface Vessel (LUSV), will consist of vessels hundreds of feet long designed to work with other large U.S. Navy ships, potentially carrying significant firepower as part of a distributed concept of operations [30]. The Ghost Fleet Overlord Program has already had multiple vessels transit from the U.S. Gulf Coast through the Panama Canal to the U.S. West Coast [14]. This program allows for the U.S. Navy to perform physical exercises to learn more about and mature the autonomy systems, as well as demonstrate system reliability and enable fleet-operator feedback for autonomous vessels. With each of these programs, being able to consistently field an unmanned vessel without it breaking down would reduce costs associated with having a crew on board the ship.

Table 2: Unmanned Surface Vehicles in the United States Military

Name	**Range(km)**	**Length(m)**
Unmanned Influence Sweep System (UISS)	139	14
LUSV	8334	76
Sea Hunter	18520	40
MUSV	8334	12-50
GARC Optionally Manned	444	≤ 7
ADARO	NA	1
MUSCL	NA	2

3.3.2 Unmanned Underwater Vehicles (UUVs)

When it comes to unmanned vessels under the surface, there are two main categories of vehicles. There are autonomous underwater vehicles (AUVs), where human interaction is very minimal and the vessel acts of its own accord, and there are remotely operated vehicles (ROVs) that have been designed to operate underwater. Gliders are a common subtype of AUV for very long endurance missions. Gliders are detailed in their own section of this report.

- Autonomous Underwater Vehicles (AUVs) - In the realm of autonomous vehicles, AUVs are one of the newer expansion areas. AUVs are designed to provide medium to long-term presence in the ocean without constant human guidance, allowing them to often be smaller and less expensive than other systems. Boeing has developed several AUVs in the past decade. Their Echo Voyager, derived from their previous Echo Ranger and Echo Seeker, is over 50 feet long and will operate at sea for up to months at a time without physical human contact. The US Navy is using the Echo Voyager as the base design for the Orca XLUUV [30]. Similar to the USVs employed, the Orca is designed to be used for mine countermeasures and anti-submarine and anti-surface warfare. While AUVs are of more complicated design than underwater ROVs, being able to travel to any location underwater without being attached to a tether makes them ideal for exploration and collecting intelligence. Similar to the USV, the Navy has developed four classes of AUVs, ranging from XLUUVs though smaller hand-held short-range devices.
- Remotely Operated Vehicles (ROVs) - Although unmanned, ROVs are controlled by a crew, team, or individual aboard a vessel or on land. ROVs came into use in the middle of the twentieth century, and ROV technology developed rapidly soon after. They are used in a variety of underwater missions, but more importantly, they can reach areas not accessible by divers. In these situations, ROVs can carry cameras to photograph and take videos of underwater areas, and they can also be equipped with mechanical arms to move objects around. Though they are essential to the industry today, the limitations that come with being attached to a tether could be offset with improved autonomous technology and autonomous underwater vehicles. For that reason, ROVs are not further discussed here.

Table 3 includes a list of UUVs in the U.S. Military, sorted into their respective categories. They are sized based on diameter and sorted into four categories: extra large, large, medium, and small. Extra large UUVs have a diameter greater than 84 inches, large UUVs have a diameter between 21 and 84 inches, medium UUVs have a diameter between 10 and 21 inches, and small UUVs are less than 10 inches in diameter [30]. The smaller UUVs are very similar to aerospace UAVs in that their missions are normally short enough that maintenance can occur between missions, and mission planning horizons are typically measured in hours, not weeks. However, the Orca XLUUV has a proposed range of 6,500 nm. With a max speed of 8 knots reported, this suggests that missions will certainly exceed 800 hours, placing it into a similar category as long-duration surface vessels.

Table 3: Unmanned Underwater Vehicles in the United States Military

Name	Category
ORCA	Extra Large
Snakehead Ph1 Vehicle	Large
Mk18 Mod 2 Kingfish	Medium
LBS AUV Razorback	Medium
Knifefish	Medium
Mk18 Mod 1 Swordfish	Small
IVER	Small
Sandshark	Small

3.3.3 Gliders and Simpler Craft

Gliders are UUVs that use buoyancy control to propel themselves through the water instead of propellers or thrusters. Most gliders use hydrofoil wings to propel forward while descending to the desired depth and ascending back to the surface. Deployments are long and cover large areas, making gliders ideal for collecting large amounts of ocean environmental data.

The glider programs researched for this project include the Slocum AUV, the AUV Seaglider, and the SeaExplorer [23, 41]. These gliders are all designed to operate in depths of up to 1000 meters, and a Deep Glider variant of the Seaglider achieved a repeated depth of 6000 meters in 2010. Gliders can be deployed for weeks to months at a time and can collect information, including salinity, chlorophyll content, temperature, direction and speed of currents, ocean depth, and more. They surface regularly to report their location and allow scientists to collect the data they have collected. The gliders can run on rechargeable batteries, allowing savings in money and time.

Another glider system that functions differently from the aforementioned gliders is the Wave Glider from Liquid Robotics. The Wave Glider has two parts: a float that stays on the water surface, and a sub, which is connected to the float through an eight-meter-long umbilical cable [53]. It is different from the other gliders in that it remains on the water surface and uses harnessed solar energy and wave energy for increased mobility. Both types of gliders are some of the longest-duration marine autonomous systems in use today. However, their overall mechanical and system complexity is also quite limited.

Finally, several groups have proposed simple surface craft, normally using solar or solar and wind power to conduct long missions. Ocius technology in Australia has developed hybrid sail/solar vessels that also use pitch fins for propulsion that can patrol for long distances conducting basic surveillance tasks [24]. In recent testing, it is reported that four of these vessels have combined to cover 12,000 km in testing. The largest currently in service is believed to be the *Beth* with a length of roughly 7m. Project Mahi launched a solar-powered 4m long boat in 2021 with the goal of crossing the Atlantic Ocean. The vessel left Spain in September 2021, heading westward with the goal of making it to the Caribbean [47]. Contact was lost with the vessel in January 2022, with the vessel showing signs of distress. In March 2022, the vessel was found on a beach in Martinique. However, it is not clear whether it sailed all the way there or drifted from the time contact was lost in January.

3.4 Comparison of Aerial, Ground, and Marine Autonomy

Autonomous technology has been utilized in air, ground, and marine vehicles for nearly a century. Investment in machines with high levels of autonomy continues to grow, both in commercial and military markets. While sensors and the removal of onboard human operators may be common in many existing systems, each area's use of autonomy has evolved differently. In terms of required maintenance, endurance, and desired level of autonomy, the current state and next steps in the evolution of autonomous ships is unique from other systems. Each of these three areas, maintenance, endurance with reliability, and level of autonomy, will be compared in turn.

3.4.1 Maintenance

Maintenance approaches differ across the air, ground, and marine domain. The maintenance strategies of UAVs and UGVs generally can follow their crewed counterparts. Typically, minimal to no maintenance is done during operational missions, and the end of each mission the vehicle's health status can be checked by humans who can also carry out maintenance, even if the vehicle's operations and journey are still fully autonomous. For smaller USV and UUV that are hosted aboard a large platform, a similar approach is also possible. This mimics the situations where helicopters are maintained aboard ships today.

When designing UAVs, reliability, maintainability, and availability are factors that are considered similar to conventional aircraft. Petritoli et al. [35] propose a maintenance approach for UAVs showing this component-focused reliability similarity. Though there are new systems that make the vehicle autonomous, the overall goal is to create an unmanned aircraft that is as reliable as a conventional aircraft. While it is in the air, there is no engineer on board to make repairs, so the vessel must be able to sustain itself until it can land and be fixed. UAV's when in operation, are maintained relatively similarly to crewed aircraft. UAV operators and pilots are based in the United States in Nevada and Tampa Bay, whereas the maintainers are deployed with the aircraft to an air base in the theater of operation. The primary difference in maintenance is the additional upkeep of remote systems, as well as the mission package for the UAV. For the small/portable UAVs such as the Raven the doctrine is to view them as more expendable. The ideal result would have the drone land close by to its operator and to be recovered and stowed. This results in the portable UAV's maintenance schedule occurring either back in the safety of a base or not at all.

Many UGV today are modifications of existing ground vehicles, and their maintenance approach still follows that of the host platform. In August 2017, the U.S. Army carried out a demonstration that featured a robotized Polaris MRZR military all-terrain vehicle with a tethered drone, an automated M113 armored personnel carrier, and a self-driving Humvee with an automated machine gun. While the level of autonomy demonstrated was groundbreaking, the vehicles themselves are built and maintained the same way their manned counterparts are.

The maintenance of larger UUVs and USVs is more specialized because their longer missions may mean fewer opportunities for humans to carry out health checks. Remote operators monitoring system health are entirely reliant on the ship's ability to track its own systems and the performance of its sensors. At the time of this report, the US Navy has highlighted increasing the reliability of hull, mechanical, and electrical systems on-board as one of six enabling capabilities for future USVs [31]. If on-station crews that repair the vessel following a damage event or a malfunction are established, mechanics and technicians will need to be retrained, as an on-board crew would usually be carrying out preventative maintenance or resolving issues as soon as they arise. To date, most vehicles other than gliders have been early prototypes, so established maintenance philosophies do not appear to have emerged. Rødseth and Mo provide a simple single-incident storyboard on how remote maintenance notifications could impact both maintenance and mission planning in the commercial arena [38]. However, consistent frameworks for approaching the maintenance scheduling problem and assessing the impact of machinery condition on ongoing missions do not seem to be well-explored currently. Recent work has begun to explore detailed reliability studies into machinery systems that could form future building blocks of such frameworks [17, 18].

3.4.2 Human-Free Endurance and Reliability

Closely related to the maintenance philosophy is the idea of human-intervention-free endurance for each platform. At present, the majority of the ground and air vehicles operate without human contact for hours to tens of hours (with some smaller UAVs only operable for minutes at a time). As discussed previously, the larger USV and UUV have much longer targeted human-free endurance times. However, at the current time, it is not clear how close the system designs are to achieving these timeframes.

The achievable human-free endurance currently appears to be limited primarily by the complexity of the hull, machinery, and electrical systems. Currently, simple systems like underwater gliders have shown the ability to spend weeks to months at sea. The loss rate for these systems is likely higher than what would be accepted for a larger and more costly system. Looking at the operational experience of 56 gliders between 2008 and 2012, Brito et al. [6] calculate that the probability of a deep-water glider completing a 90-day mission was roughly 0.5, and a shallow-water glider was 0.59. Rudnick et al. [40] had slightly more positive statistics for 297 glider missions from 2004 to 2016, noting that while 28% of missions had some sort of error, only 16% of missions had a critical fault related to the glider's ability to fly. Rudnick et al. also noted by the last three years of operation, glider losses (e.g. the vehicle was never recovered) were one per just over 8 years of operational time. For these deep-water gliders, Rudnick notes that the mode of the mission length is broad, with roughly half the missions lasting between 95 and 135 days. For relatively simple vehicles, the achieved levels of reliability has proven acceptable. However, these loss rates would likely not be tolerable for larger and more expensive assets.

As systems get larger and more complex, in general, the publicly acknowledged human-free endurance lengths have fallen. Additionally, reliability data for such systems is lacking. While seafloor mapping and exploration vessels are beginning to be fielded in large numbers, most of the other larger autonomous vessels are currently prototypes with only a small number in service, limiting the amount of observed reliability data that is available. A table of the publicly documented (articles, press releases, company social media posts) maximum mission length of autonomous vessels is present in Table 4. Many sources of information did not provide complete details on these missions; for example, *Nomad*, and *Ranger* the total length of the mission is known, but how many times humans boarded the vessel or provided maintenance to equipment was not released. Other platforms, such as the Space-X rocket recovery barge *A Shortfall of Gravitas* have had social media claims of being capable of autonomous operation, but details of the missions achieved in this mode (if any) are currently lacking. Others, such as the autonomous vessel *Mayflower*, started on very long voyages, in this case, a trans-Atlantic crossing, only to have an equipment fault cancel the voyage after only a few days. A second crossing was more successful but had an unplanned stop in the Azores for maintenance and eventual landfall in Canada, not the U.S. to shorten the final leg owing to additional faults emerging.

For truly human-free endurance with good reliability, there are few data points that are promising. The Sea-Kit *Maxlimer*, with two 18kW diesel generators, has achieved mission lengths of 22 days without any humans on board. The U.S. Navy Sea Hunter has transited from the U.S. West Coast to Hawaii and back (roughly 10 days of travel time). On the outboard voyage, the vessel was boarded three times, to fix one engine shutdown and two generator issues [45]. On the return voyage, the system completed the 10-day transit without boarding. Likewise, the *Mayflower* platform above had a journey length of approximately 14-16 days on its two legs from the UK to Canada, finishing both with significant faults. This would seem to indicate that 2-3 week voyages are now closely possible. Interestingly, in assessing machinery alarm data for a larger and more complex RoRo vessel, BahooToroody et al. assessed about a two-week period for unattended operation, although this was raised to 13 weeks if remote reconfiguration of the plant was possible [3]. However, these studies do point to a roughly common timeframe for current systems with purely unattended operation. Currently, system health assessment and mission-replanning does not seem to be widely studied in any of these vessels.

3.4.3 Existing Schemes to Rate Autonomous Capabilities

The phrase "autonomous vehicle" is too broad to accurately communicate what level of self-sufficiency a vehicle possesses. As these platforms develop in land, air, and sea roles, various rating schemes have been proposed to classify vehicles based on their autonomous capability. One of the first major efforts was sponsored by NIST [25], termed ALFUS it proposed a three-segment method for classifying the amount of autonomy in a system. The components of ALFUS are shown in Figure 3, encompassing how independent of human oversight the system is, how complicated a mission it can handle, and how complex the external environment is that it must handle. ALFUS was focused primarily on the AGVs for the U.S. Army's failed Future Combat Systems concept. However, the resulting concept is still very valuable. By broadening the autonomy definition beyond just the level of human independence, the ALFUS framework addresses some of the issues highlighted in this report for long-term autonomous missions. ALFUS, like most ground and air autonomy discussions, is silent on the issues of maintenance and logistics, as these items would only appear in the mission complexity subsection.

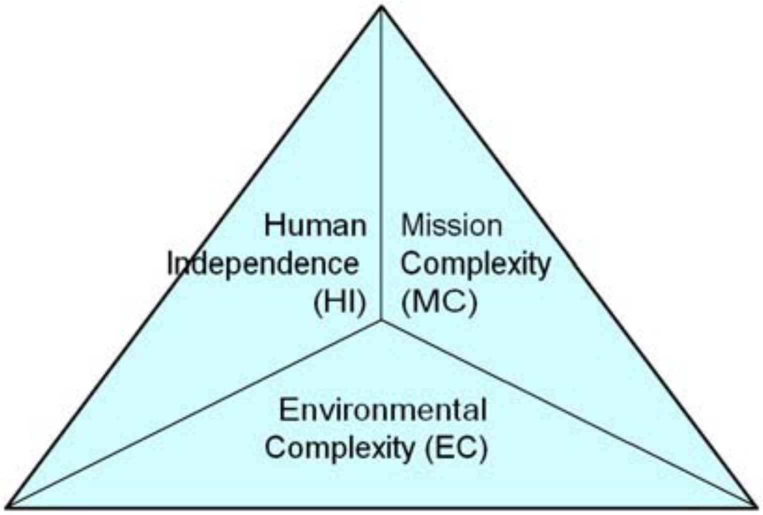
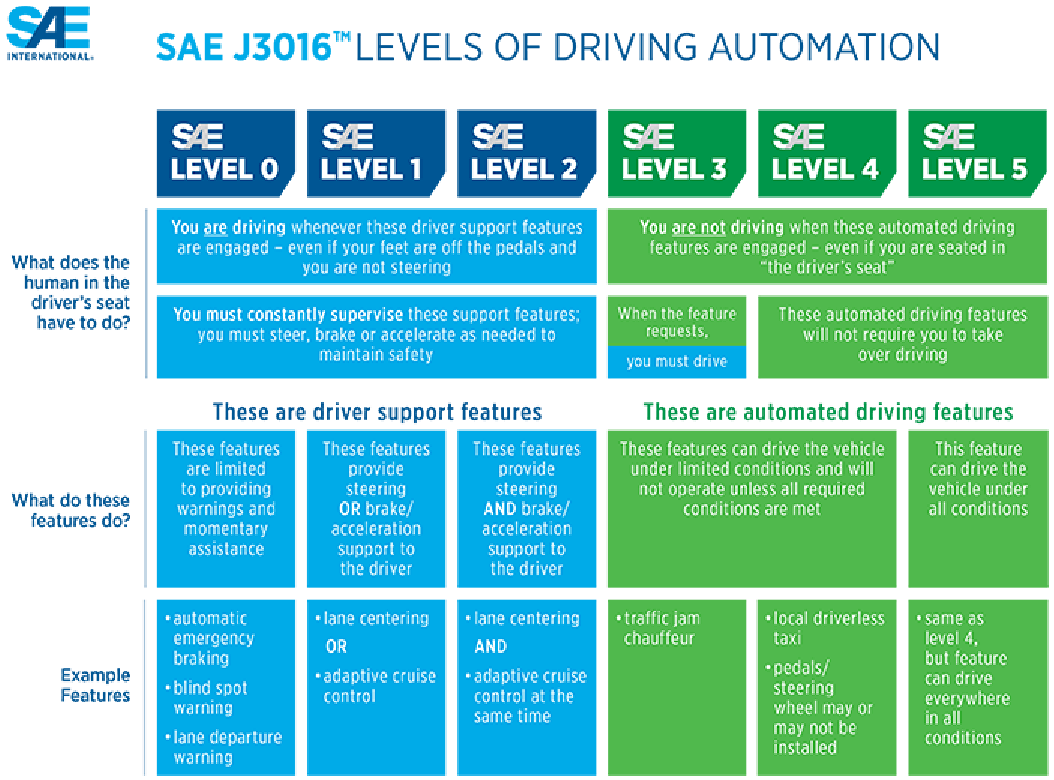


Figure 3: ALFUS Three-Component Autonomy Rating [25]

Since the development of ALFUS, most subsequent rating scales have been simpler, using a single, overall metric for the level of autonomy. For UGVs and land-based automotive vehicles, the globally accepted standard appears is the SAE J3016TM "Levels of Driving Automation" that defines the six levels of driving automation, from no automation to full automation. It was issued, in part, to speed the delivery of an initial regulatory framework and best practices to guide manufacturers and other entities in the safe design, development, testing, and deployment of highly automated vehicles (HAVs). These levels have been adopted by the U.S. Department of Transportation and the document became a global standard adopted by stakeholders in automated vehicle technology. Figure 5 shows the levels are described in a figure from SAE's website in consumer-friendly terms.

For air vehicles, several competing standards have been proposed by industry groups and individual manufacturers. Many of these take their inspiration from SAE J3016TM. Exyn Technologies [15] recently proposed a scale for drones, following closely on the overall concepts of SAE J3016TM, with a breakpoint between operator-enhancing operations and truly autonomous operations between levels three and four on the scale. Interestingly, Exyn notes



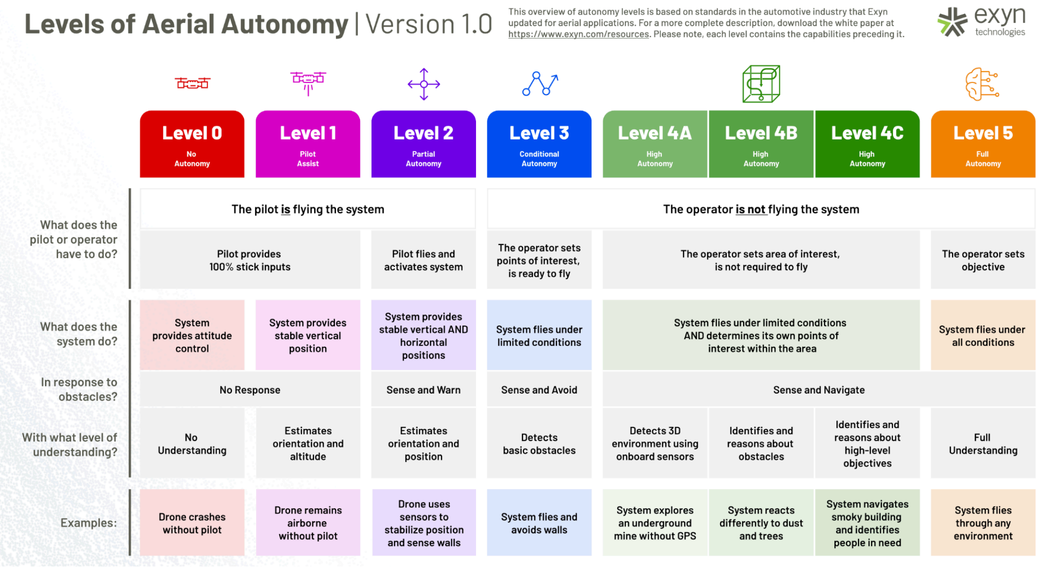
SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/ acceleration support to the driver	These features provide steering AND brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering OR • adaptive cruise control	• lane centering AND • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Figure 4: SAE J3016 Levels of Driving Automation have become the global standard for classing ground based autonomous vehicles. After SAE, `https://www.sae.org/`

that their most advanced drones are now at level 4A (as of 2021), indicating that for short flights, the drones can now operate without any guidance other than a high-level mission plan. However, such drones also do not carry humans, and the consequences of a system failure are often limited to the monetary loss of the drone. Large autonomous aerial platforms do not seem to have a publicly released scale to rate their autonomy, though ratings about these systems' ability to navigate over urban areas and the ability to interface with the broader air traffic control system do provide metrics to rate their capability.

In the maritime industries, there are several schemes for organizing ships by level autonomy that have been developed by classification societies and international bodies. While these depart a bit further from SAE J3016TM in the details of the level, they still feature a single overall categorical scale with supporting sub-system descriptions. One such scale is the "Maritime Autonomous Surface Ships (MASS) UK Code of Practice" developed in the United Kingdom [56]. The scale defines six levels of autonomy of the vessel referring to the levels of control, as listed in Table 5. Similar to the two scales reviewed above, level three in this scale marks a breakpoint between a system where the human will be the party ultimately resolving issues and systems where the autonomy functions play this role. Similar to the ground vehicle and drone scales, there is no consideration of maintenance and logistics in this scale, the focus is on decision-making.



Levels of Aerial Autonomy | Version 1.0

This overview of autonomy levels is based on standards in the automotive industry that Exyn updated for aerial applications. For a more complete description, download the white paper at https://www.exyn.com/resources. Please note, each level contains the capabilities preceding it.

exyn technologies

	Level 0 No Autonomy	Level 1 Pilot Assist	Level 2 Partial Autonomy	Level 3 Conditional Autonomy	Level 4A High Autonomy	Level 4B High Autonomy	Level 4C High Autonomy	Level 5 Full Autonomy
What does the pilot or operator have to do?	The pilot **is** flying the system			The operator **is not** flying the system				
	Pilot provides 100% stick inputs		Pilot flies and activates system	The operator sets points of interest, is ready to fly	The operator sets area of interest, is not required to fly			The operator sets objective
What does the system do?	System provides attitude control	System provides stable vertical position	System provides stable vertical AND horizontal positions	System flies under limited conditions	System flies under limited conditions AND determines its own points of interest within the area			System flies under all conditions
In response to obstacles?	No Response		Sense and Warn	Sense and Avoid	Sense and Navigate			
With what level of understanding?	No Understanding	Estimates orientation and altitude	Estimates orientation and position	Detects basic obstacles	Detects 3D environment using onboard sensors	Identifies and reasons about obstacles	Identifies and reasons about high-level objectives	Full Understanding
Examples:	Drone crashes without pilot	Drone remains airborne without pilot	Drone uses sensors to stabilize position and sense walls	System flies and avoids walls	System explores an underground mine without GPS	System reacts differently to dust and trees	System navigates smoky building and identifies people in need	System flies through any environment

Figure 5: Industry standard for smaller drones proposed by Exyn [15]

Table 4: Voyages and Voyage Durations Reported in Open Media for a Variety of USVs

Ship	**Date**	**Distance** *nm*	**Time** *days*	**Notes**
Sea Hunter	Jan 2019	5000	–	Transit to and from Hawaii, some boardings reported but not clear what was maintained.
Ranger	Nov 2021	4700	74	Ghost Fleet vessel, crewed but 97% transit autonomous with remote shore control.
Nomad	June 2021	4421	–	Ghost Fleet vessel, crewed but 98% transit autonomous with remote shore control.
Mayflower	June 2021	–	3, 16	Planned trans-Atlantic crossing, 1st failed owing to fault, second broken into roughly 2 2-week legs
Sea Machines	Oct 2021	1027	13	Had stops, was in remote control mode
USV Maxlimer	Aug 2020	–	22	Remote control, but no stops or human intervention
Benjamin Franklin	Feb 2013	7939	365+	Wave glider from Liquid Robotics
Soleil	Jan 2022	130	0.3	222m RoPax ferry, the largest USV known to date
A Shortfall of Gravitas	July 2021	100?	–	Space-X drone recovery ship, reportedly able to operate without tugs, unclear if actually has
Bluebottle	Late 2021	>1000	–	Four slightly different vessels all completed long transits. Most under 10m long
Mahi 2	Sept 2021	3455	119	Contact lost at distance/time given. Vessel later found on beach completing Atlantic crossing, not clear if it drifted or sailed the last quarter of the journey.

Table 5: Maritime Autonomous Surface Ships (MASS) Level of Control Definitions [56]

Level	**Name**	**Description**
0	Manned	Vessel/craft is controlled by operators aboard
1	Operated	Under Operated control all cognitive functionality is controlled by the human operator. The operator has direct contact with the unmanned vessel over e.g., continuous radio (R/C) and/or cable (e.g., tethered Unmanned Underwater Vehicles—UUVs and Remotely Operated Vehicles—ROVs. The operator makes all decisions, directs and controls all vehicle and mission functions.
2	Directed	Under Directed control, some degree of reasoning and ability to respond is implemented into the Unmanned Vessel. It may sense the environment, report its state, and suggest one or several actions. It may also suggest possible actions to the operator, e.g., prompting the operator for information or decisions. However, the authority to make decisions is with the operator. The unmanned vessel will act only if commanded and/or permitted to do so.
3	Delegated	The unmanned vessel is now authorized to execute some functions. It may sense its environment, report its state and define actions, and report its intention. The operator has the option to object to (veto) intentions declared by the unmanned vessel during a certain time, after which the initiative emanates from the unmanned vessel and decision-making is shared between the operator and the Unmanned Vessel.
4	Monitored	The unmanned vessel will sense its environment and report its state. The unmanned vessel defines actions, decides, acts and reports its action. The operator may monitor the events.
5	Autonomous	The unmanned vessel will sense its environment, define possible actions, decide and act. The unmanned vessel is afforded a maximum degree of independence and self-determination within the context of the system capabilities and limitations. Autonomous functions are invoked by the on-board systems at occasions

In 2019, Lloyd's Register revised their procedures and published them under "ShipRight Design and Construction: Digital Ships Procedure for assignment of digital descriptive notes for autonomous and remote access ships". There are seven levels identified, with the highest and lowest almost identical with the MASS definitions, and variance in the intermediate levels. The IMO took a different, more abbreviated approach to classifying autonomous systems in 2018 in the frame of a regulatory scoping exercise. These two classifications are shown in Table 6 and Table 7, respectively.

Table 6: Levels of Autonomy defined by Lloyd's Register 2019

Level	**Name**	**Description**
AL 0	Manual	No Autonomous function. All action and decision-making performed manually
AL 1	On-Board Decision Support	All actions taken by a human Operator, but decision support tool can present options or otherwise influence the actions chosen. Data is provided by systems on board.
AL 2	On and Off-Board Decision Support	All actions taken by human Operator, but decision support tool can present options or otherwise influence the actions chosen. Data may be provided by systems on or off-board.
AL 3	'Active' Human in the Loop	Decisions and actions are performed with human supervision. Data may be provided by systems on or off-board.
AL 4	Human on the loop, Operator/Supervisory	Decisions and actions are performed autonomously with human supervision. High-impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride.
AL 5	Fully Autonomous	Rarely Supervised operation where decisions are entirely made and actioned by the system.
AL 6	Fully Autonomous	Unsupervised operation where decisions are entirely made and actioned by the system during the mission.

Table 7: MASS Levels of Control according to the IMO for regulatory scoping exercise.

Level	**Description**
1	Ships with automated processes and decision support.
2	Remotely controlled ships with seafarers on board.
3	Remotely controlled ships without seafarers on board.
4	Fully autonomous ships.

In the Class Guidance for Autonomous and Remotely Operated Ships published in 2018, the DNV takes a similar approach. The levels are demarcated by letters rather than in a chronological numerical spread, shown in Table 8. In general, the methods of classification vary how many intermediate definitions of "partially autonomous" there are, and the characteristic of the system that is focused on to separate those levels. The main focus is on how humans are involved in the decision-making during a mission deployment.

Table 8: MASS Levels of Control according to the Class Guidance for Autonomous and remotely operated ships by DNV GL.

Level	Description
M	Manually operated function.
DS	System decision supported function.
DSE	System decision supported function with conditional system execution capabilities (human in the loop, required acknowledgement by human before execution).
SC	Self-controlled function (the system will execute the operation, but the human is able to override the action. Sometimes referred to as 'human on the loop'
A	Autonomous function (the system will execute the function, normally without the possibility for a human to intervene on the functional level

These IMO and classification society guidelines deviate a bit from the overall structure of SAE J3016TM, focusing more on who has the ultimate decision-making capability in most situations. This may reflect the slower pace of decision-making for vessel navigation compared to road driving, which allows more supervisory action. It may also reflect the presence of a professional crew on board, or in a remote shore control station, that is paid to monitor automated systems. However, similar to air and ground vehicles, concerns over longer-term decision-making, mission re-planning, logistics, or assessing the health of the vehicle do not appear in these frameworks. The lack of these topics may also be a reflection of the types of maritime autonomous vessels proposed so far by the commercial world - mainly shore-controlled automation of smaller coastwise vessels that can rely on shore support for maintenance.

Notably, none of these frameworks follow the lead of the ALFUS framework in looking at a multidimensional understanding of the level of autonomy. Each reviewed framework uses a fixed, ordinal scale in a single dimension, most commonly the role of the human in decision-making. While compact and easy to understand (and compare systems), the single-metric approach seems limited when addressing the concerns for long-term autonomy covered in the introduction of this report. For this reason, a new autonomy scale will be proposed in the following section.

3.4.4 Proposed New Scheme for Autonomy and Endurance for Long-Duration Maritime Platforms

Maritime platforms are unique in that their long-duration missions can introduce new requirements for autonomous systems, including assessing system health, re-planning missions based on system status, considering repair logistics, and related longer-term planning tasks. This variety of tasks makes it difficult to assign a single ordinal metric that can capture the full complexity of these systems. Following the lead of the ALFUS rating system, a three-component rating system is proposed to compare different vessels or proposals for autonomous systems. The selected three components are:

- **Decision-making:** Similar to the existing scales discussed above, it is important to capture the role of the system vs. the human operator in decision-making. The decision-making scale will be expanded to include longer-term planning tasks as well as the decision/supervision difference seen in existing standards.
- **Endurance time:** Vessels can be ranked on their proposed endurance time. Many early concepts in the commercial world are addressing the long-term decision-making and logistics challenges by avoiding them altogether and focusing on short-range vessels. For such vessels, like current air and ground autonomous systems, maintenance and logistics can take place after the mission is completed.
- **System complexity:** Vessels can also be ranked based on the complexity of systems on-board. For vessels where long endurance is needed, one option is to minimize the complexity of the systems to increase reliability. Gilders are an excellent example of this, they use relatively limited and simple components (compared to internal-combustion engines) to achieve long mission lengths. Of course, such simple systems are more limited in the missions they can accomplish.

For each of these scales, a number of different levels divisions were created, based both on what is currently in service, as well as what is desired for the future. These are shown in Table 9, Table 10, and Table 11. This three-component system can be combined into a single rating string for each vessel, for example, a vessel rated *4C2* would be a survey-type vessel, remote-controlled and capable of deployments up to one week in length. This rating scheme allows both the complexity of the vessel as well as the time horizon of its operation to be captured in the rating scheme. This allows greater granularity when comparing different vessels - for example, a gilder is likely to be able to deploy far longer than a complex vessel with several engines and complex mission payloads. However, the glider may not have more advanced autonomy features overall, and its ability to re-plan missions in face of hardware faults or unexpected environmental conditions may be limited.

Based on this rating scale, a combined bubble plot of the existing marine platforms reviewed earlier in this chapter was made. The analysis was based on the publicly documented completed voyages in early 2022. As this field is moving rapidly, the plot may not represent the full development potential of each vessel in the future. In this approach, the decision-making and endurance scales were used as the horizontal and vertical axes, and the complexity level was plotted as differently sized markers. This plot is shown in Figure 6. The plot shows a clear relationship between the three factors, the vessels with the highest endurance and most independent decision-making are currently the simplest vessels. This is logical, as both the number of systems that must be automated and the consequence of losing the vessels are reduced as the vessel complexity goes down. Additionally, vessels such as *Mahi 2* did not appear to be under control for the entirety of their voyage. *Ranger* and *Nomad* are notable exceptions, having completely relatively long transits while being significantly complex vessels. Their rating is a bit subjective - it is not clear how frequently in time humans intervened on these vessels. Public sources only state that the vast majority (more than 95%) of the mission was completed in autonomous mode.

Table 9: Proposed decision-making levels

Level	Description
0	Human on-board and in control at all times with no assisted decision-making
1	Remotely operated, but all decisions made by remote human.
2	Human on-board and in control at all times, but system may make suggestions that impact decision-making
3	Human on-board and still main controller of system. The system can prompt adjustments on its own without human approval.
4	Remotely operated with human on-board for maintenance or navigation intervention, but not normally in the decision loop.
5	Remotely operated with no humans on-board. Can do basic collision avoidance and navigation, but normally fully monitored remotely by licensed ships crews. Needs shore support for major system re-configuration, alarms, or mission changes.
6	Vehicle operates autonomously normally. A human may or may not be aboard. The system may defer to local or remote human for navigation intervention or re-configuration of systems, but humans not normally continuously monitoring or directly in the decision loop.
7	Fully autonomous without remote control option but executes a fixed mission with little or no ability to re-configure systems if a fault appears other than asking shore control for help or ending mission.
8	Fully autonomous with intelligent decision-making to re-configure systems, address weather, or adjust mission parameters over a short time horizon (hours to single day)
9	Fully autonomous with intelligent decision-making to re-configure systems or adjust mission parameters based on forecast future platform health, weather, logistical support based on mission objectives.

Table 10: Proposed platform endurance times

Level	Description
A	Missions lasting less than one hour before access to off-board assistance and repair.
B	Missions lasting less than one day before access to off-board assistance and repair.
C	Missions lasting less than 7 days before access to off-board assistance and repair.
D	Missions lasting less than 14 days before access to off-board assistance and repair.
E	Missions lasting less than 30 days before access to off-board assistance and repair.
F	Missions lasting less than 60 days before access to off-board assistance and repair.
G	Missions lasting less than 120 days before access to off-board assistance and repair.
H	Missions last more than 120 days before access to off-board assistance and repair.

Based on this plot, it is clear that high-endurance complex vessels are yet to be realized in the USV space. Vessels without human crews, but with internal-combustion engines, have not been demonstrated beyond endurance level “E” at the current time. The lack of more advanced vessels indicates that the maintenance and logistical challenges of more complex machinery installations are likely a factor in the level of autonomy that can be achieved.

Table 11: Proposed platform complexity levels

Level	Description
1	Small battery, solar, and wind-powered vessels without internal combustion engines (e.g. gliders)
2	Simple vessels with internal combustion engines, fuel systems, cooling systems, navigation systems, and one or two mission systems (e.g. <24m long survey vessels)
3	Complex vessels with internal combustion engines, multiple support systems, and more than two mission systems (e.g. sensors, weapons, cargo systems)

Additionally, the probability of mission success once on deployment cannot be rigorously determined at this stage, though both *Mayflower* and *Mahi 2* did not seem to operate as intended. Furthermore, no vessels are yet operating at levels 8 or 9 on the decision-making scale, indicating that the majority of long-term mission planning decisions are still being referred back to human decision-makers. The three-factor autonomy ranking system proposed here is useful for exploring the interaction between complexity, decision-making, and endurance. Without the ability to dis-aggregate the performance into these components, the impact of complexity on endurance would not be clear. For this reason, it has a significant advantage over single-attribute ranking systems that have been used to date.

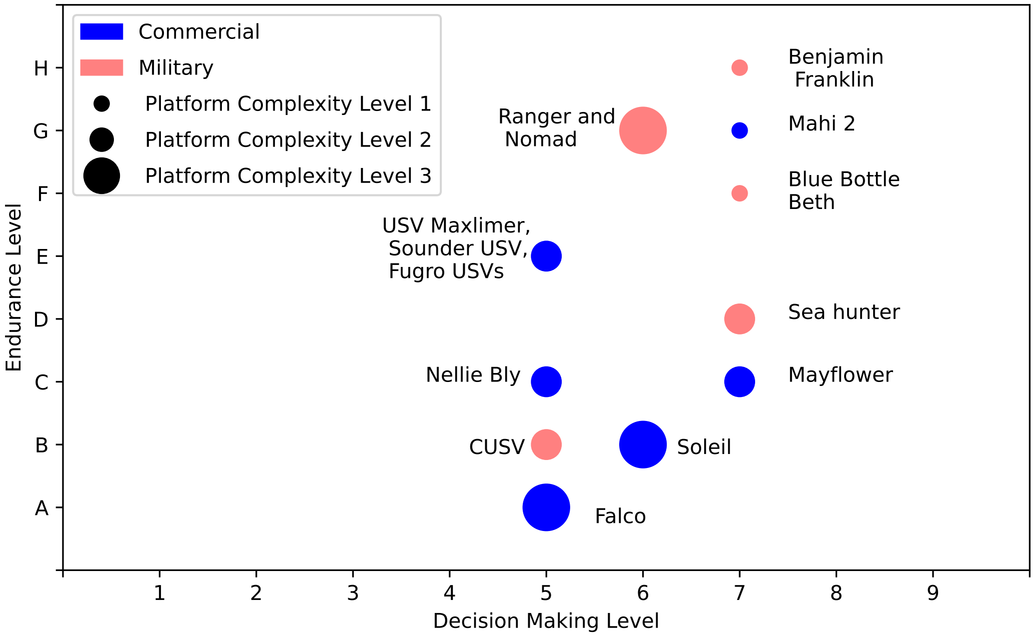


Figure 6: Current USV Systems on Proposed U of M Autonomy Scale

3.5 Summary and Shortcomings

From a review of the current work in autonomous systems, it is clear that this is a vibrant and growing area of engineering. Across air, land, and sea platforms, numerous approaches to autonomy have been proposed or are in production. However, it is clear that the sea domain has unique requirements compared to the systems proposed for air and ground. Air and ground systems remove the driver or pilot from the vehicle but normally continue to interface with the same maintenance and logistical approaches used by crewed platforms in these domains. Missions tend to be shorter in air and ground domains, rarely lasting more than a day before intervention from supporting humans is possible. Once beyond the smaller sizes of AUVs, the marine domain in marked by far longer deployments. This means that the vehicles themselves will have to handle some system health assessments and re-configuration, and maintenance may need to shift from an ongoing model performed daily by the crew to a periodic intervention model.

Assessing the current state of marine autonomy indicates that the challenges with these longer-term missions are not yet fully addressed by the technology available today. Most existing long-duration marine vessels today tend to be smaller without the use of internal combustion engines, such as gliders. Additionally, few vessels have demonstrated the ability to handle extensive system health assessment, system reconfiguration, or mission re-planning autonomously. Many existing concepts rely on a shore-based controller for such decision-making. To better capture the state of technology in the field, a new three-component ranking system inspired by the ALFUS ranking system was created. This system can highlight the shortcomings mentioned above when plotting existing vessel's completed voyages. Understanding how to assess the health of vessels with complicated HM&E systems and how the health of such systems impact mission planning is key to achieving longer-duration autonomous systems in the marine environment. These shortcomings fit under the risk of mission failure, sustainment failure, and flexibility failures highlighted in the introduction, and the literature indicates that long-range missions and sustainment are not solved today.

4 Crew and Shore Support Interviews

The review of existing systems in the previous section showed that for complex vessels, autonomous medium and long-term planning is not yet established. Developing such systems requires an understanding of what tasks are involved in planning tasks of this duration. Existing literature sources for ship's officers are primarily focused on the human aspects of leadership of the crew. At the other end of the spectrum, tactics and logistics for wartime situations also appeared in several publications. However, very few sources talk about how to assess and plan operations in terms of weather, ship health, and other factors that would be assumed to influence medium-to-long-term decision-making. Furthermore, the review of existing systems presented in the preceding section revealed that this aspect of autonomy is largely unexplored to date, with no systems scoring eight or more on the new composite autonomy scale. Thus, a better understanding of these medium- to long-term planning tasks is necessary, starting with identifying what these tasks are. To better understand what these tasks are and how these tasks are carried out today, having conversations with ship's crews was seen as a necessary step in understanding the state-of-the-art.

4.1 Interview Process

As part of the original proposal, a series of workshops were planned with naval personnel to explore these roles and confirm the understanding of the current state of autonomy. However, with the outbreak of COVID-19, holding such workshops in 2020 was not possible. Instead, a series of distance interviews were conducted with a number of members of the marine community. Switching from workshops to individual interviews reclassified the work as human subject interaction. This switch necessitated training the research team in human subject protection standards and prevented active-duty military or others employed by the Department of Defense from taking part in the interviews, owing to the type of approval that could be received in a timely fashion.

An interview protocol and data protection approach were developed and approved by the Office of Naval Research as well as the University of Michigan. Each researcher involved in the process successfully completed the University of Michigan PEERRS: Human Subjects Research Protections training before the beginning of the interview portion of the work.

4.1.1 Interview Protocol and Setup

Given the exploratory nature of the investigation, interviews were conducted in a semi-structured style. A rough list of topics to discuss was developed, but the primary objective of each interview was to allow the subject to talk about their personal view of medium to long-term planning tasks, so specific tasks and approaches could be enumerated. Before each interview, each participant was read a consenting form. This form reintroduced to the participant(s) the purpose of the research study and that their names would not be included in the report; only their branch of service, type of role, and type of vessel their experience related to would be included. Participants were not compensated for the interview work. The form is included in Appendix A.

4.1.2 Participants

As a first step, candidates were drawn from a group of retired military and active commercial sailors. Current military crews were ineligible to be interviewed directly. Participants held a variety of roles in their careers. Across a total of eight interviewees, the following roles were covered, with most people having served in three or four of these roles, and several having worked on both military and civilian ships.

- Operations officer and planner
- Main propulsion officer
- Commanding officer
- Executive officer
- Chief engineer
- Pilot
- Captain
- Port engineer and Supervising port engineer

4.1.3 Data Processing

Multiple team members participated in each interview by taking notes and asking questions, except for one interview where only one member was able to attend. After an interview was completed, each individual team member would review their notes and document the different themes they found in a spreadsheet dedicated to the specific interview. Then, the team met to discuss and review the interview and combine the individual themes into an 'integrated thoughts' list. This list included any themes from an interview that were interesting or important and also tracked how many team members wrote down the same theme in their description of the interview. The themes focused on either specific planning tasks, or approaches to planning tasks. No formal inter-rater reliability metrics were used, as the process was done at a higher level than typical coding of human subject interactions, and the researcher's notes, not a transcript, were used as the basis for comparison. Most interviews lasted 30-45 minutes, and produced between 10 and 23 different themes.

The goal of the interview process was both to identify specific medium and long-term planning tasks, as well as approaches taken to these tasks. To sort the interview data, a bottom-up affinity diagram approach was taken. First, the integrated theme list of each interview was compared to the theme lists from other interviews. Closely related themes were merged at this stage, tracking how many distinct interviews the theme appeared in. The resulting themes were then placed on a virtual whiteboard and examined for category groupings. A series of different categories emerged from this work, with a few themes spanning between categories. Ten total categories emerged from this work, including four that were more closely related to machinery systems, so a super-category for machinery systems was created. These categories are colored in blue in the diagrams below. The specific themes developed within each category are listed in yellow boxes, with a bold number after the descriptive level indicating how many interviews mentioned this theme.

4.2 Results

4.2.1 Overall Results

The results are presented hierarchically in this section, starting with the upper level of the affinity diagram shown in Figure 7. This figure shows the ten top-level categories that appeared in the interviews. By far, the most discussed aspect of mid to long-term planning and platform health was the machinery and electrical systems on the vessel. Four topics dealt with this in particular, including concerns for underway assessment of health, interaction with shore establishments, how monitoring is conducted, and considerations from the initial system design that impact operational decision-making. Six additional topics came up. Mission planning was the most extensively discussed topic of these six, which makes sense given the centrality of planning to the interview. However, this topic revealed a great diversity in planning approaches, and it was clear that there is not a standardized method to conduct mission planning on crewed vessels today. The interaction with weather systems and the shore support to the vessel were also commonly discussed topics. While specific views on autonomy were not sought out, again, given the focus of the interview, most mariners had specific concerns around autonomy. Closely related to both autonomy and shore support were data and communications concerns. Hull structure was frequently discussed but appeared to be a minor concern for the operational crews. Each of these upper-level groupings will be further expanded upon and discussed in the following subsections. Where a theme or concept would fit in more than one category, the concept was duplicated in each category that it could fit in.

4.2.2 Mechanical and Electrical Systems: Underway

One of the major talking points across the interviews was the maintenance and repair of mechanical and electrical systems. Figure 8 shows ten themes that emerged when discussing such activities while the vessel was underway. Four of these topics related to discussing preventive maintenance systems (PMS) on the vessel, with five of the eight interviews discussing daily work being governed by the PMS. T-PERP was a calendar-type PMS that was also discussed extensively. The remaining themes largely addressed unexpected repairs, stressing the need to coordinate logistics around such repairs, their frequency, and how quickly responses are made to such situations. Two interviewees made the point that for planning, the vessel is normally assumed to be fully operational with an active PMS system, and handling

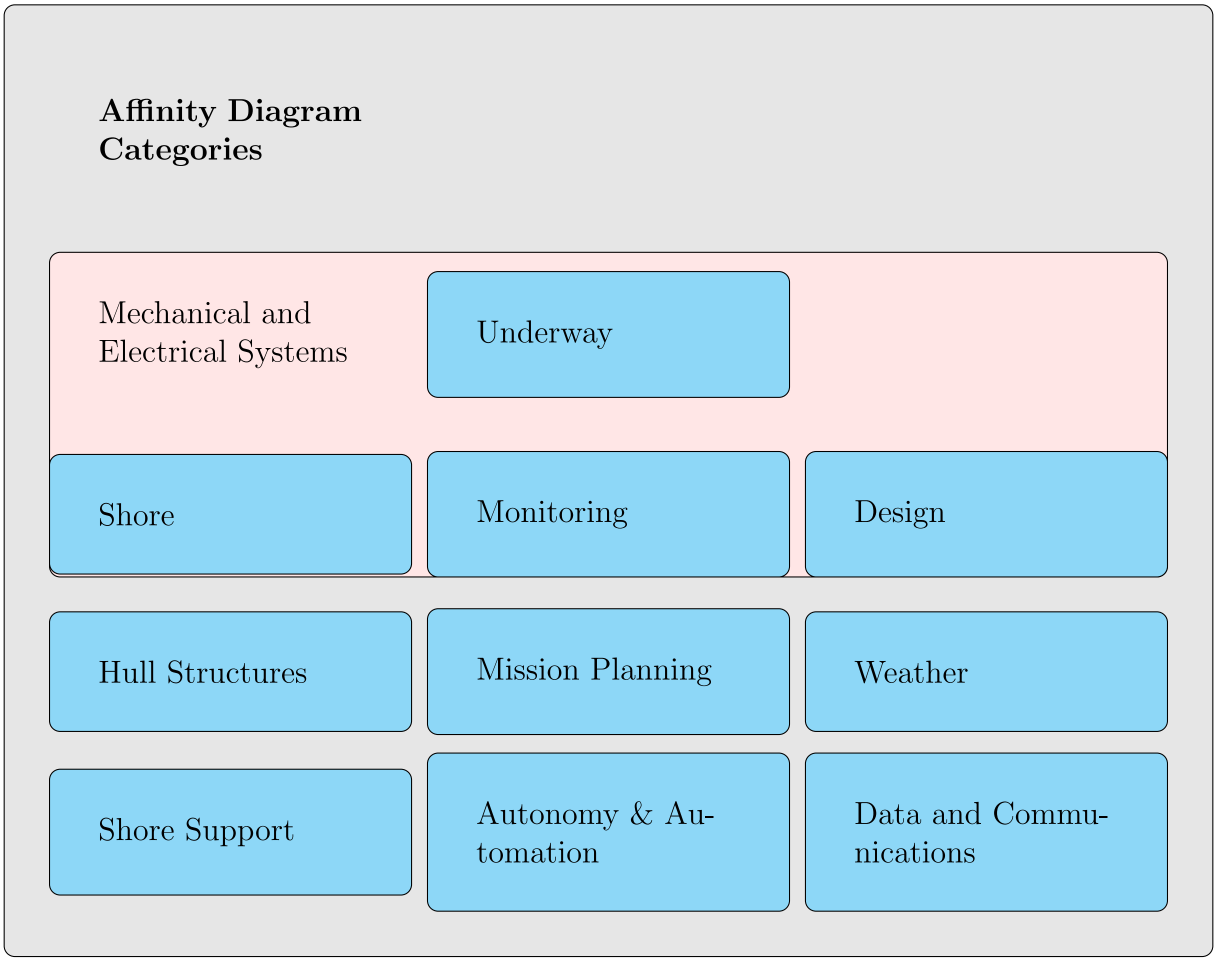


Figure 7: High-Level Categories from Mariner Interviews

a major failure would be a one-off situation requiring on-the-fly adjustment.

Using the notes related to these themes, it was clear that while underway, a vessel's crew is constantly assessing the current state and capabilities of the vessel itself as well as its machinery systems. The PMS was the focus of this work almost exclusively. It was clear that the PMS contained formal procedures, which documented which components needed attention daily, and also formally documented the maintenance actions for others both afloat and ashore. Almost every vessel discussed had some version of this system active, though the names and level of complexity differed. Notably, while the PMS served as the official record of what occurred, informal communication among the crew and between the crew and the captain was the dominant method of communicating and integrating this information aboard. There was little formalism expressed in how the captain or senior officers would integrate this information to form a health assessment for the vessel, it appeared to be done via conversation with the chief engineer, crew members, the shore establishment, and experience. Interview subjects mentioned how vessel operations such as preventative maintenance and repair work have developed from different codes and regulations and that the level of detail involved in preventative maintenance changes with the type of vessel.

While most regular maintenance is completed while underway, the criticality of specific failures can create priority changes. One other point of notice is that the vessel is assumed to be fully operational while underway, and if a major repair that is not planned or anticipated in the PMS system is needed, a one-off repair is set up at a future date. This also involved extensive preparation work with the shore establishment to ensure the correct facilities and parts would be available to complete the repair. Here, different vessel types again had different approaches. Ships with significant planned future activities (e.g. aircraft carriers, commercial ships with time-critical contracts) tended to have more people involved in such contingency planning. Smaller vessels tended to handle these situations as they arose and might be swapped out with a similar vessel to allow downtime for a major repair.

Looking at the implications of this set of themes for medium and long-term planning for autonomous vessels raises several areas of potential concern. Foremost, it was clear that assessing the health of the machinery systems is an intensely human endeavor today. Most of the actions required in the PMS were carried out by humans. Furthermore, the PMS itself did not directly yield a "state of health" for the vessel - the experience in carrying out the PMS activities was communicated through a chain of informal and casual conversations to the vessel's leadership, who then formed their own opinion and contingency plans. This process appeared to differ on different vessels and was more extensive on larger ships that were less replaceable for the company's or Navy's missions.

The maintenance and repair of mechanical and electrical systems while underway is a unique concept for autonomous vessels. On manned vessels, the crew is regularly looking at machinery to ensure they remain functional and safe. It was clear from the interviews that this is a daily task with significant work content. Sensors can gauge and report the current health of machinery, but they cannot perform repairs. If most regular maintenance is currently performed while underway, a major question is how can the same be completed on unmanned vessels. If a small issue leads to something larger and a major system breaks down, an autonomous vessel might not be able to complete its mission. Another action currently performed on manned vessels is setting up repairs. Typically, the process involves a back and forth conversation between a vessel operator and someone shoreside. Autonomous vessels will need some form of system that automatically reports parts or repairs that are needed, or the logistics chain will need to be prepared for a wider variety of repairs when the vessel pulls into port.

4.2.3 Mechanical and Electrical Systems: Shore

Shoreside support was also discussed in caring for the mechanical and electrical systems onboard a vessel. Figure 9 shows a much smaller affinity diagram that came out of this area of discussion. The primary discussion for shore support revolved around difficulties for large vessels needing to make unplanned stops for parts or repairs. Two interviewees talked about the need for coordination of such activities, focusing on surveying vessels before arriving at the repair facility to completely understand that repair, and the need for frequent communication with the shore establishment to ensure the correct parts and technicians are available.

The implications of the shore support affinity diagram for autonomous systems are very similar to those discussed previously in the underway diagram. Many operations, especially commercial, have extensive logistics infrastructures and tracking to support their operations. Shore support for autonomous vessels may look different than for manned vessels. More personnel may be needed shore-side for autonomous vessels to understand better what data is being reported, especially before extensive operational experience is collected. Shore-side support might receive information on what is broken or needs to be replaced, but the severity of the issue may not always be reported to the fullest by an autonomous vessel. Thus, some increased flexibility in the supporting logistics may be required to ensure the correct spares are on-hand.

4.2.4 Mechanical and Electrical Systems: Monitoring

The monitoring of the mechanical and electrical systems was also a topic of significant discussion, with eight themes emerging in this area and shown in Figure 10. There were two major groupings of themes in this area. The first was around the use of checklists and demonstrations to validate equipment status. It was clear that in addition to activities and conversations around the PMS, crews spent a fair amount of time using checklists and demonstrations to ensure that the equipment on the vessel would operate as needed. Daily checks are often performed and logged in the days leading up to departure to validate system conditions and create an auditable trail of capability before the vessel is underway. After yard periods, vessels often used demonstration and trialing of different load and power conditions to validate their condition. One particular example that stood out was dynamic positioning systems, where various failure modes would be simulated to ensure the vessel was capable of responding to a fault if one developed during a mission.

The second grouping of themes indicated a degree of tension around electronic monitoring systems. Six themes addressed the pros and cons of such systems. While the information gathered was sometimes seen as useful and potentially allowing failures not predicted by PMS to be caught, the systems themselves were often high-maintenance. Additionally, some crew members felt that the data collected was not useful. Several times, crew members noted cases where an engineer onboard sensed an issue before the monitoring system. This scenario is more likely to happen with mechanical systems, as the crews believe electrical monitoring sensors are very effective. Interviewees gave differing percentages of failures that are caught by humans before the monitoring system identifies them. Figures of 10% and 25% were given, as well as a comment that the majority of failures are caught via monitoring, but a significant minority are sensed by the crew - often from feeling something off in vibrations or seeing a fluid leak. One interviewee made the point that sometimes adding redundancy in case of failure may be preferable to adding additional monitoring. This was also something that varied with vessel age, with the older vessels having much more limited monitoring systems and more modern vessels often collecting far more signals and constantly linking them back to shore.

The monitoring affinity diagram introduces two additional challenges for autonomous systems. First, demonstrations are extensively used alongside the PMS to determine the current state of health of the vessel's machinery and ensure it is ready for deployment. Such a capability would need to be built into an autonomous vessel or another health assessment approach developed. Secondly, modern machinery and systems have improved self-monitoring systems, which will be vital for autonomous vessels. Many times on crewed ships it is cheaper to carry more spares than try to monitor everything, but if there is nobody on board, would more monitoring systems be more optimal than carrying spares even if cost is driven up? Such failures could also be handled by increased redundancy, presenting a tradeoff of approaches - how should monitoring and redundancy be allocated during the design phase?

4.2.5 Mechanical and Electrical Systems: Design

The final area of commentary on mechanical and electrical systems was the influence of the ship design on these systems. Here, most of the themes that emerged were one-off, and they are shown in Figure 11. Some of these are as expected, focusing on accessibility for maintenance. For example, newer ships are designed to be more accessible on the inside, maintenance was not always considered in the design, and older ships are more often forced to return to port or drydock for repairs and modifications than newer vessels. Designing for redundancy is important as well, and more unique ships featured a higher focus on redundancy than other vessels. The level of acceptable risk also changes with vessel type and is an important parameter to set during design. Communications and navigation systems are generally fail-safe, but if they fail then oftentimes, the crew cannot fix these items themselves, especially in commercial service. In this case, a technical support team is required to board the vessel to fix the issue. Different machines onboard have different levels of importance in terms of failure. Items such as engines and generators are more likely to have longer discussions about repairing or replacing, whereas pumps or valves can often be repaired onboard while underway.

While system features and placement are always important to think about in designing a vessel, they are still important in autonomous vessels. It might be easier to place something in a tight spot when there is nobody onboard, but more than likely someone will still have to be able to access that machinery at some point, even if pierside. Furthermore, if a part or system fails on an autonomous vessel while underway, the best option might not always be to wait until pierside to carry out the replacement. If the repair is simple enough to be done at sea, then having the space to safely and effective maneuver within the vessel is extremely important. Risk acceptance and risk level is another important parameter for autonomous vessels. In some cases, it may be possible to explicitly take higher risks than on crewed vessels, especially if the cost or weight savings is significant. However, not all risk metrics in conventional design regulations are explicit, so establishing a variable risk baseline may require more exploration.

4.2.6 Hull Structures

When asking about the current state and capabilities of the vessel, the health of the vessel's hull was a question posed to the participants. Hull structural ultimate strength, extreme load prediction, hull degradation through corrosion and fatigue are all common engineering concerns on crewed vessels. However, these concerns did not seem to impact underway decision-making. The most common answer was that while underway, the structural health of the vessel is not a main concern and is something better dealt with in port or dry docks. Repainting and coating are important to ensure that corrosion is controlled and limited was something the crew did focus on.

Given that there are many more vital issues while underway than health of the hull, it is understandable that structural health is not a constant concern. For USVs, it is not clear if a similar approach would work. While painting and corrosion control can be moved to pier side work, this further complicates access and maintenance in a limited period of time. USVs are mostly smaller today, and depending on their speed profile, they may have to consider structural strength as part of their mission plans. Higher-speed vessels with structural loading limitations have been damaged in recent Navy experience, including incidents aboard *Spearhead*-class EPFs, 01 level structural fatigue cracking in the trimaran LCS, and failures on the experimental HSV-1. How such failures would be sensed and operations reconfigured on a crewless vessel is not clear.

4.2.7 Mission Planning

Not unexpectedly, given the topic of the interviews, mission planning featured extensively in all the conversations. This lead to a situation where there were a number of planning topics that did not fit well under any of the other affinity diagrams; these topics were gathered in a general planning diagram. This is shown in Figure 13. This was the largest affinity diagram, with fourteen different themes emerging from the interviews, including nine of the fourteen being mentioned in multiple interviews. One strong takeaway from the diagram is that there is extensive planning going on. Geographic location, fuel, vessel condition, and spare parts were all mentioned as considerations for such planning. Informal, daily meetings were mentioned as the dominant way senior officers assess the vessel's health and these concerns while making mission plans. Several interviewees mentioned the availability of spares as a factor in planning, and three specified that their planning horizon extended out to several months in the future. However, there appeared to be little consensus or standardization on how to plan. Submarines had a different series of factors to consider, with topics such as weather (or fuel for nuclear submarines) entirely absent. Differences between transit and patrol, and differences between civilian and military planning, were also mentioned during interviews. Overall, the categories of concerns appeared common, but the response taken to these concerns seemed to vary widely.

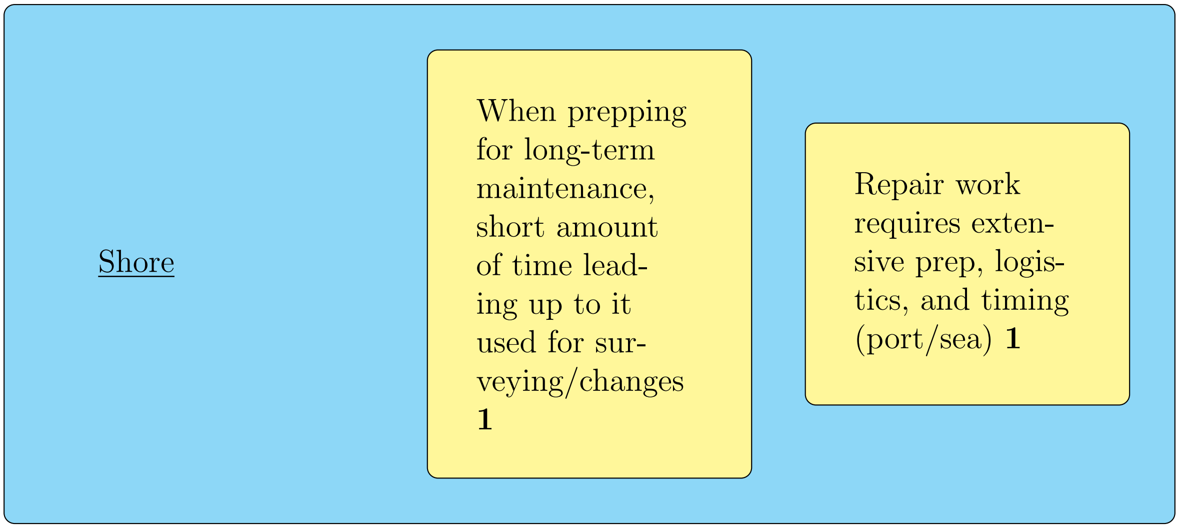
Planning around machinery failures was a second common theme. Four people specifically mentioned planning around failures of particular machines as part of their planning process. Others noted that major repairs occurred on-demand, and that most planning assumed the vessel to be fully operational. However, machinery failures and starting missions with some equipment non-operational (e.g. planning for a degraded state) were also discussed. This lack of consensus around machinery planning was reflective of the overall mission planning diagram- interviewees voiced common concerns and considerations, but many had their own way of incorporating these concerns into plans.

Finally, geographic and port considerations were also widely mentioned. Weather, specifically, was often tied to geographic location and season. Here, a range of approaches were used. Many people reported using shore-based support to help weather-route or plan future operations, such as over-the-side work or helicopter operations. Interestingly, most senior officers also reported using informal or personal weather sources as a method for double-checking the professional services, including apps on Smartphones or websites. Geography and ports also factored into the logistics discussed above, as spare part availability changed with the operational area. Finally, the heavy administrative load of pulling a vessel into port was also mentioned as a challenge for autonomous vessels. A wide variety of government-mandated information needs to be provided in certain regions of the world, and a crewless vessel would have to figure out a way to replicate this.

Underway

- Crew performs daily PMS on machinery **5**
- Vessel ops including PMS have developed from ISM code and reqs **1**
- Level of detail in PMS changes with ship type **1**
- Criticality of failure determines how it is reported and swiftness of response **2**
- Repair work requires extensive prep, logistics, and timing (port/sea) **1**
- T-PERP program replaces equipment on a schedule based on likelihood of failure, regardless of health **2**
- Major repairs are on-demand when something breaks, vessel assumed fully operational **2**
- Ops management is an entire department **1**
- Machinery downtime is the biggest failure **1**
- Most regular maintenance done while underway **1**

Figure 8: Mechanical and Electrical Systems Underway Affinity Diagram

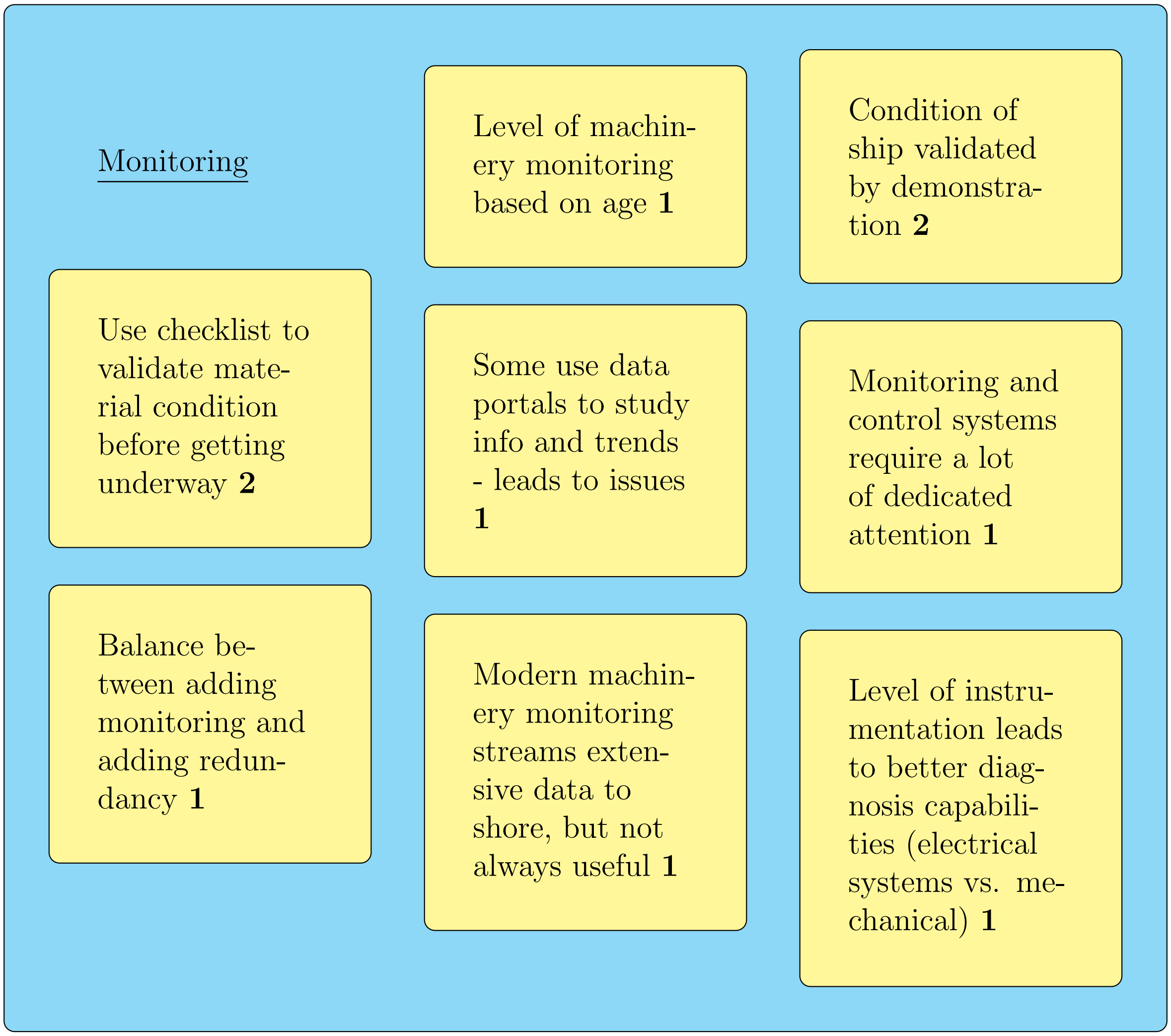


Shore

When prepping for long-term maintenance, short amount of time leading up to it used for surveying/changes **1**

Repair work requires extensive prep, logistics, and timing (port/sea) **1**

Figure 9: Mechanical and Electrical Systems Shore Support Affinity Diagram



Monitoring

Level of machinery monitoring based on age **1**

Condition of ship validated by demonstration **2**

Use checklist to validate material condition before getting underway **2**

Some use data portals to study info and trends - leads to issues **1**

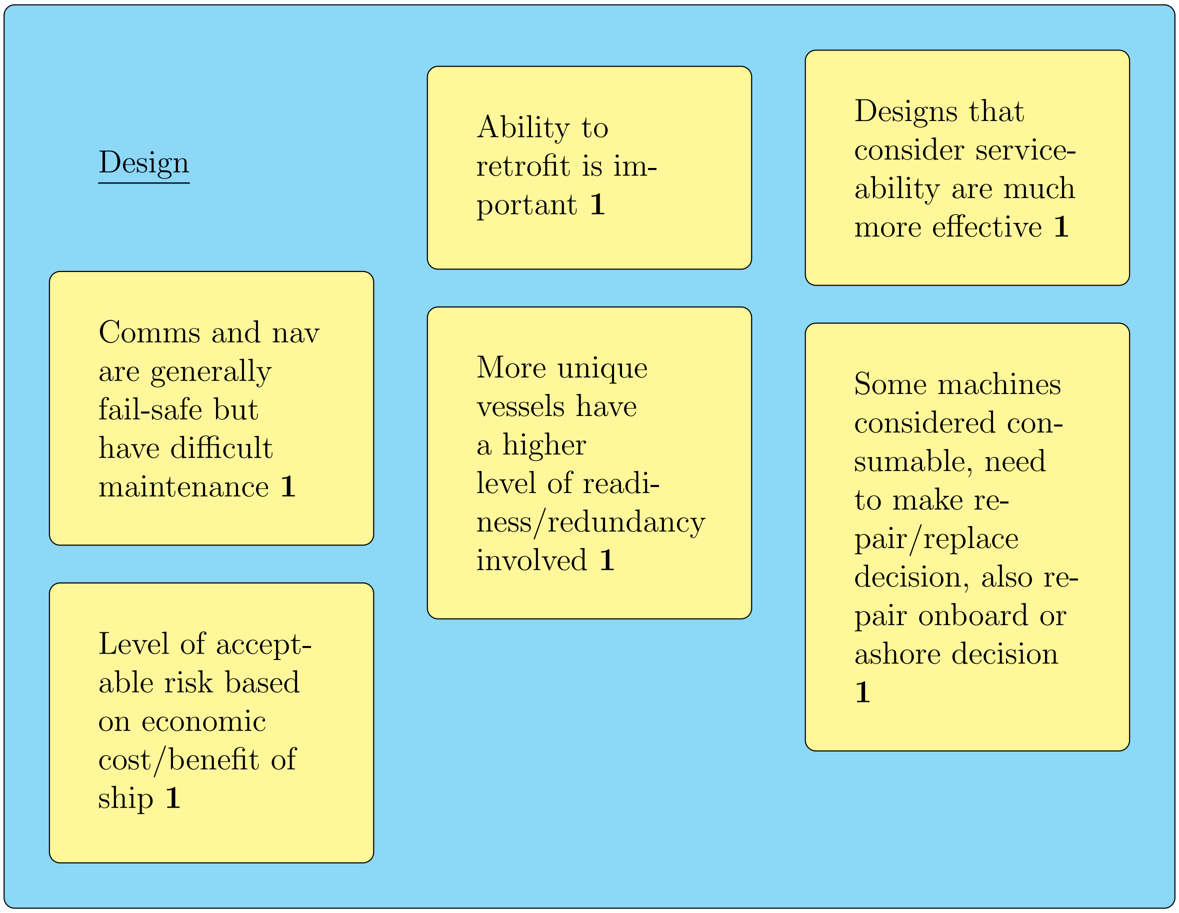
Monitoring and control systems require a lot of dedicated attention **1**

Balance between adding monitoring and adding redundancy **1**

Modern machinery monitoring streams extensive data to shore, but not always useful **1**

Level of instrumentation leads to better diagnosis capabilities (electrical systems vs. mechanical) **1**

Figure 10: Mechanical and Electrical Systems Monitoring Affinity Diagram



Design

Ability to retrofit is important **1**

Designs that consider serviceability are much more effective **1**

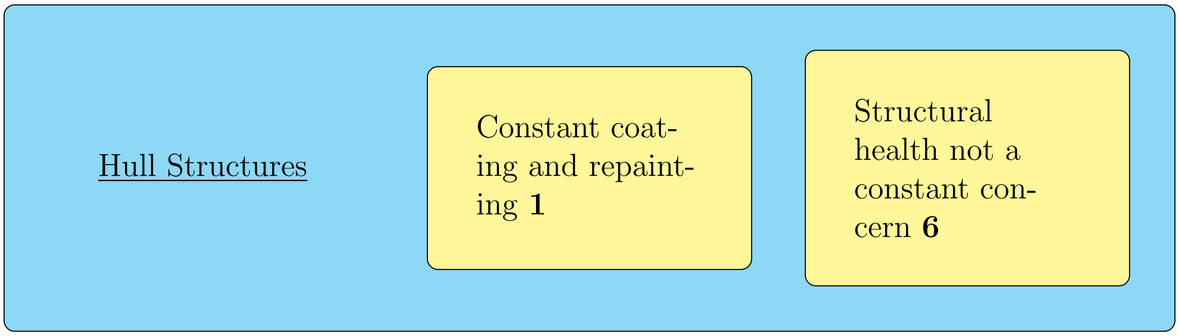
Comms and nav are generally fail-safe but have difficult maintenance **1**

More unique vessels have a higher level of readiness/redundancy involved **1**

Some machines considered consumable, need to make repair/replace decision, also repair onboard or ashore decision **1**

Level of acceptable risk based on economic cost/benefit of ship **1**

Figure 11: Mechanical and Electrical Systems Design Affinity Diagram



Hull Structures

Constant coating and repainting **1**

Structural health not a constant concern **6**

Figure 12: Hull Structures Affinity Diagram

Mission Planning

Fuel management is central concern **2**

Operational planning always includes potential failures **4**

Contingency plans for submarines different than surface ships **1**

Operational readiness, environmental factors, fuel, speed, spares involved in planning **2**

Operational planning is many months **3**

Different voyage planning skills needed for transit and patrol operations **1**

Geographical location and time of year affect mission planning and logistics **3**

Daily meetings to discuss material condition **2**

Civilian side sees more people involved in short-term planning than long-term planning **1**

Diesel submarines have to focus on battery **1**

Mission starts with vessel not at full health, must handle degraded condition **2**

Port visits have both administrative and operational concerns **2**

Machinery downtime is the biggest failure **1**

Major repairs are on-demand when something breaks, vessel assumed fully operational **2**

Figure 13: Mission Planning Affinity Diagram

Overall, the mission planning diagram appeared to extend themes first seen in the machinery and electrical diagrams to wider concerns, though there was less standardization seen here than there was with the PMS approaches for machinery and electrical. For a crewless vessel, the diagram highlights important planning tasks that must be completed - an integration of local weather, vessel conditions, fuel reserves, geographic location, and speed (influence where you need to be when) were discussed. It was also clear that a weeks-to-month planning horizon is necessary. How the crewless vessel should approach these tasks is not clear. A variety of differing, largely informal discussion-based approaches were reported. It is clear that a good degree of information synthesis is needed in this planning, as well as listening to the thoughts of multiple crew members. Initially, these tasks could simply be moved shore-side, and replicated by humans. However, such an approach requires significant communication with the vessel. In the future, a fully self-contained capability would require developing a level of formalization for these procedures and implementing it into a control structure. This task would be large, and would benefit from further crew interviews and more detailed information about differing planning approaches.

4.2.8 Weather

Another factor affecting mission planning that was asked about was weather and environmental scenarios. The weather-related affinity diagram is shown in Figure 14. Weather is an important variable for mission planning, and contingency plans are built around different scenarios that may arise. While engine room work is not largely impacted by current weather, scheduling for work on deck is highly weather-dependent. Different vessels and companies have different strategies for planning based on weather. In many cases, short-term weather is concluded through applications or websites which can be accessed onboard, and long-term weather planning can be done through customized products for individual voyages. Therefore, there are always multiple planning loops and constant information gathering ongoing solely for weather. Similar to other medium and long-term planning tasks, the approach taken to plan with weather forecasts was not standardized, and a significant amount of experience-informed judgment was reported.

For the crewless surface vessels, weather planning will have to be included. Shore support stations would be able to conduct similar weather planning to what is done today; however, if the vessel is not in contact with shore stations, or if it needs to sense and react to local conditions (e.g. the equivalent of conducting deck operations on a crewed vessel), the vessel itself will need to be able to reason about weather. How the vessel can sense weather, and potentially predict the future evolution of the weather is also an area worth exploring. For submarines, the impact of weather was generally much smaller, and for sub-surface crewless vessels, it may not present as much of a challenge as it did for crewed vessels.

4.2.9 Shore Support

An unexpected result from the interviews was the realization that most medium and long-term planning tasks are conducted with extensive support from shore establishments. The

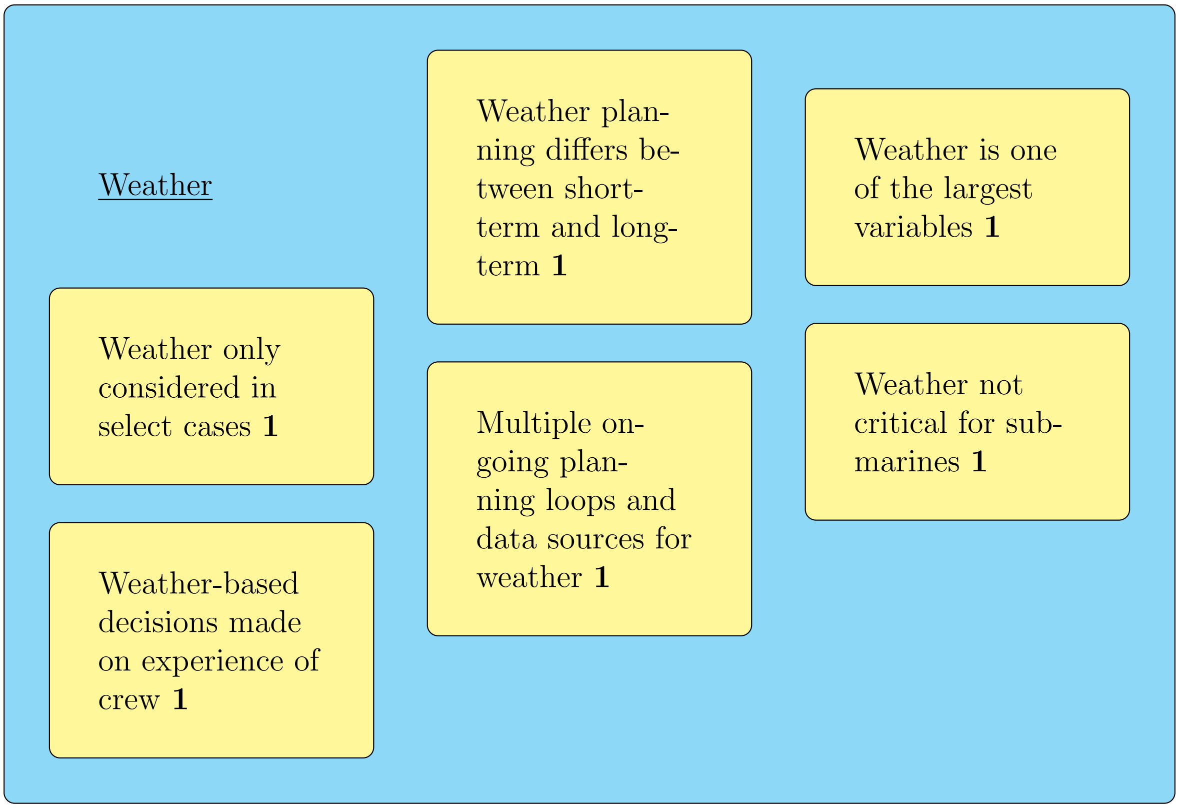
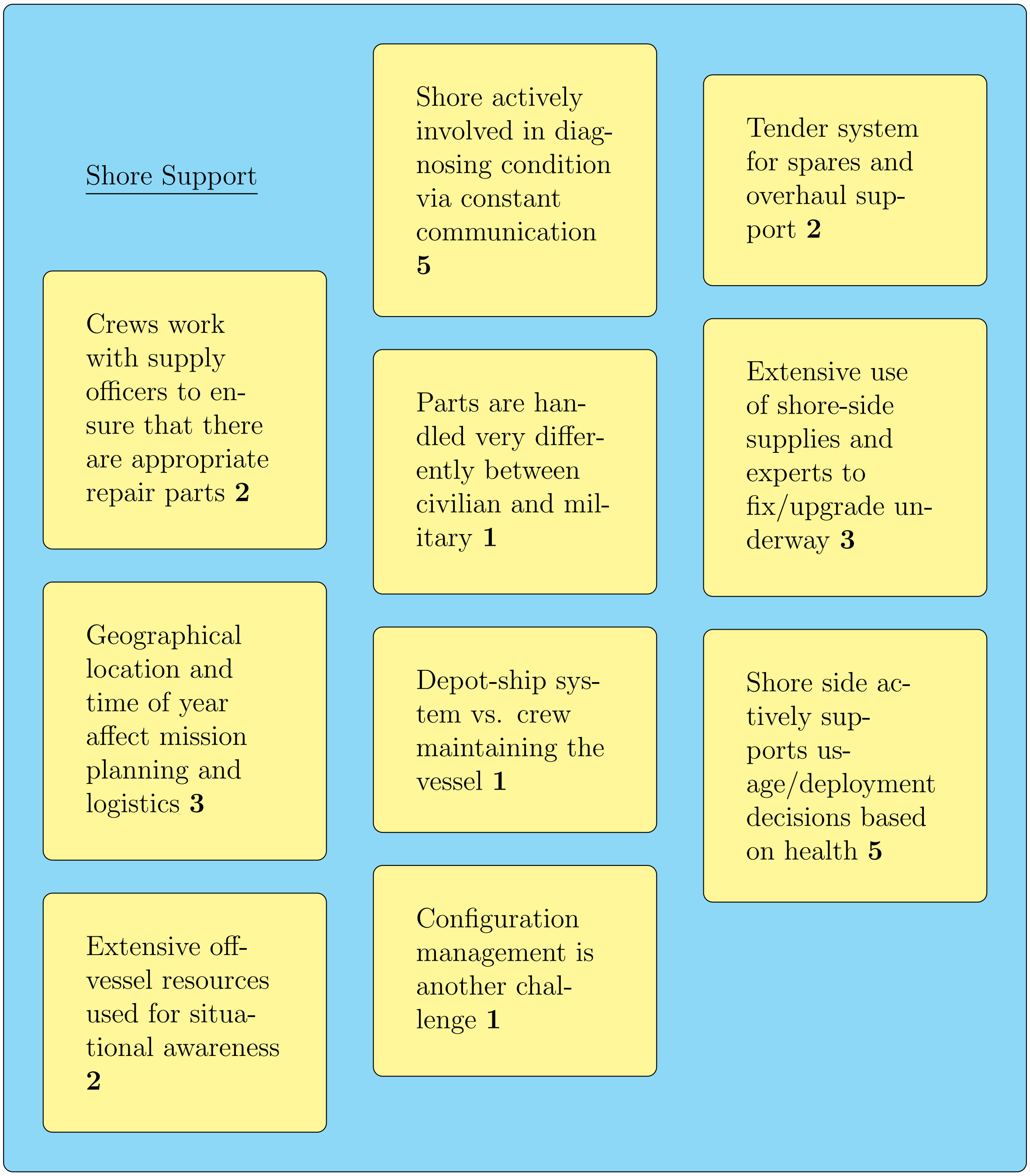


Figure 14: Weather Affinity Diagram

shore support affinity diagram is shown in Figure 15. Participants were asked about the depth of assistance from shore-side commands or other vessels, and much feedback came from those who had worked in roles including fleet operations engineer or port engineer. One of the more common themes is that communication between ship and shore happens frequently, with the ship providing updates on different issues, especially critical issues. Five of the eight interviewees talked about using shore support to diagnose problems aboard, and a further five also talked about shore support being involved in assessing operational options given the degraded state of the vessel. The use of shore-based resources, such as AIS or media reports on political situations to help maintain overall situational awareness was also mentioned.

Beyond these high-level themes involving shore support, there were a series of more detailed themes that continued to surface. The role of the shore establishment in providing timely spares was widely discussed, including the difference between civilian and military approaches and different approaches between crew-maintained vessels and those where extensive shore-side support was used for maintenance. One participant mentioned how shore-side experts determined when and if support needed to be brought out to fix major issues while underway. Also, the deployment location and time of year are major considerations in terms of quantities of spares and fuel carried onboard. Winter months can be difficult in many places, and hurricanes can move quickly during hurricane season, so there is a limited time frame to make mission-changing decisions.



Shore Support

Crews work with supply officers to ensure that there are appropriate repair parts **2**

Geographical location and time of year affect mission planning and logistics **3**

Extensive off-vessel resources used for situational awareness **2**

Shore actively involved in diagnosing condition via constant communication **5**

Parts are handled very differently between civilian and military **1**

Depot-ship system vs. crew maintaining the vessel **1**

Configuration management is another challenge **1**

Tender system for spares and overhaul support **2**

Extensive use of shore-side supplies and experts to fix/upgrade underway **3**

Shore side actively supports usage/deployment decisions based on health **5**

Figure 15: Shore Support Affinity Diagram

Shore support will be vital for autonomous vessels, especially in the case of long-term deployments. Pre-operation planning accounts for many situations that may arise, but the sea is unpredictable. If an extreme weather event arises, mission-changing decisions must be made quickly. For manned vessels, crew experience and communication between ship and shore are the major factors in making these decisions. For unmanned vessels, shoreside support may need to update the mission to avoid any possible hazardous situations. The use of offboard expertise in assessing machinery health and additional operational concerns is also notable and further complicates the concerns raised in the machinery and electrical section above. Finally, as was also discussed in the machinery and electrical section, coordination with the shore support enterprise for spare parts is also important and must be considered for crewless vessels.

4.2.10 Autonomy and Automation

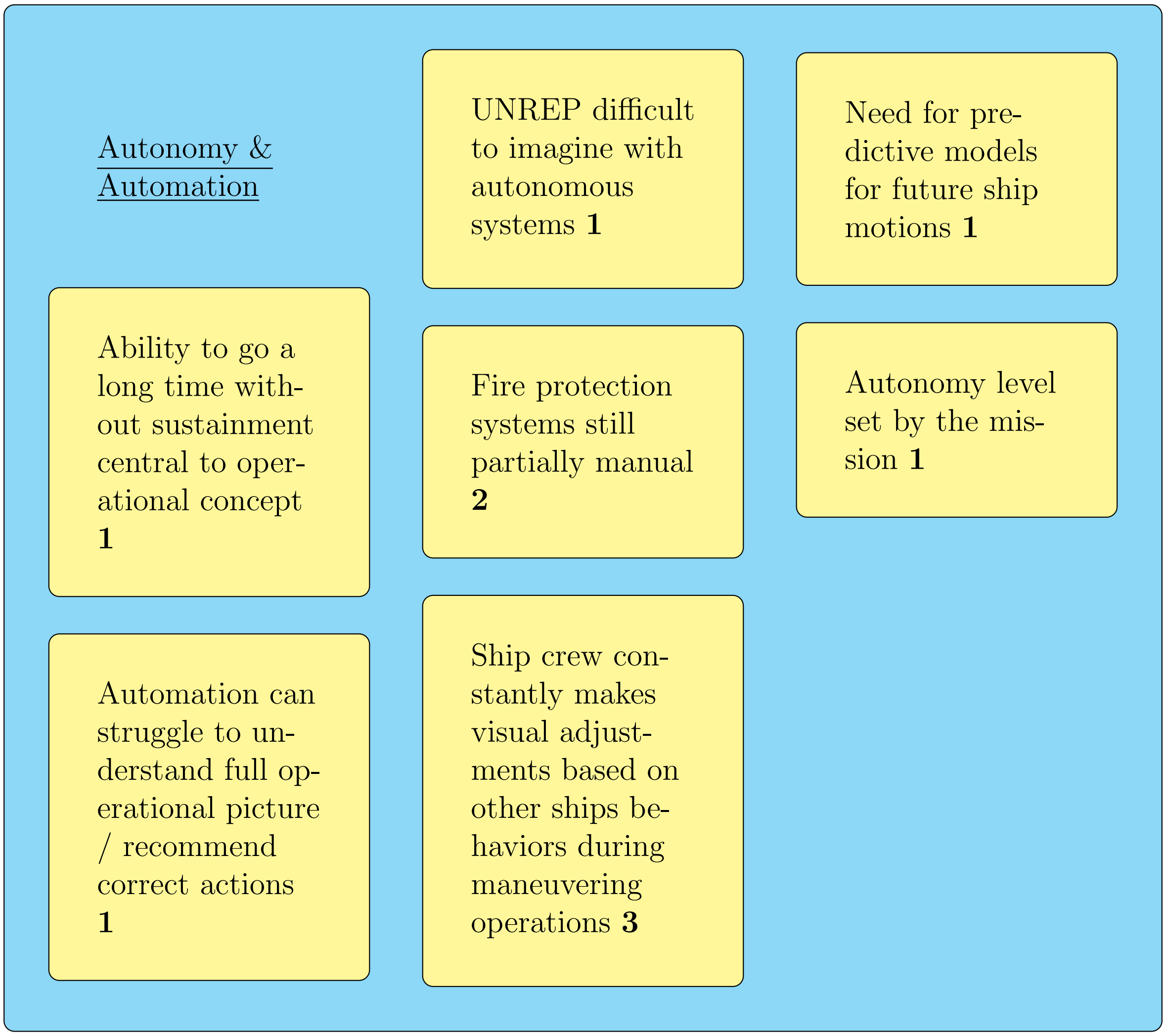
While autonomous solutions to planning challenges were not directly asked of the inteviewees, many participants wanted to discuss what an autonomous future might look like, and seven themes emerged from these discussions. These are shown in Figure 16. A handful of these dealt with perceived challenges, especially in short-term decision-making during operations. Three participants noted that experienced crews are constantly using visual information to make adjustments during maneuvering, including watching other vessels and inferring from their actions what they might be intending to do. Commercial vessels are sometimes non-responsive, and military vessels such as carriers have large safety zones which need to be maintained, so manual changes must be made. Systems such as fire protection systems are mostly autonomous but still have manual components, especially in submarines. This, plus a general concern that an autonomous system would struggle to understand the full operational picture was noted. Additionally, UNREP operations with autonomous systems were also hard to imagine, but have been key for current crewed U.S. Navy operations.

Several smaller themes also emerged from this discussion, including a view that autonomy levels could be set by the mission requirements - an approach that makes sense given the initial focus of autonomy on short-duration missions or tedious but single-purpose tasks, as discussed in section two. The ability of the autonomy system to be able to predict the future state of the platform was also discussed, especially in regard to predicting ship motions.

The discussion around autonomy did not reveal extensive areas of concern for future crewless vessels, at least regarding medium to long-term planning. The need for improved autonomy for close maneuvering and responding to a crisis such as a fire are clear. Additionally, the general concern about autonomy systems being able to understand the context of an operation and predict future platform performance was notable, and would impact the types of planning considered in this work.

4.2.11 Data and Communications

The final theme that emerged was one of data and communications, shown in Figure 17. As noted in the overview of the affinity diagrams, themes that would fit into more than



Autonomy & Automation

UNREP difficult to imagine with autonomous systems **1**

Need for predictive models for future ship motions **1**

Ability to go a long time without sustainment central to operational concept **1**

Fire protection systems still partially manual **2**

Autonomy level set by the mission **1**

Automation can struggle to understand full operational picture / recommend correct actions **1**

Ship crew constantly makes visual adjustments based on other ships behaviors during maneuvering operations **3**

Figure 16: Autonomy and Automation Affinity Diagram

one diagram were duplicated to be placed in both diagrams. In this case, this last diagram mainly contains themes that were discussed elsewhere, with two new themes as well. Communication with the shore establishment and daily informal meetings aboard as critical to conducting planning have been mentioned before, but also fit here as the two main communication needs. Additionally, communication and data transfer is at least partially dependent on the criticality of the data to be transmitted, with large or unexpected repairs necessitating more communication. The two new areas mentioned included the fact that if communication devices fail on board, repair and maintenance are difficult to perform, and often require specialist technicians. Some vessels were reported to be carrying dedicated engineers for control and data systems, given their importance and the difficulty for existing crew members to work on them. Finally, in the military arena, maintaining secure communications was also mentioned as a concern.

In addition to the other concerns discussed around these themes, the ability to maintain communication with crewless vessels is clearly important. While some missions may require that

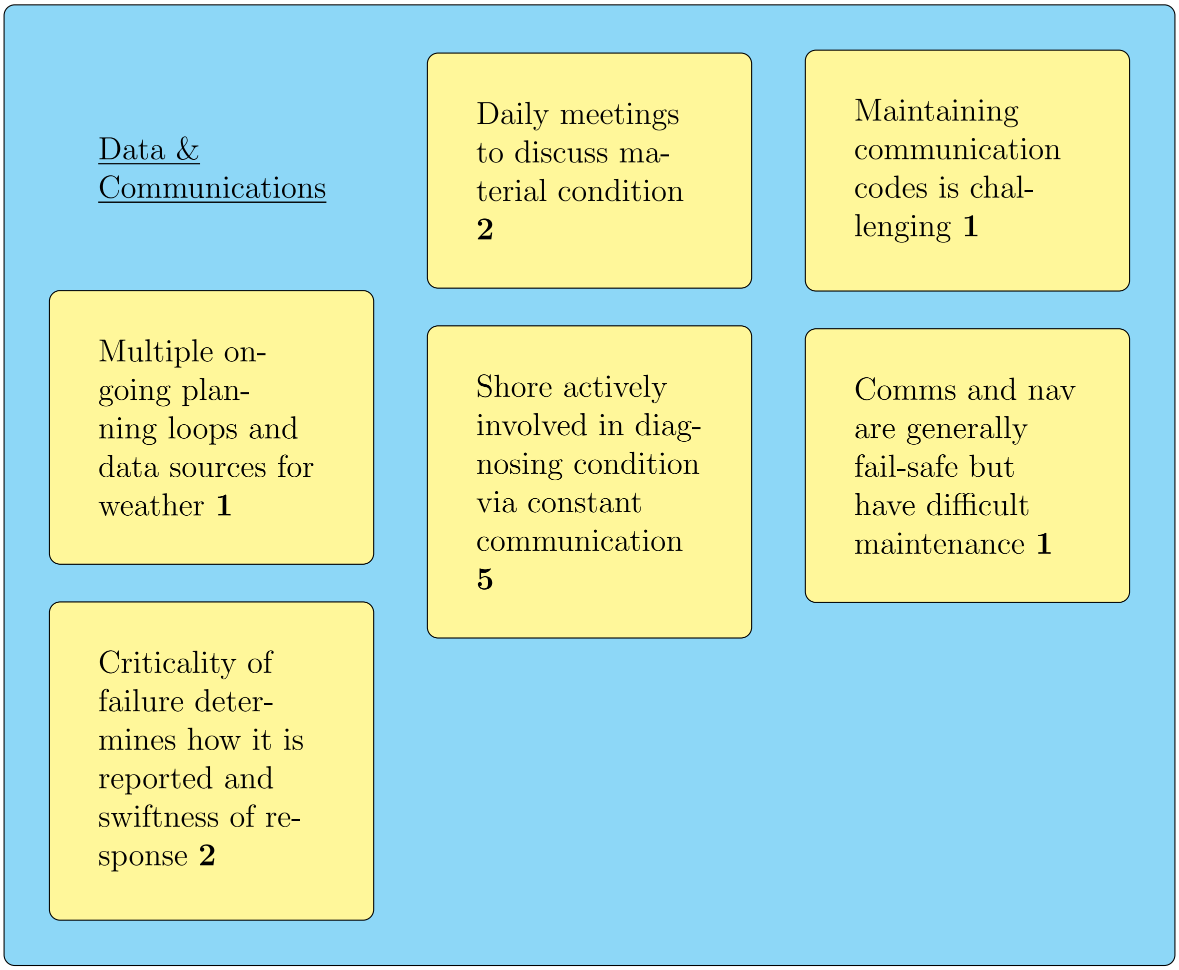


Figure 17: Data and Communications Affinity Diagram

this communication be minimized, the ability to at least receive weather and the ability to inform shore support of the logistical needs of the vessel appear important. Additionally, the specialized nature of communication gear can further complicate the logistics of supporting a crewless vessel. If special technicians are needed, but the need is not known ahead of time, the vessel may be delayed in returning to service.

4.3 Summary of Findings and Analysis of Results Applied to Crewless Vessels

Overall, the interviews confirmed that medium to long-term planning tasks are widely performed, involving both onboard crew and supporting shore establishment. However, it is equally clear that there is a lack of standardization in how this planning is performed. Differences in the interviews tracked across both ship type and personal preference. It was clear that informal communication onboard, between the various departments of the vessels and ultimately the vessel's captain was critical in constructing a view of the vessel's current health and future capability. The exact process used to integrate different sources of information varied widely, but it was always described in informal terms, such as a daily meeting over coffee, or a combination of officially sanctioned weather plans with past judgment and data from personal smartphone apps. This was in sharp contrast to the machinery and electrical PMS, where tasking was formally planned, executed, and audited.

The overall informality of the planning makes it hard to imagine a straight transfer of a human process to an autonomous process. Digging deeper into the background of the topics raised in the interviews revealed some important themes that may need to be considered. First, the informality of the process clearly allowed multiple viewpoints to be shared and understood before a decision is made. The use of multiple viewpoints on important decisions is a hallmark of modern bridge resource management approaches for human crews. This diversity in viewpoints provides robustness by applying different experience sets and mental models of the situation simultaneously, reducing the chances that an important factor is overlooked. How an autonomous system could achieve similar robustness is not currently clear. Second, the role of experience and learning and adapting from previous success and failure with the vessel was also mentioned. This would imply that the autonomous vessel may need to self-assess and upgrade its own approaches over time.

Several additional themes also emerged related to details of the implementation of autonomy. The extensive role of checklists and demonstrations was noted in proving equipment is operable today. These tasks were performed pre-mission and also after a repair. An equivalent approach would be needed for a vessel without crew, as without physically exercising some systems, their health and capability cannot be fully assessed. Additionally, there are a number of failures today - put at or above 10% of all failures - that are not caught by monitoring systems but by the crew directly. The equivalent means of detecting such failures, or allowing them to progress so that a monitoring system could catch them, will need to be examined.

Close coordination with the shore establishment was another common theme seen across multiple affinity diagrams. The need to pre-plan repair logistics, the availability of spare parts, and the need to schedule repairs for a limited time pier-side were all highlighted as planning tasks done in conjunction with the ship and shore establishment today. A crewless vessel will need to be maintained in more of a pit-stop fashion, and here the ability to tell what needs to be done aboard before the vessel enters harbor will be essential. The ability to temporarily put some human crews onboard at sea may also be attractive, whether temporarily from a tender, or riding the vessel for a short duration. Additionally, it was clear that vessels today depend on the shore establishment for help in diagnosis failures, receiving weather reports, and a myriad of other information and administrative tasks. How these tasks are split between the shore and the vessel for crewless vessels is not clear.

The interaction between design and operation was also highlighted across multiple affinity diagrams. In design, the tradeoff between adding redundancy or adding increased monitoring was mentioned for crewed vessels, and the ability to assess such redundancy in the future will become only more important, especially given the limitations of remote monitoring discussed above. All the systems onboard will also have to address maintenance and repair considerations- it was clear from the discussion of the machinery and electrical PMS that there is extensive work being done onboard today. This work will need to be eliminated or moved to defined logistical windows with a crewless vessel. Finally, the ability to directly assess and vary the level of risk for different missions also seems important for crewless vessels. Explicit risk analysis was not commonly discussed in the interviews - checklist and demonstrations to back up design-phase risk approaches such as FMECA were all that were mentioned. Thus, the current crew's sense of risk, like much of the medium-to-long-term planning tasks, appeared informal and experienced-based. To move this sort of reasoning to an automated system would most likely require more formality in risk assessment and calculation.

The areas and challenges discussed represent a first pass at listing the types of skills a crewless vessel would need to acquire to replace human crewed vessels. It is important to note that not all of these tasks need to be fully automated. Licensed crews sitting in a shore-side control facility could continue to use many of the informal integration approaches discussed here, though their "input" from the vessel would be more limited, and there would be a need for frequent communication with the vessel. As crewless vessels attempt longer-term missions or potentially decide on their own without communicating back to shore, the ability to understand and reformulate these tasks for a computer implementation becomes increasingly important.

5 LTA Simulation

5.1 Introduction

The state-of-the-art review and crew interviews suggest that long-term mission planning is an under-explored gap in our current ability to make long-duration autonomous vessels. This opens the question of how good would such mission planning have to be to have a positive operational impact? In this section, a simple simulation of a fleet of vessels is made to begin exploring the tradeoff between being able to plan and operational effectiveness. Compared to the bottom-up approach taken in the last two sections of the report, this section takes a distinctly top-down approach. The vessel model is very simple, with a single health parameter, and the mission is for a fleet of 10 vessels to maintain a patrol line. Four different approaches to planning based on asset health alone (no fuel or weather considerations) are explored:

- A run until complete failure model where the vessel continues the mission until it is incapable of further tasking
- A run until an initial defect is noted, even if the vessel is still mission capable.
- A probabilistic model, where the shore control center set an acceptable risk mission for failing during the mission based on fleet-wide average statistics.
- An intelligent sensing model where the vessel can perform limited prognosis on its own state and adjust mission plans accordingly.

All four models (and several sub-variations) are run for the patrol line mission. The impact of the planning approach on a number of operational parameters is then assessed.
The simulation results observed have generally agreed with intuitions about the performance of long-term autonomous marine systems. While the simulation is designed to be generic and agnostic to vessel type or architecture, trends can be observed in some proposed replacement strategies that suggest that even imperfect planning can have a large positive impact on mission effectiveness. The results and current limitations of the model leave ample room for refinement and evolution of the model and simulation to further identify focus areas, including adding logistics and weather considerations.

The simulation is limited in several regards, and the descriptions that follow are by no means exhaustive. A primary limitation of the simulation is that it does not allow for any decision flexibility or adaptation during a mission. One could imagine a scenario where a vessel reports damage to its base, and the instructions provided to the vessel differ depending on the fleet or theater-wide situation. This decision flexibility is a key focus of future work - however, it requires non-trivial complications to the simulation. The design of the simulation is inherently iterative and time-dependent. While physically this is not a significant limitation, for more complex models it could prove an impediment to efficient computation. Finally, the current model bears little resemblance to any actual vessel or physical rules. While this ambiguity is also a capability described above, the lack of physics-based models in the simulation leaves uncertainty in the results.

5.2 Simulation Structure

The simulation has been designed as a lightweight time-domain model-based tool to assess focus areas for the needs of long-term autonomous vessels and look at the influence of prior planning on operational success. The details of the model currently implemented are described in Section 5.2.1, though the simulation is designed to be mostly agnostic to the details of the model. At its core, the simulation creates instances of the model (vessels) and executes a mission over a defined time period. The mission considered for this work is the maintenance of a basic patrol line at a fixed distance from a base. The input parameters and result metrics for the simulation are discussed in Section 5.2.3 and Section 5.2.4 respectively. Both inputs and result metrics are considered to be independent of the model details.

The code base (available on GitHub) consists of classes and functions written in Python 3. To the extent possible, standard Python packages are used to maximize compatibility. Some exceptions were made for plotting and animating functionality, data handling (Pandas was used), and design space exploration. A README accompanies the codebase, which provides more details on dependencies and running the simulation.

5.2.1 Model

There is little convergence among concept designs for unmanned or optionally crewed naval platforms (referred to as USVs). Existing prototype and demonstration vessels exhibit a wide range of capabilities for autonomy, size, and hull morphology. Accordingly, the model for this study makes no assumptions about the nature or abilities of the USVs in the simulation. Instead, USVs are defined with a single characteristic - cruising speed, which allows variation of transit time in the simulation.

The concern for any vessel embarking on a mission is the ability to sustain mission capabilities for the length of the deployment. In the case of an optionally crewed vessel or USV, the health of the vessel's mechanical, electrical, and structural components are the primary concern. The current model encapsulates the health of all of these systems into a single damage state. For simplicity, there are four damage possible states: Intact, Light Damage, Heavy Damage, and Sunk. Vessels are initialized in the Intact condition, and progress sequentially until sinking. A vessel in the Light Damage condition is still operationally capable, but has detectable degradation, Heavy Damage condition cannot carry out its patrol duties, and Sunk vessels are removed from the simulation upon sinking.

The length of time spent in each phase of life is determined by a lognormal distribution, giving the mean time the phase lasts with a standard deviation. When a specific vessel is placed into service, a draw is made from each of the three lognormal distributions - intact time, light damage time, heavy damage time (sunk is a permanent state), and the specific times drawn are assigned to each state on that particular vessel. The model is extensible for the use of other distributions, but caution should be taken to ensure negative times are never assigned.

5.2.2 Simulation Types

For this study, four simulation types were analyzed. Each simulation type has a set of conditions or rules applied to it to represent a strategy for long-term autonomy. The simulation types are meant to demonstrate the benefits of probabilistic and prognostic damage-prediction systems. Each simulation type is described briefly below, with a list of rules the simulation follows in each type.

Type 1 Meant to represent a vessel design with no ability to mission plan. The vessel will remain at patrol until it reaches heavy damage, then attempt to return to base.

- Vessels patrol until reaching a heavy damage state
- Upon reaching a heavy damage state, vessels abandon their patrol and return to base immediately
- Upon returning to base, the vessel is replaced and the replacement leaves immediately
- Vessels are removed upon returning to the base or sinking

Type 2 Meant to represent a minimal and very conservative method of mission planning.

- Vessels call for help upon reaching light damage
- Vessels patrol until relieved at the patrol line
- Only vessels on the patrol line can call for replacement
- Vessels are removed upon returning to the base or sinking

Type 3: A form of mission planning where a vessel's time in service is based on their expected probability of entering heavy damage, and they call for a replacement when exceeding that time.

- Vessels call for help upon exceeding a time limit based on a probability, on average for the vessel class, of entering the heavy damage state. This is expressed as a percentage (e.g. 80% chance of completing the mission on average) by the shore decision staff.
- Vessels also call for help if they enter heavy damage prematurely, or before the time limit calculated
- Only vessels on the patrol line can call for replacement
- Vessels are removed upon returning to the base or sinking

Type 4: A form of mission planning where vessels are equipped with a prognosis system that predicts that the vessel will enter heavy damage with varying time horizons and reliability.

- Vessels call for help when the time remaining in the intact and light damage states is less than the time horizon provided by the prognosis system.
- Vessel is only able to call for help if the prognosis system is functional at that time step (a random determination)
- A replacement will not be called if it would arrive before the vessel enters heavy damage
- Only vessels on the patrol line can call for replacement
- Vessels are removed upon returning to the base or sinking

5.2.3 Input Parameters

In the current configuration, the simulation has four input parameters. These parameters are described briefly below and will be referenced extensively in the results and discussion. There are also a number of parameters that are fixed for all simulations, such as the number of vessels and length of the simulation. These can be modified, but would change the simulation results significantly and are not variables of interest, and therefore not considered inputs for the simulation yet.

`transit_time_ratio` The transit time to the patrol location as a fraction of the fixed mean time in the intact condition. For this purpose, only the distance from the base normal to the patrol line is taken, so some patrol locations are farther and thus have longer transit time.

`lifespan_var` The amount of variability in the distributions used to generate lifespans as a percentage (1-99) of the fixed mean time for each lifespan.

`prob_heavy_damage` Only used in Simulation Type 3. This is the prior probability of entering the heavy damage state that is acceptable to the shore control center. Using the mean values and standard deviations of the two lognormal distributions for intact and light damage extents, the operational time before entering the heavy damage state, with a given confidence, can be found via Monte Carlo simulation. This probability is expressed as a percentage chance (1-99), and the Monte Carlo results then convert this into a time at which to request a replacement. If the vessel enters the heavy damage state before this, a replacement request can be made.

`prognosis_time` Only used in Simulation Type 4. This is the warning time provided by a prognosis system as a fraction of the fixed mean time in the intact condition.

5.2.4 Result Metrics

Four metrics are derived from the simulation to represent the results of each simulation. The metrics are: mean quality of service (QOS), number of vessel switch-outs or replacements, the number of vessels sunk, and the maximum number of vessels at once. The metrics were shown to be minimally correlated in Section 5.3.

The mean quality of service is an average over the entire simulation of the quality of service at each time step. Quality of service is the fraction of patrol areas in the simulation that are successfully patrolled. If there is a vessel in the area for a given time increment, and it is at a damage level deemed acceptable enough to carry out its duties, the program will mark that area as successfully patrolled for that time increment.

The number of vessel switch-outs or replacements is a count of the number of vessels that were replaced over the course of the entire simulation. The rules for when vessels are replaced differ by simulation type, and are described in Section 5.2.2. Note that the simulation has no provision to re-deploy vessels, so it is assumed that each vessel is replaced with a new, unique vessel.

The number of vessels sunk is a count of the number of vessels that were sunk over the course of the simulation. Vessel sink when they exceed their combined lifespan in all damage states, and the vessel is replaced with a new vessel from the base. For the simulation as currently configured, a sunk vessel is a rare occurrence, so often the number of vessels sunk is zero.

The maximum number of vessels at once is the maximum total number of vessels in one time step over the course of the simulation. No data is recorded for the number of vessels at any given time step.

5.2.5 Running the Simulation

The simulation is run in the time domain, as described above. The simulation progresses through time steps, updating the location and damage status of each vessel at each time step. Generally, vessels are assigned a destination (either the patrol location or base) and move towards that destination each time step. If the vessel reaches the destination, it loiters at the patrol location or is retired at the base. Meanwhile, the damage state is progressed independently of the actions of the vessel with each time step.

Within the model, lifespans are determined as random values from defined distributions (see Section 5.2.1) meaning the values differ for each vessel. This variation means two runs of the simulation with equal input parameters will not necessarily have equal results. To account for this, the simulation can be run several times, in repeated trials. Results from all simulations are reported and analyzed in bulk, as described below.

Mapping and Animation To aid in debugging and visualization, the simulation can produce maps of all vessels at each time increment. The map shows vessels colored to indicate the damage state of each USV. The maps can be animated to show the progression of the simulation through time. An example of the maps created is provided in Figure 18.

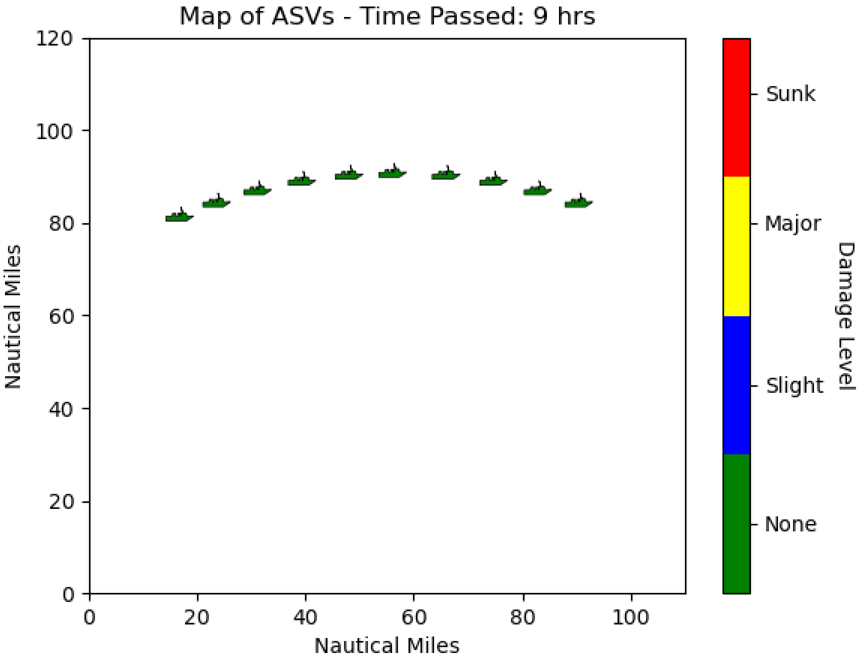


Figure 18: Map plots used to visualize simulation progress. Color of vessel icons indicates damage state.

Statistics and Analysis While the maps and animations of simulations are a very useful visualization of a single simulation, the goals require statistics performed on the results of a large number of simulations. Statistics are calculated across each set of input parameters and each simulation type. The most valuable statistics are the arithmetic mean, and variance. The student's t-test can be used to assess the significance of the difference between two samples, for example two simulation types with the same input parameters. An analysis of variance (ANOVA) can be conducted to determine if any sample differs significantly from others.

5.3 Model Validation

Without a physical analogue, it is not possible to rigorously validate or benchmark the performance of the model. However, in keeping with the simulation goals validation steps were undertaken to ensure the model and simulation was robust and not prone to unintended variability or error.

Unit Testing Unit testing refers to conducting a series of tests at the lowest level of the simulation to check outputs versus known results. A robust unit testing framework was built for functions where applicable. Unit tests can be used to validate the installation of the simulation, and ensure all required packages are installed. Unit testing also confirms any modifications or additions made to the codebase have not disrupted the simulation functionality.

Regression Testing Regression testing refers to running the simulation for a set of inputs where the results are known to check perform of higher-level simulation functions. Regression testing functionality is built into the controller written for the simulation. The regression testing function assigns three sets of input parameters, using `transit_time_ratio` to create two edge cases and one middle case. The random number seed is fixed in the case of regression testing as well, to ensure the same random variables are chosen from the assigned distributions.

No Correlation in Results Several design space exploration experiments were used conducted on the simulation. Design space exploration provides coverage of the whole range of inputs possible and is a method of efficiently sampling all possible outcomes of the simulation. From a design space exploration, no strong correlation between any pair or set of result metrics was observed. Figure 19 provides scatter plots, plot of correlations, and correlation values. The lack of correlation between results indicates that the result metrics are independent and describe different aspects of the results.

5.4 Results

Several key results observed in initial simulations are described below. A goal of this simulation was not select the best possible simulation type, but rather to explore model sensitivities and differences between strategies. As such, the results focus on driving parameters or major trends observed. The results presented are not an exhaustive view, but rather an initial exploration.

5.4.1 Transit Time as Primary Driver

The transit time ratio (described in Section 5.2.3) was expected to influence results in all strategies strongly. The simple physical explanation of this is that as the patrol line is farther from the base, the harder it is to maintain coverage as vessels break. This general explanation can be observed in Figure 20, where the transit time ratio is plotted against the mean quality of service for 3200 simulations as part of a design space exploration. There is a

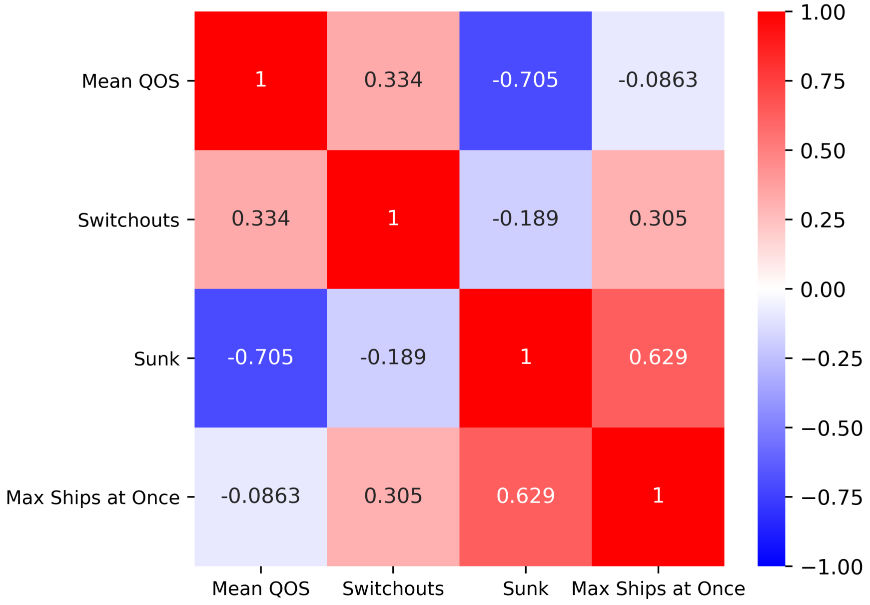


Figure 19: Multivariate correlation plot of result metrics from a Design Space Exploration experiment shows a minimal correlation between metrics.

negative correlation observed between the variables. There is a clearer "floor" in the quality of service that is correlated with the transit time ratio. At low transit time ratios (patrols very close to the base) the quality of service is tightly clustered, and generally very high. At high transit time ratios, the quality of service is widely spread and can be quite low. The large spread seen is because in a design space exploration, all variables are simultaneously varied. The weak negative correlation suggests that generally, as transit time is increased, service quality will decrease.

5.4.2 Efficacy of Prognosis System

Simulation Type 4 is the only strategy that employs a prognosis system to predict when the vessel will enter heavy damage. The prognosis system is assumed to function perfectly and will call for a replacement vessel when the time until failure falls below the transit time for the replacement vessel. To demonstrate the ability of the prognosis system, a test matrix was created to hold inputs other than the prognosis time constant and varying prognosis time. Figure 21 shows the results in a scatter format. One data point is displayed for simulation type 1, 2, and 3 because the results are unaffected by the variation of prognosis time. Three prognosis times are plotted as well.

Of note in these results is the relative efficiency of the prognosis system in increasing the quality of service with fewer vessel switch-outs. The strategies of calling for help at light

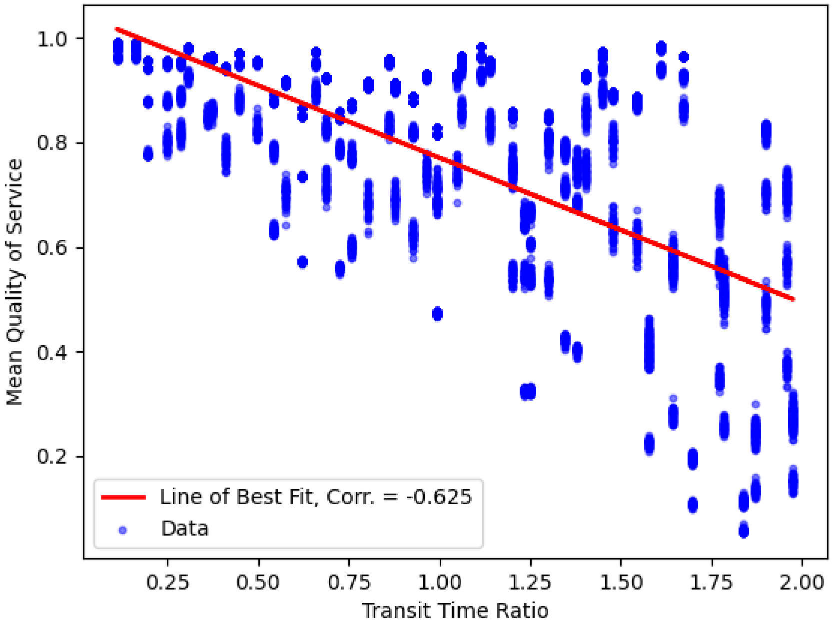


Figure 20: Transit time ratio versus mean quality of service for all simulations from a design space exploration.

damage (type 2) and avoiding a probability of heavy damage (type 3) both provide a high quality of service for this set of input parameters, but require nearly twice as many switch-outs as the prognosis system results. By comparison, the strategy of only leaving the patrol line at heavy damage without calling for a replacement (type 1) has a low quality of service with the fewest switch-outs used. A prognosis time equal to the transit time provides nearly equal quality of service as the type 2 and type 3 results, with about half the switch-outs. Also of note is the diminishing returns seen in increased prognosis time. There is no demonstrable benefit in increasing prognosis time past the transit time because the vessel avoids calling for help before it is needed. Additionally, a prognosis time of only 20% of the transit time provides a significant increase in quality of service from the type 1 results, without requiring as many switch-outs as the longer prognosis time results.

5.4.3 Efficacy of Probabilistic System

Simulation Type 3 is the only strategy that employs a probabilistic system to avoid the vessel entering heavy damage. The system will call for help when the vessel reaches the time corresponding to a specified probability of entering heavy damage, based on an inverse cumulative distribution of the average intact and light damage lifespans. A test matrix was created to hold inputs other than the probability of heavy damage constant and varying the probability of heavy damage to avoid. Figure 22 shows the results in a scatter format. One data point is displayed for simulation type 1, 2, and 4 because the results are unaffected by the variation

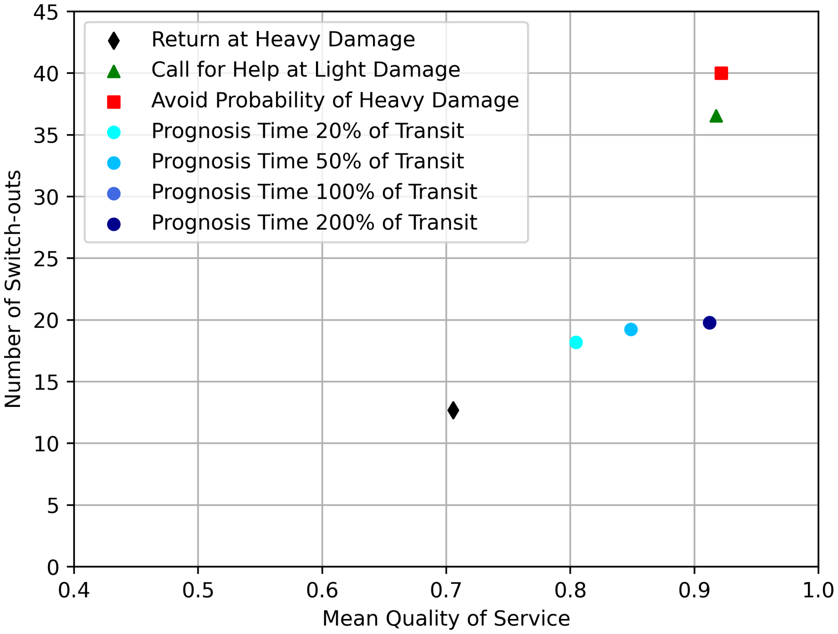


Figure 21: Mean quality of service and number of vessel switch-outs for several replacement strategies and a range of prognosis times.

of the probability of heavy damage. Four probabilities of heavy damage to avoid are plotted as well.

There is a general trend of increasing quality of service and vessel switch-outs as the probability of damage to avoid decreases. For both a 40% probability to avoid and a 60% probability to avoid, there are 30 vessel switch-outs yet the 60% probability of avoidance has a higher quality of service. This suggests there could be clustering of the number of switch-outs with this set of input parameters - which could be an important phenomenon and design criteria for a probabilistic system.

5.4.4 Rarity of Sinking

As discussed in Section 5.2.4, vessels sinking in this simulation is a rare occurrence. This can be shown by observing the number of vessels sunk in 3200 simulations comprising a design space exploration, seen in Figure 23. The majority of simulations experience zero sunk vessels. Interestingly, there are also peaks at 10 vessels sunk and 20 vessels sunk. This indicates that in cases where vessels do sink, the entire fleet is likely to sink. This is likely the result of a high-risk strategy (e.g. run until heavy damage - Type 1) encountering a lower standard deviation in the vessel's lifespan, causing them all to sink in a short time period. The very low density of results at other densities indicates rare events, which could be a result of several ”low picks” or random values for lifespans that are below the mean value.

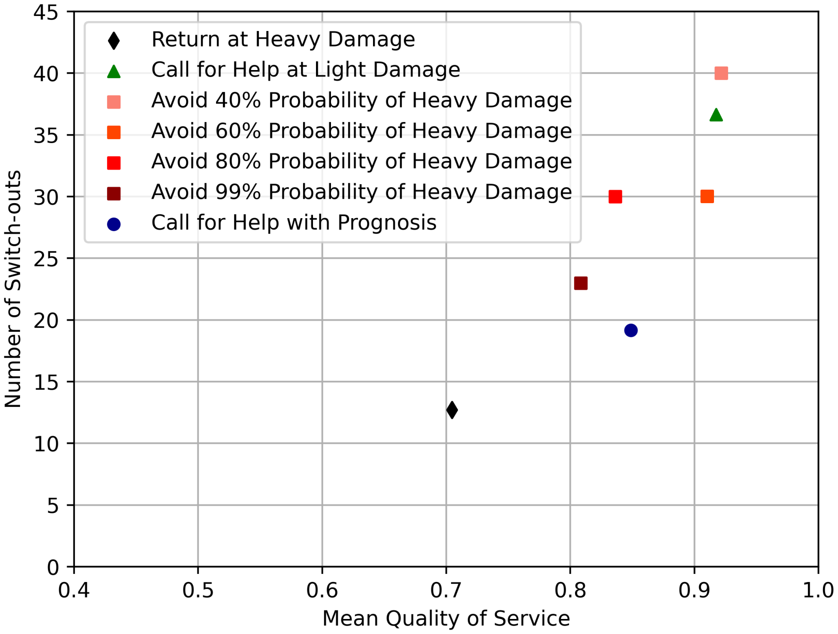


Figure 22: Mean quality of service and number of vessel switch-outs for several replacement strategies and a range of probabilities of heavy damage to avoid.

5.5 Discussion

An initial takeaway from the simulation results observed to date suggests that generally intuition on the behavior of long-term autonomous systems holds. This affirms the suitability of the model to inform further work and identify potential design drivers. The transit time ratio and quality of service results (Figure 20) are an example of confirmed intuition. While the correlation is weak, and suggests nuances in the relationship, there is a negative correlation between the variables as might be assumed.

Results on the efficacy of prognosis systems that sense damage before it occurs also affirm intuitions that these systems can allow a fleet to provide more efficient coverage. As Figure 21 shows, prognosis systems can increase the quality of service with minimal increases in the number of vessel switch-outs. Questions remain about how these systems might be affected by more realistic reliability distributions (currently they're assumed to always function) as well as how much prognosis is actually possible in a complex system.

Further exploration is needed to understand the circumstances where a probabilistic damage avoidance system excels. Figure 22 highlights an interesting case whereby increasing the probability of damage to avoid, the quality of service increases without requiring more vessel switch-outs. While generally, it appears that higher values of probability to avoid perform

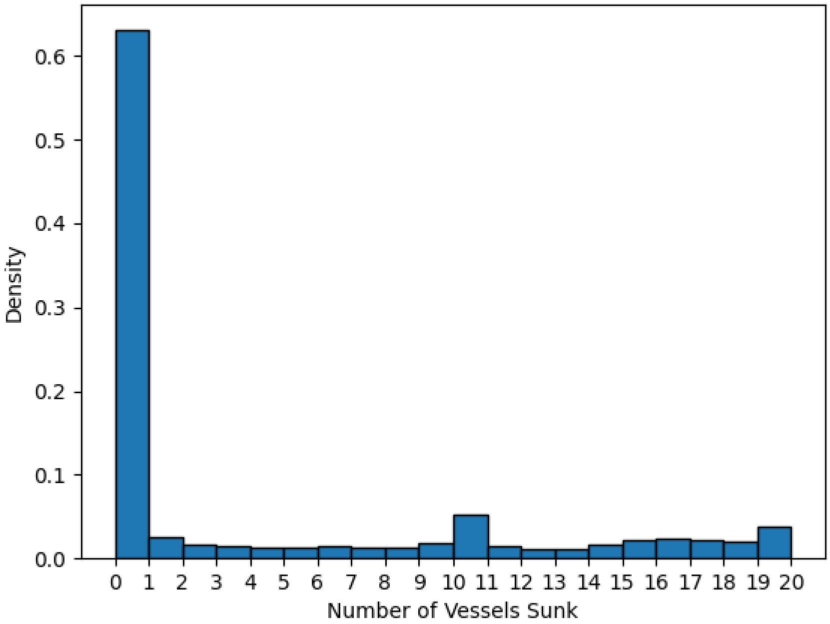


Figure 23: Density histogram of the number of vessels sunk in a design space exploration.

better, this case indicates there could be a range of input parameters for which probabilistic systems are especially well suited.

Finally, the scarcity of sunk vessels observed (Figure 23) indicates that the risk of sinking is not a driver for this specific model and simulation. That is not to say sinking vessels are never a concern, and sinking vessels should be evaluated in future models as well, as they likely represent a significant loss for the operator.

Overall, this top-down modeling approach shows promise. It demonstrated that even imperfect planning is useful for increasing operational effectiveness, and shows that a fairly basic simulation can help model the impact of different planning types. Continued development of this type of simulation, with additional detail as discussed below, could replicate some of the planning challenges and possible solutions discussed in the crew interviews. These sorts of simulations can also put numbers against the three categories of risk presented in the introduction.

5.6 Future Work

This simulation is intended to inform and guide further simulations and laboratory-scale testing to explore the needs of long-term autonomous marine systems. The current model and simulation contain several limitations which could be addressed with further development. Several potential areas for future development of the model and simulation are included in the list below. This is not an exhaustive list, nor a plan for further development, but serves to illustrate the potential of the simulation.

- Introduce reliability variation to the prognosis system and probability of heavy damage system to emulate onboard sensing failures.
- Allow decision flexibility or adaptation of the strategy and simulation rules based on the circumstances and surrounding vessels. For example, if less than a certain fraction of patrol areas are covered, vessels may alter their replacement behavior.
- Build more components into the model, adding subsystems that can degrade separately. Different damage levels may be the threshold for effectiveness in different systems and could affect the performance differently. Additionally, logistics could be included to support these different components.
- Progress between damage states differently depending on what the vessel has been doing. For example, the vessel might be expected to accumulate more damage while transiting to the patrol area than while loitering at the patrol area.
- Add a simulation type, or adjust all simulation types to allow vessels to be repaired at the base and redeployed after a set period of time. This would reduce the total number of vessels used, which while not currently a result metric, could be a useful measure of a strategy's effectiveness.

6 STPA

6.1 Background

System Theoretic Process Analysis (STPA) is a relatively new hazard identification technique for the design stage of complex engineered systems. It has been developed from STAMP, Systems-Theoretic Accident Model, and Processes. Both STPA and STAMP focus on control structures as well as component failures to look for possible hazards from the interaction of humans and complex engineered systems. Several written sources exist documenting the theory and examples associated with STPA, but the primary source of information on STPA as modified and applied here was gathered from Leveson's and Thomas's *STPA Handbook* [28].

The theoretical framework for STPA is derived from the System-Theoretic Accident Model and Processes (STAMP). Most casualty prevention theories before STAMP focused on modeling systems and preventing failures through the system's individual components rather than as a whole. This bottom-up approach can effectively identify hazards when all the components of a system act independently of one another, but it is often not able to identify hazards stemming from emergent properties which develop when these components interact. Contrarily, STAMP's top-down approach allows it to capture more of these complex hazards while also accounting for abstract sources of losses such as software, humans, and organizations.

While there are multiple STAMP-based tools in existence, STPA is a very common one because of its proactive approach to controlling system hazards early in the design process. There are four steps involved in any basic STPA:

1. Define the Purpose of the Analysis
2. Model the Control Structure
3. Identify Unsafe Control Actions
4. Identify Loss Scenarios

There is no designated point to add STPA into a design process, but it is often most effective when incorporated at the very beginning, looking at high-level interaction and then crowing through the design in detail as controllers and controlled processes are added. In the present study, only a static, high-level analysis of crewless systems could be made, and this ability to refine the model over time was not present. Without the ability to complete the STPA analysis to the level of individual controllers, two modified STPA approaches were explored here. The first used an abstraction of a crewless vessel, and identified the dominant information pathways that would be required for achieving long-term autonomy. The second focuses on higher-level control structures exclusively, including design and approval loops, and identified areas where either control, analysis, or decision-making would need to be advanced to achieve medium to long-term autonomy on complex vessels.

6.2 Previous STPA Analysis

STPA is a hazard analysis technique developed by Leveson designed to prevent system losses through creating system constraints [28]. Since its inception, STPA has been used in several aerial and marine applications, including dynamic positioning systems [39] and assessing safety for inland passenger ship operation [55].

Regarding aerial systems, Chen et al. [10] performed STPA regarding take-off for a complex UAV system. They developed a control structure and identified control actions and unsafe control actions for the system. Stoll [48] applied STPA to a DLR high altitude platform project to detect potential accident scenarios.

Sayers et al. [43] used a security-based form of STPA, STPA-sec, to focus on early security requirements for an unmanned aerial system. Similarly, Torkildson et al. [54] compared three security and safety analysis methods for the autonomous vessel REVOLT. Dghaym et al. [16] used STPA and a security-based form, SE-STPA, to model safety and security risks for a framework of autonomous marine systems, including UUVs and USVs. Omitola et al. [33] also used STPA-sec in the security analysis of an unmanned marine system's navigation module. They identified system-level security hazards and constraints.

Most maritime-focused STPA analyses have focused either solely on the navigation aspect of a vessel or on engineering systems. Wrobel et al. [62] examined the process of ships' collision avoidance and performed a case study on an accident where the MV *Corvus J* collided with the MV *Baltic Ace* in the North Sea in 2012. Later, they revisited their work to identify existing and future research directions [61]. Sultana et al. [49] applied HAZOP and STPA to ship-to-ship LNG transfer systems and concluded that STPA can be applied to more complex systems. In two separate works, Bolbot et al. [5] [4] performed an STPA analysis on a diesel-electric propulsion system of a cruise ship and then a hybrid-electric propulsion system.

To date, little research has been done using STPA regarding mission planning and more abstract sensing-of-health tasks. Some work on applying STPA to business processes and similar information-flow oriented applications has been reported [28] that can be adapted for this task. This is a research gap that, when explored, can open up other opportunities and further development of STPA for autonomous marine systems like USVs and UUVs.

6.3 STPA Analysis 1: Abstract Crewless Vessel

6.3.1 Analysis Setup

The initial STPA approach involved adapting vessel-specific studies from the literature to a nominal USVs, considering all possible systems that would commonly be on such a craft. Per the first step of any STPA, the losses, hazards, and system-level constraints needed to be defined. As advances in vessel autonomy are still a work in progress, there are varying degrees of automation that can range from a primarily user-based interface with the ability for simple autonomous tasks, to a fully autonomous interface with no user involvement aside from human supervision. This first study was done as a broad exploratory analysis of what might be required on a hypothetical crewless vessel that still kept all of the systems of a large, complex, crewed vessel today. This would identify all of the possible information exchanges and control structures that might emerge as crewless vessels become more complex.

The following list of losses comprises the likely areas of value to the stakeholders involved with building, purchasing, and operating a fully autonomous vessel. These losses were inspired by previous studies which focus on loss of life, property, and environmental damage, and the three-component risk model introduced in the first section of this report.

- L-1: Loss of life or injury to people
- L-2: Irreparable damage to vessel
- L-3: Loss of communication with vessel
- L-4: Loss of vessel's autonomous mission capabilities
- L-5: Environmental loss
- L-6: Loss of sensitive information

Next, the following list of hazards highlights the circumstances that would lead to a loss under worst-case conditions.

- H-1: Vessel does not maintain minimum separation standards with surrounding craft [L-1, L-2, L-3, L-4]
- H-2: Vessel does not maintain minimum separation standards with fixed or environmental objects [L-2, L-3, L-4, L-5]
- H-3: Vessel navigates through too shallow of waters [L-2, L-4, L-5]
- H-4: Vessel is technologically overtaken [L-3, L-4, L-6]
- H-5: Vessel-to-satellite or other external navigational device communication is not being received [L-3, L-4]
- H-6: Vessel's righting arm is reduced by pooled water, ice, or other unplanned loads that accumulate during operation [L-2, L-4]
- H-7: Hull structural integrity is lost [L-1, L-2, L-4]
- H-8: Propulsion, Auxiliary, and/or Machinery systems onboard are unable to perform mission tasks [L-1, L-2, L-4]
- H-9: Vessel is unable to track unexpected or planned component deterioration over time [L-1, L-2, L-4]

Finally, the following list of system-level constraints pinpoint the conditions necessary to avoid each respective hazard.

- SC-1: Vessel must satisfy minimum separation standards from surrounding craft [H-1]
- SC-2: Vessel must satisfy minimum separation standards with fixed and environmental objects [H-2]
- SC-3: Vessel must ensure charted course does not take it into too shallow water [H-3]
- SC-4: Vessel must incorporate security measures and safeguards to protect against and/or mitigate losses from a cyberattack [H-4]
- SC-5: If communication between vessel-to-satellite/other external navigational device is hindered, then measures must be taken to navigate by other means [H-5]
- SC-6: If unplanned loads accumulate during operation, then those loads must be detected, and measures must be taken to remove them [H-6]
- SC-7: Vessel's hull integrity must be maintained under worst-case conditions [H-7]
- SC-8: Propulsion, Auxiliary, and/or Machinery systems onboard must be able to perform mission tasks at all times when the mission requires [H-8]
- SC-9: Vessel must be able to track component health in order to prevent unexpected and time-based deterioration [H-9]

6.3.2 Control Structure Development

The modeling of a control structure maintained started with a high-level sketch of the principal actors, and then became more refined as different processes and controllers were broken down into more specific components. Figure 24 shows the major components that were initially generated for the control structure. In chronological order, the autonomous vessel controller was diagrammed, then the shore-based control center in communication with the autonomous vessel controller, and then the vessel body in communication with the autonomous vessel controlled processes, and finally the physical and cyber environments capable of influencing aspects of the entire control structure. Figure 24 provides a preview of how the following subsections interact with one another.

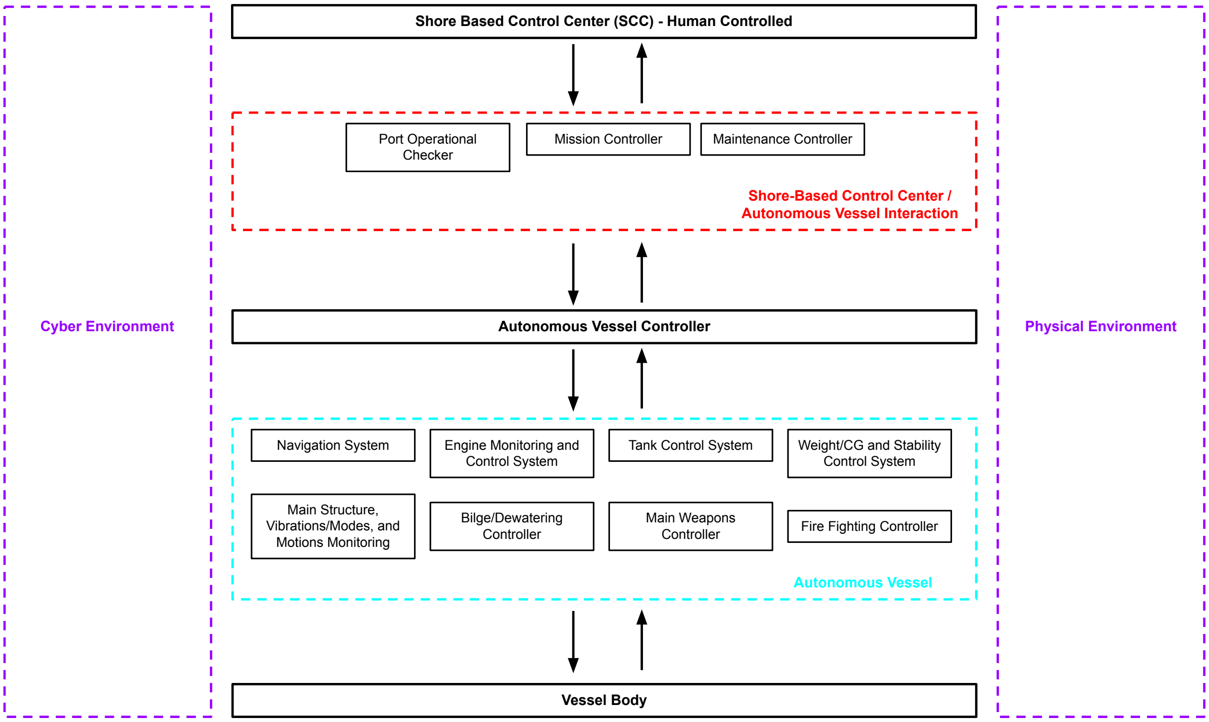


Figure 24: Control Structure Preview

6.3.3 Autonomous Vessel Controller

For the purposes of this project, it was assumed that the autonomous vessel controller should be capable of directing tasks to be carried out on the physical vessel based on mission information received from a higher authority. There were a total of eight controllers/monitors to which the autonomous ship controller would need to send control actions and from which it would need to receive feedback in order to operate the vessel smoothly and completely.

- Navigation System
- Engine Monitoring and Control System
- Tank Control System
- Weight/CG and Stability Control System
- Main Structure, Vibrations/Modes, and Motions Monitoring
- Bilge/Dewatering Controller
- Main Weapons Controller
- Fire Fighting Controller

These lower-level controllers and monitors were developed primarily from accrued knowledge with some influence from papers similarly applying STPA to vessel autonomy; most notably, *A framework to model the STPA hierarchical control structure of an autonomous ship* from Chaal et al. [9] laid out the control structure for an autonomous navigation system that was partially adopted and provided inspiration for the engine and stability controllers. These controllers are described in Table 12 and Table 13.

Table 12: Controlled Processes of Autonomous Vessel Controller

Controller / Monitor	Control Actions	Controlled Process	Feedback
Autonomous Vessel Controller	-Navigational input or commands -Planned routing	Navigation System	-Navigational feedback
	-Vessel power arm/disarm -Desired speed and direction	Engine Monitoring & Control System	-Vessel power armed or disarmed indicator
	-Constraints & ballast levels -Time into mission for ballast change	Tank Control System	-All consumable tank levels
	-Lightship weight & CG data -Variable payload info (load/unload) -Heel, trim, & roll period constraints	Weight/CG & Stability Control System	-Flywheel & fin status
	-Periodic data collection signal -Strain & vibration constraints	Main Structure, Vibrations/Modes, & Motions Monitor	
	-Bilge pumps arm/disarm	Bilge/Dewatering Controller	-Indicators for high bilge water levels -Amount of water build up and discharge
	-Vessel weapon systems arm/disarm -Sensor systems arm/disarm	Main Weapons Controller	-Target in or out of range for original mission -Artillery discharged
	-Vessel fire fighting arm/disarm	Fire Fighting Controller	-Fire indicators for each compartment -Amounts of water or powder discharged
Navigation System	-Start lookout	Situational Awareness System	-Info on fixed and moving objects
	-Depth limits -Object separation limits	Collision Avoidance System	-Real time collision & grounding risks
	-Desired speed and heading info	PNT System	-Actual speed and heading info
	-Generate route plan command	Route Planning System	-Route planning status
	-Communicate collision avoidance or emergency	Reporting & Communication System	-Reporting Status -Target ship messages
	-System on/off	Weather Monitoring System	-Sea state info -Atmospheric weather info
	-Anchoring or mooring command	Anchoring & Mooring System	-Status of command
Weather Monitoring System	-Weather data collection command	Weather Sensors	-Atmospheric weather data
		Motion Gauges	-Sea state related motions data
Engine Monitoring & Control System	-Engine arm/disarm	Prime Mover Controller	-Operational metrics & warnings
	-Generator and/or IPS arm/disarm	Electrical Distribution Controller	-Operational metrics & warnings
	-Propulsion, steering arm/disarm	Propulsion / Steering Controller	-Operational metrics & warnings
	-Auxiliary arm/disarm	Auxiliary Controller	-Operational metrics & warnings
Prime Mover Controller	-Power engine(s) on/off	Engine(s)	-Operational metrics (i.e. RPM, power output, etc.)
Electrical Distribution Controller	-Power generator(s) on/off	Generator(s)	-Operational metrics (i.e. amps, voltage, power, etc.)
	-Power IPS on/off	Integrated Power System	-Operational metrics (i.e. electrical power draws)
Propulsion / Steering Controller	-Power prop. on/off -Desired speed	Propeller(s) or Waterjet(s)	-Operational metrics (i.e. RPM, efficiency, etc.)
	-Power steering on/off -Desired heading	Rudder(s), Surface Drive(s), or Jet Nozzle(s)	-Operational metrics (i.e. angle of attack)
Auxiliary Controller	-Power auxiliary component(s) on/off	Individual Auxiliary Components	-Operational metrics (i.e. temps, fluid/gas flow rates, etc.)

Table 13: Controlled Processes of Autonomous Vessel Controller (cont.)

Controller / Monitor	**Control Actions**	**Controlled Process**	**Feedback**
Tank Control System	-Low level constraints for mission	Consumable Tanks Tracker	-All consumable tank levels
	-Ballast tanks fill/empty arm/disarm	Ballast Tanks Tracker	-All ballast tank levels
Consumable Tanks Tracker	-Indiv. low level constraints	Individual Consumable Tanks	-Indiv. consumable tank levels -Low level indicators
Ballast Tanks Tracker	-Fill or empty command	Individual Ballast Tanks	-Indiv. ballast tank levels -Tank filling or emptying indicators
Weight/CG & Stability Control System		Tank Control System	-All tank levels
	-Fill or empty override command	Individual Ballast Tanks	
	-Solid payload info (i.e. UUV & CRRC launch)	Payload Tracker	-New weight & CG info for all solid payloads
	-Flywheel accel/decel command	Flywheels	-Spin rate, ramp up, ramp down, oscillation data
	-Retract or extend command	Retractable Fins	-Fin appendage data (% they are jutting out)
		Motion Gauges	-Heel, trim, roll period data
Payload Tracker	-Indiv. solid payload info (i.e. UUV or CRRC launch)	Individual Payloads	-New weight & CG info for solid payload
Main Structure, Vibrations/Modes, & Motions Monitor	-Periodic data collection signal to sensors	Motion Gauges	-Acceleration & motions info
	-Periodic data collection signal to indiv. sensors	Individual Structural & Vibration Gauges	-Strain gauge info -Vibration gauge info for sensors in various areas
Bilge/Dewatering Controller	-Indiv. bilge pump on/off	Individual Bilge Pumps	-Bilge pump operational indicators -Indiv. compartment water levels
Main Weapons Controller	-Environmental conditions -Target info	Individual Weapons	-Artillery levels -Operational indicators
	-Weapon sensors on/off	Weapon Sensors	-Target info
Fire Fighting Controller	-Sprinkler power on/off	Sprinklers	-Sprinkler water levels -Temperature levels -Smoke levels
	-Normal extinguisher power on/off	Normal Fire Extinguishers	-Extinguisher levels -Temperature levels -Smoke levels
	-CO2 extinguisher power on/off	CO2 Fire Extinguishers	-Extinguisher levels -CO2 levels -Temperature levels -Smoke levels

6.3.4 Shore-Based Control Center

The shore-based control center was designated as a human-controlled element overseeing the actions of the autonomous vessel while ensuring its longevity and mission success. While this controller would have some interaction with the autonomous vessel-controlled processes, it was also designated to have three unique controlled processes of a higher authority:

- Port Operational Checker
- Mission Controller
- Maintenance Controller

Table 14 details the interactions of the shore-based control center with these new controlled processes, as well as those already established with the autonomous vessel controller.

Table 14: Controlled Processes of Shore-Based Control Center

Controller / Monitor	Control Actions	Controlled Process	Feedback
Shore-Based Control Center	-Perform check command	Port Operational Checker	-Status of check -Check complete -Results of check
	-Initial mission selection from a prompt of vessel mission capabilities (i.e. patrol a route, deploy or collect a UUV) -Forecasted weather conditions (wind speed, sea state)	Mission Controller	-Mission progress (via a percentage) -Mission abandoned/replanned indicator -Live metrics (i.e. speed, duration, location)
	-Performance or time constraints for maintenance -Unplanned maintenance metrics -Forecasted weather conditions -Recently carried out maintenance metrics	Maintenance Controller	
		Navigation System	-Fixed/Moving object or collision warnings
		Engine Monitoring & Control System	-Warning/Failure indicators
		Consumable Tanks Tracker	-Low level indicator
		Weight/CG & Stability Control System	-Unstable warnings
		Main Structure, Vibration/Modes, & Motions Monitor	-High deformation warnings -High vibration warnings -High accel or motion warnings
		Bilge/Dewatering Controller	-Compartment flooding warnings
	-Human SCC permission to engage threat	Main Weapons Controller	-Info on threat detection that was unplanned
		Fire Fighting Controller	-Fire warnings
Mission Controller	-Navigational task selection -Speed & heading info	Navigational / Propulsion Tasks	-Task chosen indicator -Task available indicator
	-Machinery task selection(s)	Machinery Tasks	-Machinery task(s) complete
		Navigation System	-Info on immovable object in mission path -Dangerous weather info -Info from other vessel
		Consumable Tanks Tracker	-Low level indicator
		Maintenance Controller	-Mission override commands
Navigational / Propulsion Tasks	-Task command -Specific port guidelines	Enter Port	-Task complete
	-Task command -Specific port guidelines	Leave Port	-Task complete
	-Task start -Task end or duration to end	Idle or Anchor	-Task complete
	-Task start -Route info -Task end	Cruise Route	-Task complete
Machinery Tasks	-Machinery task command(s)	Autonomous Vessel Controller	-Machinery task(s) progress

Table 15: Controlled Processes of Shore-Based Control Center (cont.)

Controller / Monitor	**Control Actions**	**Controlled Process**	**Feedback**
Enter Port	-Permission for vessel to carry out task -Cruising speed	Autonomous Vessel Controller	-Task status
Leave Port	-Permission for vessel to carry out task -Cruising speed	Autonomous Vessel Controller	-Task status
Idle or Anchor	-Permission for vessel to carry out task -Permission to end task	Autonomous Vessel Controller	-Task ongoing notification
Cruise Route	-Permission for vessel to carry out task -Cruising speed	Autonomous Vessel Controller	-Task ongoing notification
Maintenance Controller	-Time between sensor checks -Data deterioration constraints -Forecasted weather conditions -Recently carried out maintenance measures	Planned Maintenance Tracker	-Indicator that metric evades constraint
	-Arm/Disarm -Unplanned maintenance metrics	Unplanned Maintenance Checker	-Recommended maintenance feedback
Planned Maintenance Tracker	-Expected model data for tasks & weather -Recently carried out maintenance measures	Data Fusion Model(s) (i.e. digital twin)	-Model health results
Unplanned Maintenance Checker	-Constraint values resulting in vessel damage	Data Fusion Model(s) (i.e. digital twin)	-Model health results
Data Fusion Model(s) (i.e. digital twin)		Navigational / Propulsion Tasks	-Info from navigational task performed
		Machinery Tasks	-Info from machinery task performed
		Engine Monitoring & Control System	-Possible failure data
		Main Structure, Vibration/Modes, & Motions Monitoring	-Possible deformation data
		Bilge/Dewatering Controller	-Possible water damage or flooding data
		Fire Fighting Controller	-Possible fire damage data

6.3.5 Vessel Body

At the lowest level of authority in the STPA is the vessel body. While the vessel body houses all aspects of the autonomous vessel controller, it only interacts with certain controlled processes. The following table outlines control actions and feedback between the vessel body and the controlled processes of the autonomous vessel controller.

Table 16: Interactions between Autonomous Vessel Controller Components and the Vessel Body

Controller / Monitor	**Control Actions**	**Controlled Process**	**Feedback**
Collision Avoidance System		Vessel Body	-Vessel local position
PNT System			-Vessel speed & heading
Route Planning System			-Vessel geographic position
Engine(s)	-Possible induced vibrations		
Generator(s)	-Possible induced vibrations		
Propeller(s) or Waterjet(s)	-Propulsion impacts		
Rudder(s), Surface Drive(s), or Jet Nozzle(s)	-Maneuvering impacts		
Flywheels	-Possible induced roll, pitch, or yaw		
Retractable Fins	-Appendage drag		
Motion Gauges			-Vessel motions
Individual Structural & Vibration Gauges			-Vibrations & strain

6.3.6 Physical and Cyber Environments

For the final part of the STPA control structure, it was important to simulate some possible external influences within the cyber and physical environments. Rather than coming directly from the STPA handbook, this part of the analysis was adopted from the cyber-physical system's (CPS) master diagram discussed in Carreras Guzman et al. [8]. Along with the CPS master diagram, prevention barriers were added to the STPA diagram as they are shown in the cyber-physical harm analysis for safety and security (CyPHASS) diagrams also used by Carreras Guzman et al. The prevention barriers are very basic, but they give a general idea of protective measures against physical and external influences that the vessel is not necessarily programmed to handle directly. The following table displays these influences from the cyber and physical environments.

Four threats listed in the physical environment do not have any prevention barriers associated with them, and these four threats include threatening enemy vessels, the sea floor, an obstacle, and external environmental disturbances such as wind, waves, and currents. These threats do not have any barriers because they are more common occurrences that are dealt with within the control structure through various feedback and control action loops. A threatening enemy vessel, for example, will have information picked up by the main weapons controller, will send feedback all the way up to the shore-based control center, and will receive control actions back on how to engage the threat. External environmental disturbances will impact the ship's body directly, which will result in vessel motions and vibrations picked up by motion and strain gauges, and those signals will continue to be fed back up the control structure to be managed.

Table 17: External Cyber & Environmental Influences and their Associated Prevention Barriers

Environment	**External Influence**	**Control Structure Recipient**	**Prevention Barriers**
Cyber	Data Networks	Shore-Based Control Center	-Firewall -Antivirus software -Encryption technology -Other IT technology
	Satellite Systems	Situational Awareness System	-Encryption technology
	Radar Systems	Collision Avoidance System	-Antiflooding technology -Antijamming technology
	Marine Radios	Reporting & Communication System	-Coded messages -VPN network -Wireless access monitoring
Physical	Electric power supply infrastructure	Shore-Based Control Center	-Alarms -Security cameras -Backup generators
	Adversaries boarding vessel	Autonomous Vessel Controller	-Water cannons -Vessel alarms -Disable manual vessel commands
	Threatening enemy vessel	Main Weapons Controller	
	Sea floor	Collision Avoidance System	
	Obstacle	Situational Awareness System	
	External environmental disturbances	Vessel Body	

6.3.7 Visualized Control Structure Diagrams

The complete control structure, as detailed by all of the previous tables is very large and intricate, and it cannot be legibly fit into this report. A PDF version, that is viewable by zooming into the PDF image is included in the appendices in Figure 27. To give at least some sense of the control structure layout and controllers influencing controlled processes, though, the following figure details a simplified version of the diagram.

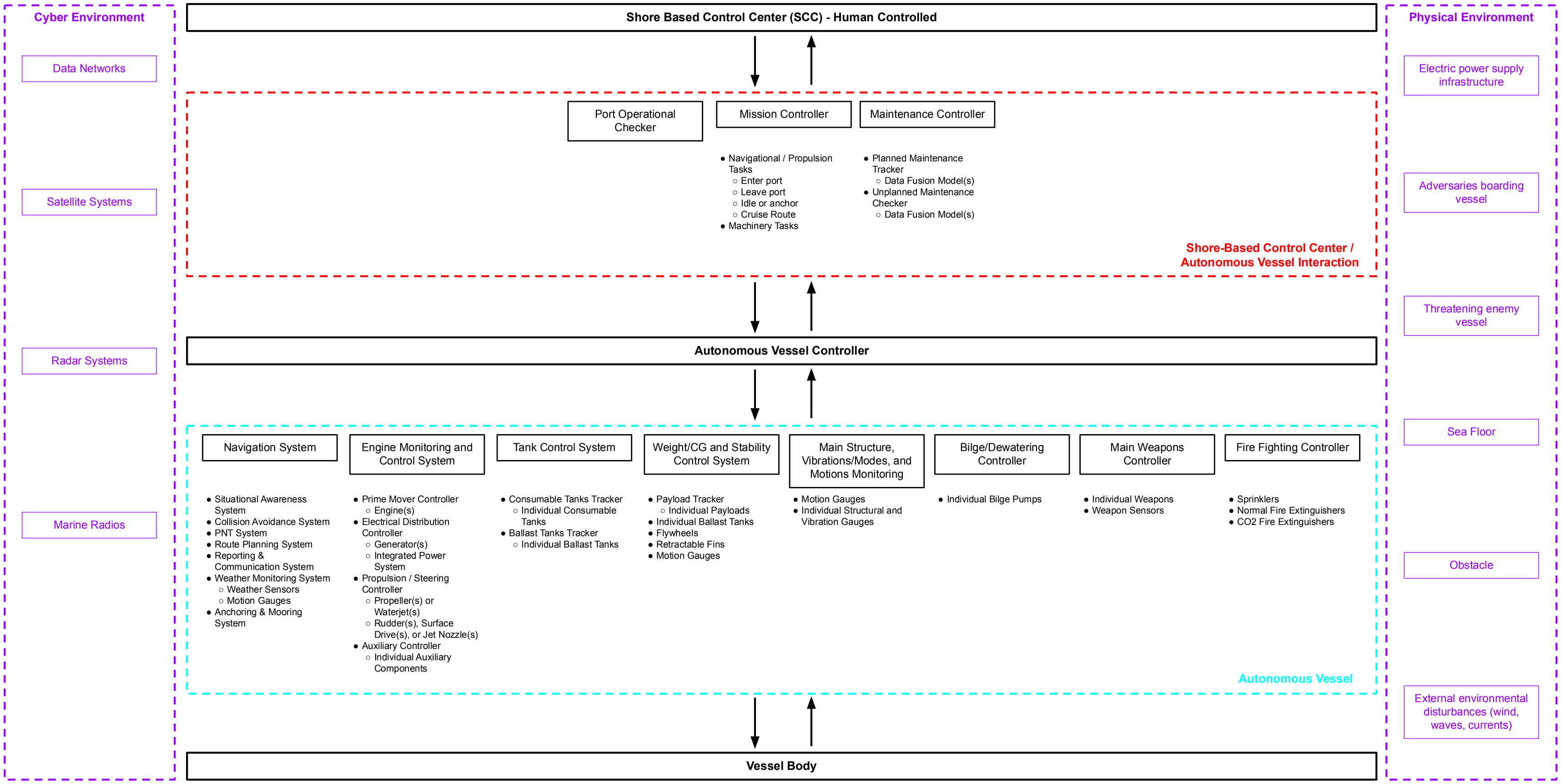


Figure 25: Simplified Control Structure

6.3.8 Conclusions and Shortcomings from STPA Study 1

At this point in the study, unsafe control actions and loss scenarios could be developed if another round of detailed information was available on the individual controllers. However, the scale of such an undertaking would be large for a completely abstract vessel such as the one presented here. The initial modeling of the control structure of a fully autonomous vessel demonstrated all the different controllers that would be working in tangent with one another, and it would be unrealistic to think that each one of these controllers can be explored in the context of a research proposal. It will be up to the project team to single out various controllers, expand on their controlled processes, and start identifying unsafe control actions and loss scenarios for those specific controllers. Additionally, feedback from others in the industry that have more experience with autonomous vessels is desired for the current state of the team's control structure. As stated prior, while some elements of the control structure were partially adopted from the work of others, much of it is based on the project team's own knowledge and brainstorming. Innovative future vessels may adopt different internal architectures that may omit some of these elements and add some others. Thus, the first STPA study is useful for highlighting the number and nature of the control loops that are likely to be present on a crewless vessel; it is difficult to use it to develop prioritized research areas or test cases for autonomous vessels.

6.4 STPA Analysis 2: Higher Level Control Actions

6.4.1 Analysis Setup

While the first STPA was able to identify many hardware and local systems control loops that were necessary for a crewless vessel, the lack of another level of detail in terms of controllers made it hard to come up with a list of unsafe control actions. Additionally, from the hardware-center viewpoint, any unsafe control actions would be specific to specific hardware implementations. However, the background work, interviews, and simulation all suggest that for medium to long-term autonomy, the least understood part of the problem is how the crew integrates and evaluates information today. These planning loops could potentially be made more explicit by modifying the STPA approach taken to address the information flows independent of the hardware of the system. This would be similar to using STPA to look at organizations and decision-making processes which has been documented before [28], though some computational steps would still need to be explored.

To conduct this form of STPA, the first step was to re-examine the loss hierarchy from the standpoint of failing to complete a mission successfully. This is a different loss scenario viewpoint from the prior iteration, which looked at more conventional losses of the vessel, to people or causing environmental damage. However, this viewpoint aligns with the focus of this work on medium to long-term planning tasks that can help move the next iteration of autonomy forward. The revised loss scenarios, and the hazards under them, are shown in Section 6.4.1. Note that some hazards would mainly be a result of short-term systems failure that are outside the scope of the current STPA; these hazards were highlighted in shaded rows, and not considered in the development of the control structure.

Table 18: Losses and Hazards for Second STPA

L-1:	**Loss of control of the vessel**	
	H-1	Loss of communication to vessel
	H-2	Vessel captured - physically or technologically
	H-3	Fuel exhaustion
	H-4	Complete machinery failures
	H-5	Vessel loses watertight integrity
	H-6	Vessel capsizes
	H-7	Vessel runs aground, strikes another vessel, navigational failure
	H-18	Fire on board
L-2:	**Loss of mission capability via poor mission planning**	
	H-8	Vessels enters area where ship motion disables mission equipment
	H-9	Vessel cannot make required speed to complete mission owing to sea state
	H-10	Vessel must conserve fuel and cannot execute planned mission
L-3:	**Loss of mission capability via damage to vessel**	
	H-11	Structural failure onboard
	H-12	Impact/Green seas damage to sensor, propulsion or other equipment
	H-13	Propulsion devices entangled
	H-7	Vessel runs aground, strikes another vessel, navigational failures
	H-18	Fire on board
L-4:	**Loss of mission capability via unexpected failure onboard**	
	H-14	Component failure without redundancy (fails, filters clogged, etc.)
	H-15	Inability to reconfigure system after failure
L-5:	**Loss of availability from unexpected maintenance needs in port or at sea**	
	H-16	Unable to diagnose condition to plan for maintenance
	H-17	Too time-consuming to replace parts owing to vessel design

From the list of hazards and losses, a list of corresponding system constraints was developed. These constraints are shown in Section 6.4.1. Similar to the losses and hazards above, some constraints that were generated would be handled by hardware autonomy or control systems onboard. As the focus for this STPA was medium to long-term planning actions, these shorter-term constraints were highlighted by shading the row they were in. These shaded constraints were not considered in the development of the control structure.

6.4.2 Control Structure

Based on a combination of the losses, hazards, and control actions, as well as the understanding from the interview process of planning tasks, a hypothetical control structure was developed exploring a crewless vessel for long-duration planning. In structuring this control approach, five major actors were identified:

- **Ship:** This is the physical hardware of the vessel, including hull structure, machinery, and electrical components. This system primarily interacts with the **Short-term planning** and control system above (e.g. existing onboard control functions for engines, autopilots etc.). It responds to commands from the short-term planning system and provides feedback to it through a variety of sensors (pressure, current, temperatures, image/video files etc.). The sensors onboard are influenced by the **Design and Support** deciding what to monitor. Physical inspection reports from the vessel, potentially with linguistic and other non-numeric ways of recording data are also produced by the **Ship** actor.
- **Short-Term Planning and Tasks:** This actor represents the short-time-horizon control systems on board the vessel. Machinery controls, navigation controls including course-keeping, collision avoidance, fire detection and response, and similar short-time-horizon tasks are included here. These controllers receive mission plans (e.g. sailing directions, waypoints, system configuration) from the **Medium and long-term planning** block above. This block may also receive demonstration or check commands to try to assess system health from the **Medium and long-term planning** block. Sensor feedback is received from the physical ship, used for local control actions, and also forward to the **Medium and long-term planning** block. Given that many control structures are software-defined, this block also interfaces with the **Design and support** block, sending errors and problems back, receiving updated models and parameters back, and updating the model in-service.
- **Medium and Long-Term Planning:** This block handles the tasks that have been the primary focus of the current report. This includes assessing the state of the ship from the sensor feedback forward from the ship via the **short-term control** block, and reasoning about future mission plans. We proposed that this block should be comprised of three sub-blocks: a mission planner to integrate how and where the vessel will operate while balancing risk and logistical considerations. This is the closest comparison to the role of the captain today. This calculation is supported by two other calculation blocks, a digital twin to model the evolution of the vessel's health and performance over time and a risk acceptance calculation. These later two steps appear to be done informally today, often by discussion and based on experience from the human crew. The challenge here is to make these "softer" human-focused decision processes more explicit.
- **Operations:** Operations represents the remaining shore control functions when the vessel is capable of making medium to long-term planning decisions on its own. Here, information on legal matters, mission goals, and off-ship shore support is coordinated, with data flowing from the vessel, and high-level goals being sent back to the vessel. An important part of this task is setting the acceptable risk level for the vessel. Unlike crewed vessels, where the safety of life mandates a high safety level at all times, the risk accepted by a crewless vessel could be changed on a mission-to-mission basis, depending on the importance of the task at hand and the value of the platform. Even with the

vessel making its own planning decisions, information about offboard support - spares, fuel, and logistical information will not be fully available on board, and will need to be coordinated. Legal matters such as port arrival in overseas nations are likely going to require human assistance from shore as well.

- **Design and Support:** Design and support represents the engineering support for the vessel. While this is typically mainly done at the design stage on crewed vessels, for a crewless vessel to "learn" from experience, models and criteria will also have to be updated through life as experience with the vessel is gained. Thus, in the control structure, design and support are tied to all four of the other structures. During the design phase, the capabilities of the onboard planning routines and the tradeoffs between adding more monitoring sensors and the reliability and power of the monitoring system must be resolved. Additionally, the allowable risk level may need to vary depending on the operational concept, and such variable risk, and the implications on the design, must be assessed. During operation, monitoring, control, and decision-making algorithms may need to be updated as experience is gained with the platform.

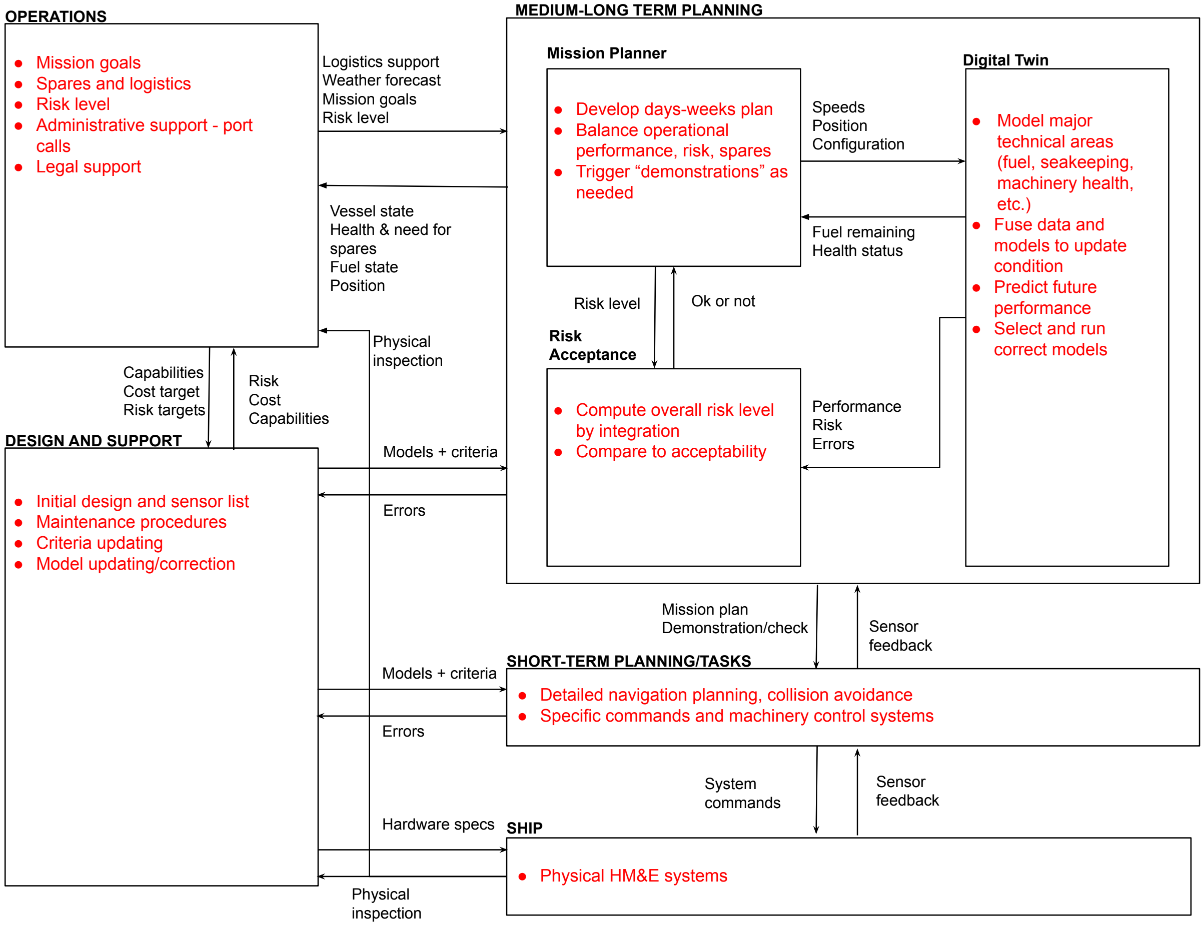


Figure 26: Second STPA Control Structure

Table 19: System Constraints for Second STPA

System-Level Constraint	**Hazards**
Vessel must be able to forecast future fuel usage accurately, accounting for weather and machinery health, or abandon mission	H-3, H-10
Vessel must know the health of all critical machinery components	H-4, H-16, H-14, H-15
Vessel must be able to predict system-level capability given component health	H-4, H-15
Vessel must be able to detect leaks from fluid systems	H-5
Vessel must not enter weather/speed combinations that endanger structure or stability	H-5, H-6, H-11, H-12
Vessel must be designed to withstand foreseeable flooding	H-5
Vessel must possess adequate intact stability for operations	H-6
Vessel must not enter weather/speed combinations that prevent equipment from functioning	H-8
Vessel must be able to predict safe speed given weather forecast	H-9
Vessel must be able to path plan around weather system to complete mission	H-10
Vessel must be able to sense debris in water	H-13
Vessel must be designed to be able to clear propulsors from nets and debris	H-13
Vessel design must ensure sufficient redundancy when sensing and prognosis capability is insufficient to ensure mission success	H-14
Vessel design must ensure sufficient cross-connection of components so that systems can be reconfigured when component reliability insufficient	H-15
Vessel must be able to sense structural damage to plan for repairs	H-16
Vessel must be able to sense and communicate logistics and repair needs	H-16
Maintenance facilities are prepared for any potential repair	H-16
Design must provide sufficient access for repairs when assembling physical system	H-17
Vessel shall be designed to prevent the spread of fire onboard	H-18
Vessel shall be designed to detect and extinguish a fire that occurs	H-18
Vessel shall be designed to minimize the potential for a fire onboard	H-18
Design and operational standards can accurately predict variable risk level	All

6.4.3 Tabulated List of Shortcomings

In a conventional STPA analysis, Figure Figure 26 would be further refined in detail, and then unsafe control actions that could lead to one of the hazards occurring defined. Here, a departure from the formal STPA approach was made. Based on the control structure shown in Figure 26, each control system and its links were initially assessed for the maturity of each area, and topics that may need further exploration were highlighted in Table 20:

6.4.4 Conclusions and Shortcomings from STPA Study 2

A modified STPA approach was taken focusing on the higher-level control strategies, with losses and hazards focused on the unique aspects of the crewless platform problem and a control structure inspired by the tasks identified during the human crew interview process. Compared to the first STPA, this leads to the ability to identify specific areas for algorithm improvements. While many of these are known, such as improved digital twin capabilities, the control structure also highlighted the need to handle variable risk levels and merge multiple sources of data. These are the tasks that were largely done by informal processes in the human crew interviews; the lack of formalization around these processes means that it is not unexpected that these tasks do not have algorithmic equivalents yet. The second STPA study was able to develop a list of communication and algorithmic challenges covering five major actors for the crewless vessel, these were summarized in Table 20.

6.5 Conclusions from STPA Work

Two modified versions of the STPA hazard analysis technique developed by Leveson were applied to a notional crewless vessel. The first approach used an abstract concept design, drawn from past STPA literature, and team brainstorming to come up with a notional control structure. Losses and hazards were all-encompassing safety issues, as in previous studies. Taking a conventional systems-based view of the vessel, the resulting control structure identified the large number of systems that would need to be controlled in parallel, with fairly complex information flows, to realize a crewless vessel. However, this abstract vessel approach struggled to identify areas to prioritize for research, and without more information about hardware and control systems, it was difficult to refine it further. These shortcomings lead to taking a second STPA approach, where higher-level control actions between the vessel, shore, and engineering actors, were explored. In developing the second approach, the losses and hazards were restricted to those unique to the crewless vessel, and a nominal control structure was developed, building from the conclusions of the in-person interviews. While this means the STPA would not be able to identify all possible real-world loss scenarios, it allowed for greater granularity in the crewless control structures. The second approach was more successful in highlighting control structures, communications, and algorithms that would need additional development for a long-term crewless vessel to be successful. These areas were highlighted in Table 20.

Table 20: Areas for Development Based on Second STPA

Actor	**Topics for Development**
Ship	• Incorporating non-numeric sensed data - e.g. inspection reports • Catching failures not sensed by traditional systems
Short-Term Planning and Tasks	• Continued growth in the robustness of autonomous navigation • Ability to respond to more complex alarms - e.g. fire, flooding • Identifying errors in control models to return to design and support task, and updating models during the service life
Medium and Long Term Planning	• Algorithms for data-model fusion • Algorithms to integrate system-level health from component readings • Algorithms to detect errors in prediction for transmission to design and support task • Explicit risk acceptance algorithms to replace experience-based implicit methods used today • Methods for long-term mission planning balancing risk, vessel health, and logistical concerns
Operations	• Ability to communicate and set variable risk level • Ability to prepare for “pit stop” style maintenance
Design and Support	• Ability to update models and safety criteria during a vessel’s life from at-sea feedback • Ability to design explicitly for maintenance in a “pit stop” fashion • Ability to design to specified risk levels • Algorithms to examine trade space between monitoring, redundancy, and reliability when designing crewless systems

7 Research Needs and Recommendations

7.1 Overview of Needs

The exploration of the current state-of-the-art, crew interviews, and the STPA analysis have highlighted a number of challenges in implementing long-duration crewless vessels. It is clear that the technology today does not fully address the challenges of longer-term missions. Few vessels have demonstrated the ability to handle extensive system health assessment, system reconfiguration, or mission re-planning autonomously. In interviewing human crews, many of these tasks appear to be done informally now, with extensive communication and experience-based judgment used to integrate different assessments and make operational plans. The STPA analysis highlighted the types of communication and control structures that need more refinement. However, developing such algorithms in isolation is also difficult - one of the key takeaways from the human interviews was the need to fuse multiple sources of information when making decisions. For this reason, a number of demonstration cases, or scenarios, were developed that integrate several needs into one study. Such cases could help develop several algorithms at once while providing each algorithm with a wider context and outside sources of information necessary to reflect the challenges of the planning problem.

7.2 Suggested Demonstration Cases

Three proposed “demonstration” cases were developed that would allow researchers to explore the types of algorithms and control structures necessary and evaluate their performance. Each demonstration case ties together many of the control functions in Figure 26, yet does not require a complete physical vessel to be built, allowing more rapid development of medium to long-term planning approaches.

The first demonstration case would be a fuel management case. This seems to be the simplest case that would allow initial exploration of forecasts, digital twins, and a custom risk metric. Interview subjects often spoke about integrating fuel management and weather into their plans, so it is also a relevant topic to start with. A fuel management control demonstration would integrate engine and propulsion system health, weather forecasts, and added resistance models, updating these models over the course of the mission. By specifying a mission consisting of speeds and waypoints, an integration algorithm could assess the risk of running low on fuel vs. failing to achieve the mission objectives and adjust the mission plan accordingly. A probabilistic risk approach could be compared to more linguistic risk metrics in assessing mission re-planning.

The second proposed demonstration case would be a design, maintenance, and logistics case. This case would explore machinery health, looking from a design stage viewpoint initially of selecting which sensor signals to add to a design to capture machinery health without a human crew on board and how to complete all the PMS activity tasks currently done on an ongoing basis by human crews in an intermittent, “pit stop” approach when the vessel comes alongside. Again, a variable risk metric would be included at the design stage, trading off between the cost, complexity, and reliability of the monitoring system and the achieved reliability of the machinery system in service. The ability to perform such trades is a relatively unexplored area in the literature. Several interviews mentioned the tradeoff between monitoring a system to guide frequent maintenance and installing a redundant backup that would allow only post-failure maintenance to be performed; it is logical to expect a significant design tradespace to exist between these two approaches. Both time required for “pit stop” maintenance and the likelihood of not having the required spares on hand owing to undiagnosed faults would be important in evaluating the success of the responses to this case.

The third demonstration case would be a risk updating case. The informality of the final decision-making process that was apparent in the interviews strongly suggests that a variable risk acceptance approach might be necessary for crewless vessels. It also suggests that translating the definition of “acceptable” risk from human experience and subjective judgment into an automated system may be a difficult and imprecise task. Additionally, replacing human-based condition assessment with digital twins further complicates setting an acceptable risk level. Thus, this level may need to be monitored and adjusted in service. For a topic such as excessive ship motions, structural damage, or capsize risk, this case would look at setting an initial criterion, setting up the sensors and digital twin system to predict risk during a voyage, monitoring the achieved performance vs. the predicted performance, and adjusting the risk criteria accordingly. An interesting twist to demonstrate here would be the ability to combine the output of multiple models of differing fidelity or assumptions into the assessment, similar to how multiple crew members give input to decisions on board vessels today. Additionally, the problem of model elimination - where a model is dropped in the assessment would be worth exploring. This dropping could be a result of the inputs not being known with certainty (potentially a sensor failure, or a weather forecast is not received), or the model’s performance is degraded owing to changing physics.

These three demonstration cases would cover the majority of the control structures shown in Figure 26. While completing all three would not result in a complete system for application on an actual vessel, it would highlight where we are today with algorithms and approaches for these types of problems. Further demonstration cases could also be developed based on the lessons of these three cases. This, in turn, would spur further research into these areas to improve future performance and give industry the tools necessary to move towards long-term autonomy in a marine setting.

8 Conclusions

The challenge of making a marine platform autonomous for long-duration missions of weeks to months at sea, has been shown to be fundamentally different from the challenges encountered in other areas of autonomy. Self-driving land vehicles and autonomous aerial vehicles have largely been able to use the same maintenance and logistical support as their crewed counterparts. However, long-duration marine platforms will need to take on extensive responsibility for understanding their own system health and planning around maintenance, logistics, and degraded system status. These tasks have not been discussed widely in the broader autonomy literature, indicating that significant fundamental research is necessary before we can produce long-term autonomous platforms.

A review of current systems showed a clear tradeoff between platform complexity and endurance. Gliders and simple platforms have completed weeks-to-month voyages but with high loss rates. More complex vessels are still in the days-to-low-weeks range of mission lengths. In the commercial world, the focus of crewless platforms initially is on short-sea shipping and survey work, where such endurance is likely sufficient, but no existing platforms fully demonstrate what would be required for long-duration naval missions. A new three-component rating system was proposed to track platforms, using decision-making, endurance, and platform complexity as metrics.

As the long-term planning tasks that would need to be addressed for crewless platforms were not yet well documented, a series of interviews with current and former mariners was used to explore the planning approaches in place on crewed vessels. Working with an affinity diagram approach, a number of clear themes emerged from the interviews. Machinery systems were the focus of the majority of the concern around platform health, most vessels had a very well-developed preventative maintenance system (PMS) for specific pieces of machinery. However, integrating the overall health of the platform was done in a human-center manner that was not formalized as a procedure. Much of the longer-term planning was marked by this informality - not to imply that the approaches were not rigorous or successful, but they were not standardized or recorded as a formal procedure. Additionally, the interviews revealed that interactions with the shore establishment and shore engineering staff are common. Off-board help was often used in diagnosing problems, and that off-board concerns and resource availability impact onboard the planning decisions. The interviews thus produced more of a list of concerns than a definite planning approach that could be translated to a crewless vessel.

An initial simulation-based approach was then used to see if the value of automated health assessment would translate into operational gains. A simple “patrol line” simulation was used for this work, with the platform using various assumptions about overall health monitoring. The simulation was highly limited in that a single health metric was used, vs. each vessel needing to integrate an overall system health from many sub-systems. However, even this simple approach showed that the ability to forecast future health status, even if the forecast time horizon was shorter than the time to the maintenance facility, significantly improved the overall mission success and reduced the number of vessels used. This simulation supports the idea that even imperfect long-term planning systems may produce large gains in platform effectiveness vs. static rule-based approaches.

Finally, a modified STPA approach was used to try to explore significant risk areas for long-term planning systems. Two versions of the STPA approach were completed - an "abstract vessel" approach, which followed previous STPA published in the literature, but was unable to identify high-risk areas. A second STPA approach, more narrowly focused on the issues raised in the human interviews and the existing systems review, was more successful at identifying broad areas where existing algorithms may be insufficient. A table of resulting challenge areas was constructed, and three development case studies were proposed - a fuel management study, a machinery design and support case, and an adaptable risk level case. These cases represent a mix of being abstract and relatively easy to implement yet involving enough disciplines and inputs to be broadly representative of the problems highlighted in the human interviews.

The challenges of long-term autonomy at sea may be different from the challenges faced on land and in the air. This report attempts to enumerate and structure these challenges so that researchers can effectively begin to address them. While it is clear that resolving them means exploring how a human-centered knowledge integration and decision-making process can be made in an automated setting, it does appear that a step-by-step approach, using simpler case studies, could provide an incremental path to achieving this capability. In addition to completing this case study, there are many areas that deserve further research attention. The human interviews performed here were a reaction to the emergence of the COVID pandemic; the grant originally proposed to use broader workshops. Getting additional voices, including active-duty military, into the interview process would be helpful, as would discussion with the current operators of the naval autonomous vessels. As the number of autonomous vessels increases, a more detailed STPA on an as-built vessel would also be useful for identifying other areas where research is needed. This report should be seen as a first step in outlining and exploring these marine-specific challenges.

9 Acknowledgments

The authors wish to acknowledge the funding from the U.S. Office of Naval Research under grant N00014-20-1-2044, Dr. Paul Hess, ONR Code 331, which supported this work.

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A Appendix A: Interview Protocol

Information Sheet and Interview Questions
SENATOR
HUM#00179899

Principal Investigator: Dr. Matthew Collette, Associate Professor, University of Michigan
Study Sponsor: Office of Naval Research

Consent Language:
Thank you for agreeing to talk with us today. You are invited to participate in a research study about the technology needs related to making vessels autonomous for several months at a time. We realize that for crewed vessels, the officers onboard and the shore support crews are constantly conducting a variety of planning tasks. The research community does not have a good insight into these tasks, and we want to explore how crewed vessels work before exploring autonomous systems for long-duration deployments.

If you agree to be part of the research study, you will be asked about your experiences conducting long-duration planning tasks during your career. We will use written notes we take today to develop a report about the types of planning tasks carried out afloat and ashore that will be publicly available at the end of this phase of our project. Your name will not be associated with any of the notes we take today, nor will any specific names appear in the final report. We will record only your branch of service, type of role, and type of vessel your experience relates to, as well as your experience. As a DoD-funded research effort, elements within the DoD, including the Office of Naval Research Human Research Protections Program, may review study records consistent with federal guidelines, as well as the final report.

This research will benefit the naval research enterprise in working on autonomous platforms, but we do not anticipate any individual benefit from participating in this research.

We do not anticipate any risks and discomforts related to this research

There is no compensation for participating in this research.

Participating in this study is completely voluntary. Even if you decide to participate now, you may change your mind and stop at any time. You may choose not to continue the interview for any reason.

If you have questions about this research study, please contact Dr. Matthew Collette at 734-764-8422, or by email at mdcoll@umich.edu

The University of Michigan Institutional Review Board Health Sciences and Behavioral Sciences has determined that this study is exempt from IRB oversight.

Summary Information: The interviewee's experience related to (check all that applies)
Served in:

- USN

- USCG
- Commercial / MSC

Experience as:

- CO, Mate
- CE
- Port Engineer

Experience with:

- Nearshore/Coastal
- Deep Ocean

Rough Topic Guide:

For Commanding Officers/Mates

- Ask about their experience for the matrix above
- Explore what type of planning operations they did for the near term:
  - When planning operations in the next 1-4 days, such as helo operations, small boat operations, what aspects of the ship's current condition, and the wider weather/environment would you consider?
  - How might you reschedule operations frequently based on this information?
- Explore how they assessed the current state and capabilities of the vessel:
  - How did you assess the health of the vessel's propulsion and auxiliary machinery?
  - How did you assess the health of the vessel's hull?
  - How did your assessment of these areas impact your mission planning?
  - How would you make backup or contingency plans for changes in the vessel's capability or the external environment?
- Explore how they managed long-range planning:
  - How does the state of the HM&E impact your planning near and long term
  - What sort of considerations impacted longer-range planning for voyages, say weeks to months in the future?
  - How would the availability of fuel impact your longer-range planning
  - How did the availability of parts and logistics support/repair impact your long-range planning?
- Explore how the decision-making process is run:

  - Which other members of the crew would provide you input to both short (1-4 days) and long (weeks to months) planning?
  - How many iterations with shore-side commands or other vessels would occur during this planning?
  - What off-vessel resources went into your decision making?
  - How often did you coordinate with shore resources for supplies and spare parts?
- Ask for other tasks that they performed that we should be aware of that we haven't spoken about yet

For Chief Engineers:

- Ask about their experience for the matrix above
- Explore how they assessed the current state and capability of the machinery systems:
  - How did you assess the health of the vessel's propulsion and auxiliary machinery?
  - How did your assessment of these areas impact the vessel's overall mission planning?
  - Does marine growth on the outside of the ship factor into your decision making?
  - How much did the weather change both the configuration of the machinery or the need for maintenance underway?
  - How often would you make backup or contingency plans for changes in the vessel's capability or the external environment?
  - How would you communicate the state of the machinery system to the commanding officer and others?
  - How would future operational needs later in the mission impact your decisions around operations and maintenance of the vessel's machinery?
  - How does the method of assessing the health of a ship system affect your decision? (in person, via another ship's crew, sensors, or other measurement devices)
- Explore how they managed long-range planning:
  - What sort of considerations impacted longer-range planning for voyages, say weeks to months in the future?
  - How would the availability of fuel impact your longer-range planning
  - How did the availability of parts and logistics support/repair impact your long-range planning?
- Explore how the decision-making process is run:
  - Which other members of the crew would provide you input to both short (1-4 days) and long (weeks to months) planning?

  - How many iterations with shore-side commands or other vessels would occur during this planning?
  - What off-vessel resources went into your decision making?
  - How often did you coordinate with shore resources for supplies and spare parts?
- Ask for other tasks that they performed that we should be aware of that we haven't spoken about yet

For Port Engineers:

- Ask about their experience for the matrix above
- Explore how much information is communicated back from the vessels in service:
  - How often would you work on problems for vessels currently underway?
  - Before vessels arrived in port, how well could you tell what sort of maintenance and logistical support they would need?
  - Did details of the deployment, such as the weather the vessel encountered or the vessel's operating profile, change how you prepare to maintain the vessel when it arrived in port?
- Explore how much the human crew experience influenced the maintenance in port:
  - How many repairs or overhauls were clearly needed by time or obvious fault vs. repairs requested by the crew based on something they had observed when underway?
  - When assessing machinery and structures in port for repair, what techniques were used?
- Explore the architectural implications of having no crew and potentially limited access onboard for repairs (e.g., designed for machinery modules to be removed as units for the ship and worked on in shore facilities away from the vessel):
  - How much work is typically performed onboard the vessel, vs. removing a part to be repaired/reconditioned off the vessel?
  - How much pier-based shop support and infrastructure exists for off-vessel repairs?
  - How does physical access to structures and machinery impact your current repair scheduling?
- Ask for other tasks that they performed that we should be aware of that we haven't spoken about yet

B Appendix B: First STPA Detailed Control Structure

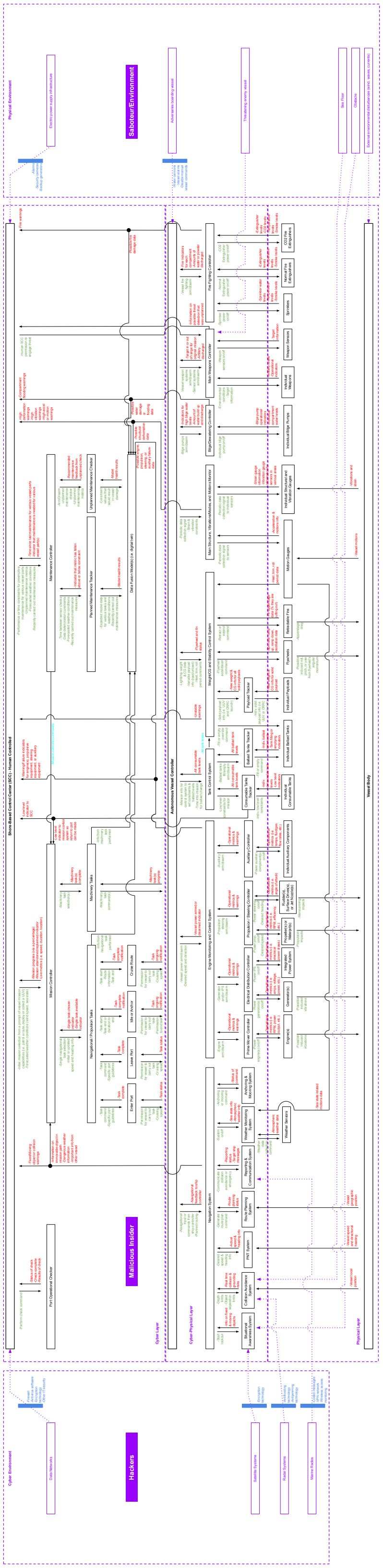

Figure 27: Complete First STPA Control Structure