# The Design of an Intelligent Decision Support Tool for Submarine Commanders

by

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B.S. Systems Engineering
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## Abstract

A recent search of headlines shows a high number of maritime collisions and accidents. The USS *Hartford,* a nuclear submarine, recently surfaced into an oil tanker just after the running aground of the USS *Port Royal* in Hawaii. Internationally, a French and British submarine collided in the Atlantic Ocean. The high frequency of these maritime accidents points to the need for a better decision support in ship and submarine navigation. Towards this end, this thesis proposes a mobile decision support tool to aid maritime commanders in maintaining situational awareness and aiding in navigation and collision avoidance.

The Mobile Situational Awareness Tool (MSAT), specifically designed for submarine commanders but extensible to all maritime settings, provides mobile information for health and status monitoring and on-the-fly path planning capabilities. The functional and informational requirements for MSAT were identified through an in-depth analysis of submarine operations, specifically through a cognitive task analysis. The MSAT design incorporates a path planning algorithm that accounts for depth, land, visibility, and other contacts to propose the most efficient path from start to finish, especially useful for navigation in littoral regions. The MSAT also provides health and status monitoring capabilities, tracking many of the important systems across a submarine to provide information to the commander, as well as maintain high situational awareness.

Human subject experiments showed that when compared to paper charts, the navigation tool in the MSAT performs significantly better with regards to both path length and the time it takes to plan a new path. For health and status monitoring, a survey of current task times revealed potential savings by the MSAT by decreasing both the average and variability of task time. By reducing the number of physical movements needed by commanders through the use of a mobile tool, time is saved that can be used for task reallocation, or promote a change in task flow.

There are many potential benefits for both the Navy and the commercial maritime community that the MSAT can provide. However, before the MSAT can become operational, there are some system implementation issues that must first be addressed.

These range from an analysis of the hardware and software required, to the changes in training that might come from the addition of a new tool. Future work is needed in this area to help move forward so that the benefits can be realized across the maritime community.

Thesis Supervisor: Mary L. Cummings
Title: Associate Professor of Engineering Systems

# Acknowledgements

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# List of Acronyms

| | |
|---|---|
| 3D | Three Dimensional |
| AIS | Automatic Identification System |
| ARL | Applied Research Laboratory |
| ARPA | Automatic Radar Plotting Assist |
| CO | Commanding Officer |
| CT | Connecticut |
| CTA | Cognitive Task Analysis |
| CPA | Closest Point of Approach |
| CPU | Central Processing Unit |
| ECDIS | Electronic Chart Display |
| EDO | Engineering Duty Officer |
| ETA | Estimated Time of Arrival |
| Ft | Feet |
| GPS | Global Positioning System |
| H&S | Health and Status |
| HCTA | Hybrid Cognitive Task Analysis |
| HMS | Her Majesty's Ship |
| Hr | Hour |
| HSI | Human-System Integration |
| Kts | Knots (nautical miles per hour) |
| Lat | Latitude |
| Long | Longitude |
| MD | Maryland |
| MPC | Model-based predictive controller |
| MSAT | Mobile Situational Awareness Tool |
| Nm | Nautical Miles |
| OOD | Officer on Deck |
| P and S | Port and Starboard |
| PAD | Predicted Area of Danger |
| PC | Personal Computer |
| PSI | Pounds per square inch |
| ROT | Rate of Turn |
| Rud. Ang. | Rudder Angle |
| SA | Situational Awareness |
| Sec | Seconds |
| SME | Subject Matter Expert |
| UAV | Unmanned Aerial Vehicle |
| UHSIS | Undersea Human Systems Integration Symposium |
| USS | United States Ship |
| UUV | Unmanned Underwater Vehicle |
| VMS | Voyage Management System |
| XO | Executive Officer |
| Yds | Yards |

# 1. Introduction

Submarines play a vital role in the nation's defense, but not without problems. Recent U.S. Navy collision and grounding incidents involving the USS *Greeneville*, USS *San Francisco*, USS *Newport News*, and more recently the USS *Hartford* along with numerous other collisions have highlighted the difficulty of submarine navigation operations (Burns, 2009; Fishel, 2009; Hamilton, 2005; NTSB, 2001; Riley, 2009; Scutro, 2007). These accidents occurred for a variety of reasons, including outdated paper charts and lack of information accessibility, in all cases leading to a lack of situational awareness (SA) by the commander.
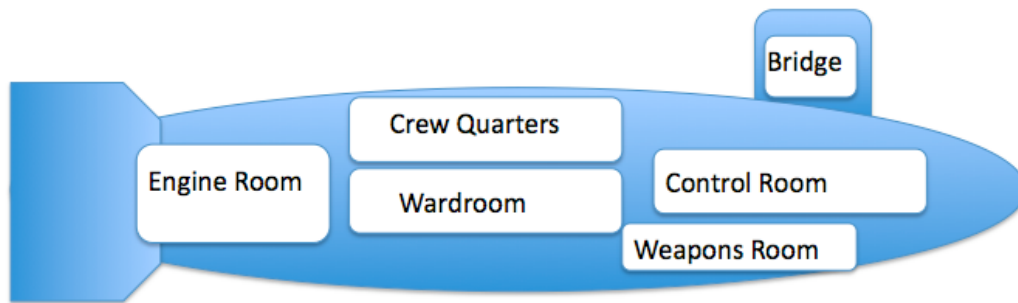


**Figure 1: Submarine Layout (Side View)**

Situational awareness has been a popular topic among both civilian and military operators ever since the term was first coined by the military (Bovier, 1997). SA, as defined by Endsley (2000), refers to the perception, comprehension, and projection of surrounding elements in an environment. Although the term is often cited in aviation contexts, the concept of understanding one's surroundings and being able to predict the future is important across many domains. The submarine environment is one realm where commanders spend a great deal of time analyzing their surroundings to build their situational awareness. The commander is in charge of safety and directs the submarine's activities, and he is responsible for these no matter where he is physically located on the sub. The problem is that the information needed to ensure safety and direct the activities of the sub is only available in the control room, notionally depicted in Figure 1. While

checking on the engine room or eating meals in the wardroom, the available information is limited.

To check the detailed information, officers must go to the control room. The control room on a nuclear submarine is where multiple information sources (including sonar, radar, Global Positioning System (GPS), and visual lookouts) are presented to the commander through surrounding displays. This information is disjointed, and during complex maneuvers, the commander may not have the full picture until it is too late. This separation of information limits the commander's SA, increasing the risk of collisions or other problems. This was the case with the USS *Greenville*, which collided with a Japanese fishing vessel while demonstrating its capabilities in the Pacific Ocean in 2001 (NTSB, 2001). During a series of turns and depth changes, the commanding officer lost SA, and ran into the Japanese vessel while surfacing, resulting in the loss of nine lives. The other accidents mentioned above also relate to a lack of SA and are discussed in further detail in Chapter 2.

Inside the modern submarine, a wealth of technology is available, but rapid development has led to the paradox of technology, where the increased functionality decreases the ease of use (Norman, 1988). The amount of information available surpasses the commander's ability to monitor and extract the necessary information, which leads to the delegation of monitoring tasks to others. Under this current operational paradigm, critical information can be missed or lost during communication, assimilation, or synthesis. This makes it difficult for the commander to create an accurate mental model and maintain appropriate levels of SA. With nuclear submarines costing billions of dollars and supporting a crew of over 100 people, it is important to ensure safety of operations for both the crew and the asset itself (Wiltrout, 2008). Therefore, there is a need to consider new ways of presenting information to the commander to not only enhance safety through improved SA, but to also establish more efficient systems management.

One way supervisors of complex systems can handle the overwhelming amount of information is with decision support tools (Delic, Douillet, & Dayal, 2001). As

technology provides an increasing amount of information to the operator, these tools act as aids in condensing information to display it in an efficient manner. There are many different technologies used in the commercial maritime environment to provide navigation decision support, such as electronic charts and commercial radar systems with automatic trajectory recommendations. Electronic chart displays and Automatic Identification Systems (AIS) have been commonplace for years in commercial maritime environment, but were not approved for military operations until 2008 (Rhodes & Delaney, 2008). AIS broadcasts commercial and merchant ship information, including position, speed, and course to all surrounding boats. With electronic charts, the AIS information can be displayed to the operator. These tools can be beneficial to the submarine community in solving some of the SA-related problems by aggregating and highlighting critical information. However, these tools are localized to the control room, are not integrated to aggregate information, and cannot be monitored at all times by the commander himself who may leave the control room at times. A revolutionary way to support the commander is to make the critical information available in an integrated fashion to the commander, independent of his location on the submarine.

Along with the need for better presentation of information, the need to be mobile is also increasing for operators in all environments. Mobile text messaging, email, Internet, and even stock trading tools are increasing in popularity. Small Unmanned Aerial Vehicles (UAVs) can now be controlled using handheld devices offering full functionality (Kutta Consulting, 2007). The increased capabilities of mobile tools can provide help in the complex submarine environment. Mobile tools would increase flexibility by allowing the commander to stay active, while presenting critical information in the quickest way possible.

Via an in-depth analysis of submarine operations, this research identified design requirements for a mobile decision support tool for commanders. A decision support tool was developed based on the identified requirements. A human subject experiment was conducted to test the effectiveness and acceptance of this tool, showing that operators performed navigation tasks more effectively and in less time with the tool when

compared to paper and pencil methods. While this thesis focuses specifically on submarine operations, any supervisor of time-pressured, complex systems could potentially benefit from this research.

## 1.1 Problem Statement

The task of commanding a submarine is a complicated process, particularly due to the large amount of data intake and the bottleneck of information going to the commander. Information displays are becoming increasingly important as new technologies aid in building the surrounding picture. For a submarine commander, there are many different tasks that must be constantly balanced, from navigation and weapons control to management of the crew and planning future paths. These high cognitive requirements demand intuitive displays that present critical information to the commander for immediate decisions. By presenting this information on a mobile device, the commander would gain a further benefit by not being confined to the control room.

## 1.2 Research Objectives

In order to address the problem statement, the overarching goal of this research is to develop a mobile decision support tool for submarine commanders. This goal is addressed through the following research objectives:

- Objective 1. **Study current submarine operations and determine the causes for operational inefficiencies.** The first step in this process is to determine how submarine operations are conducted, what the goals are, and determine the causes of recent accidents. Chapter 2 discusses background information on the submarine environment, and some current research being conducted to help address these problems.

- Objective 2. **Study the cognitive strategies employed by submarine officers during operations.** In order to achieve this objective, a cognitive task analysis (CTA) was conducted. The CTA was used to identify the information inputs and

decision processes involved in both navigation and health and status monitoring. This process and its results are outlined in Chapters 3.

- Objective 3. **Develop a mobile decision support tool for use in maritime domains.** Based on the results of the CTA, a mobile decision support tool was designed for the submarine environment, the Mobile Situational Awareness Tool (MSAT). This tool addresses a subset of the overall submarine functions listed in Chapter 2. A discussion of the design and functionality of the display can be found in Chapter 3.

- Objective 4. **Evaluate the effectiveness of the new decision support tool for the maritime environment.** Human subject testing was conducted in order to fulfill this objective. Civilian maritime operators, along with members from the Navy and Coast Guard, were tested and interviewed to gain information on how well the task of path planning could be augmented by automation. Subjects were also questioned as to how health and status monitoring on the mobile display would affect operations as compared to current methods. Finally, subjects filled out a questionnaire and were interviewed to determine their attitudes towards the mobile tool, in particular trust and confidence. Results of these tests are provided in Chapter 5.

- Objective 5. **Determine the system implementation issues involved in integrating a mobile tool into the current submarine operating environment.** The integration of any new technology involves changes beyond the tool itself. Training, manning, responsibilities and workflow can all be affected. Chapter 6 discusses the issues that must be overcome for system implementation, from software and hardware to the effects on operations themselves.

1.3 Thesis Organization

This thesis is organized into seven chapters:

- Chapter 1, *Introduction,* provides the motivation for this research, research questions, and the research objectives of this thesis.
- Chapter 2, *Background,* reviews current submarine operations and discusses some of the shortcomings. Submarine functions are broken down and described in order to generate design requirements. This chapter also discusses how mobile technology has developed in other fields.
- Chapter 3, *Design of the Mobile Situational Awareness Tool*, explains the method used for developing the MSAT. After detailing the Cognitive Task Analysis (CTA), this chapter discusses the process of determining information requirements and finishes with a description of how the final interface works to meet these needs.
- Chapter 4, *Evaluation Methodology,* discusses how the MSAT was compared to current submarine operations, and what assessment strategy was used to gauge the effects of the MSAT. An experiment comparing paper and pencil navigation versus the MSAT was performed, and results are presented.
- Chapter 5, *Results and Discussion,* explains the results of the testing including the survey feedback and trust analysis.
- Chapter 6, *System Implementation,* discusses issues with the implementation of this technology. Manning issues, task allocation, and software and hardware requirements are discussed as they pertain to the addition of a tool such as the MSAT to current operating environments.
- Chapter 7, *Conclusion,* reviews the answers to the research questions, discusses how the MSAT fits into the future submarine environment, and suggests areas for future research.

# 2. Background

This chapter provides information on current submarine operations including sea surface operations. Historical shortcomings are discussed, along with design changes provided by the newest class of submarines, the Virginia class. Previous research into path planning, automation, display design and decision support is also discussed. Finally, mobile command devices and technology are introduced to demonstrate how the advances can help a commander to remain in the loop without being tied to a specific location.

2.1 Current Submarine Operations

The Navy operates two different types of submarines, ballistic missile submarines and attack submarines. The most recent model is the Virginia attack class (Pike, 2008), which will be referenced throughout this thesis as it represents the current state-of-the-art in submarine technology.

All of the Navy's combatant submarines are nuclear-powered, which provides superior capability in terms of range and power as well as increased responsibility. Submarine operations tend to have a high stress environment, partly due to the onboard nuclear reactor. Information regarding the reactor, the cooling systems, as well as atmospheric levels throughout the submarine requires constant monitoring. This information, along with updates on surrounding ships (contacts) and weather is continuously passed up through several layers of personnel to the commanding officer (CO), who is responsible for everything and everyone on the submarine.

One commonality in all military operations is the underlying rank structure that helps to define roles and responsibilities. The hierarchy on a submarine helps to define clear positions for each member and prevents overlapping duties and tasks. The flow of information is highly vertical, with sensor operators such as sonar and radar watchmen passing information up a hierarchical chain of command to the commander of the submarine, who then builds his mental model based on the various information inputs. Most of this monitoring occurs in different stations in the control room, where various

crew members process information. The CO is then notified of any important updates as the submarine tracks along its course.

Today's submarines are capable of many different mission types, from surveillance and intelligence to sea denial and precision strike, and each mission type requires its own specific information. During each mission, priorities change, as speed is traded for silence, or an offensive position for a defensive one. The information that becomes most important for the commander changes (Norfolk Naval Base, 2008). This information comes from many stations and people across the submarine, in support of many different functions. Figure 2 shows a mapping of how these functions and missions are related.
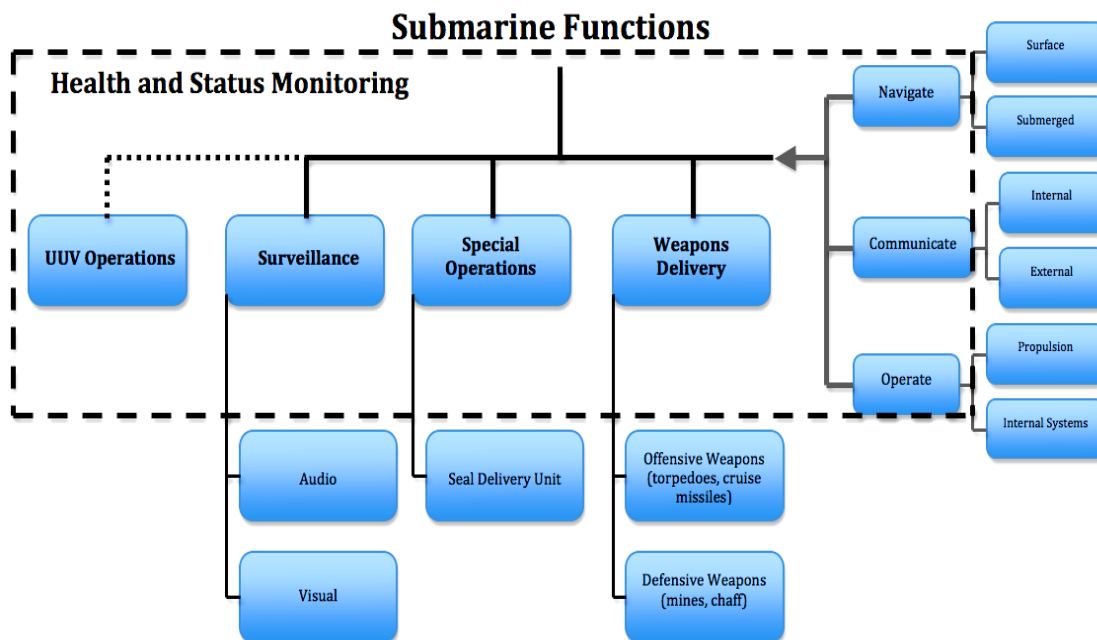


**Figure 2: Submarine Functions**

In Figure 2, basic operating functions are shown on the right (navigate, communicate, and operate), as these are required for all of the mission types shown in the middle (surveillance special operations, weapons delivery). All of these processes are accomplished with different information requirements and control inputs. Furthermore, regardless of the specific function, the commander must also be constantly involved in health and status monitoring of all systems, to ensure that the safety of the ship remains

intact. In the identification of submarine functions, future missions using UUVs were also considered, as this is a function likely to be needed in the future (Bhattacharjee, 2007).

Both between and during different missions, submarines come to the surface to update information systems. This allows the submarine to maintain contact with other ships, as well as link to Global Positioning System (GPS) and radio communication. During surface navigation, there is a great deal of effort put into path planning and navigation, as the likelihood of surrounding contacts increases and collision avoidance becomes a top priority in littoral regions (Lebkoswki et al., 2005). Although navigation tasks are critical to the safety of the submarine, they are still currently completed with paper charts and pencils on many of the Navy submarines that do not yet have Electronic Chart Displays (ECDIS) (Wiltrout, 2008). One of the advantages of the ECDIS is the ability to overlay information such as depth and surrounding obstacles directly on the chart. Electronic Chart Displays are currently available on most civilian commercial ships, but until recently they were not approved as a primary means of navigation for military ships.

In the control room, there is a crew of anywhere between eight and eighteen personnel, each member passing critical information to their direct supervisor, until the information reaches the CO. Figure 3 shows the typical layout in the new Virginia Class submarines. In the front (top of Figure 3), a pilot and co-pilot are in charge of driving the submarine using inputs on a touch screen display. The Officer On Deck (OOD) is the officer in charge of the control room, and the position rotates through crew members, including junior and senior officers. Whoever occupies the position gives navigation and monitoring orders throughout his shift. In the front of the submarine, the pilot is in charge of monitoring any warnings from the engine or pressure systems and following the commands of the OOD.

There is also a team of people who search the surrounding waterways for other contacts. At one station, a team of sonar operators listens for other boats, and at another, radio and radar operators do the same. There is also a person checking visually for other boats using photonics, and all of this information is sent to the fire control stations where

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contacts are monitored. The contact coordinator tracks these contacts as the pilot navigates along the path. Future paths are planned by the navigator, and put onto a chart by the plotter. The contact coordinator tracks information using the Voyage Management System (VMS), which is an integrated ECDIS display, discussed further in section 2.1.3. All personnel work together sending information to the OOD to keep the submarine out of harm's way.
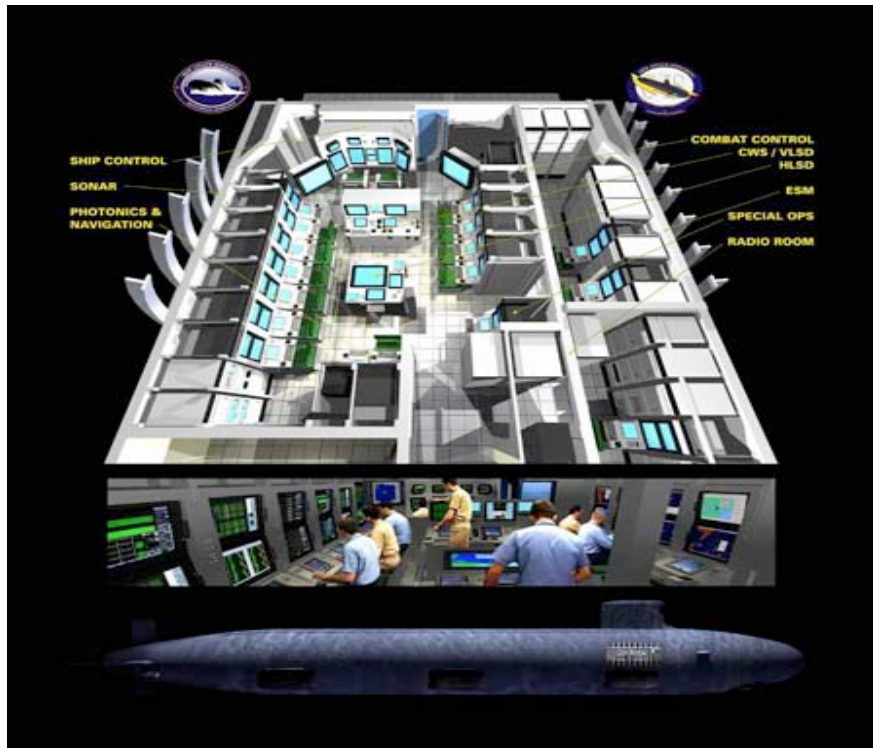


**Figure 3: Virginia Class Control Room (Connor, 1999)**

During all operations, the commander and the executive officer (XO) remain at the top level of command, with the XO aiding the commander and serving as the second in command. During complex scenarios, the CO or XO will fill the role of the OOD. This information flow is represented in Figure 4. With so many information sources and players involved, the control room becomes a very high stress area, and the shortcomings are discussed in the next section.
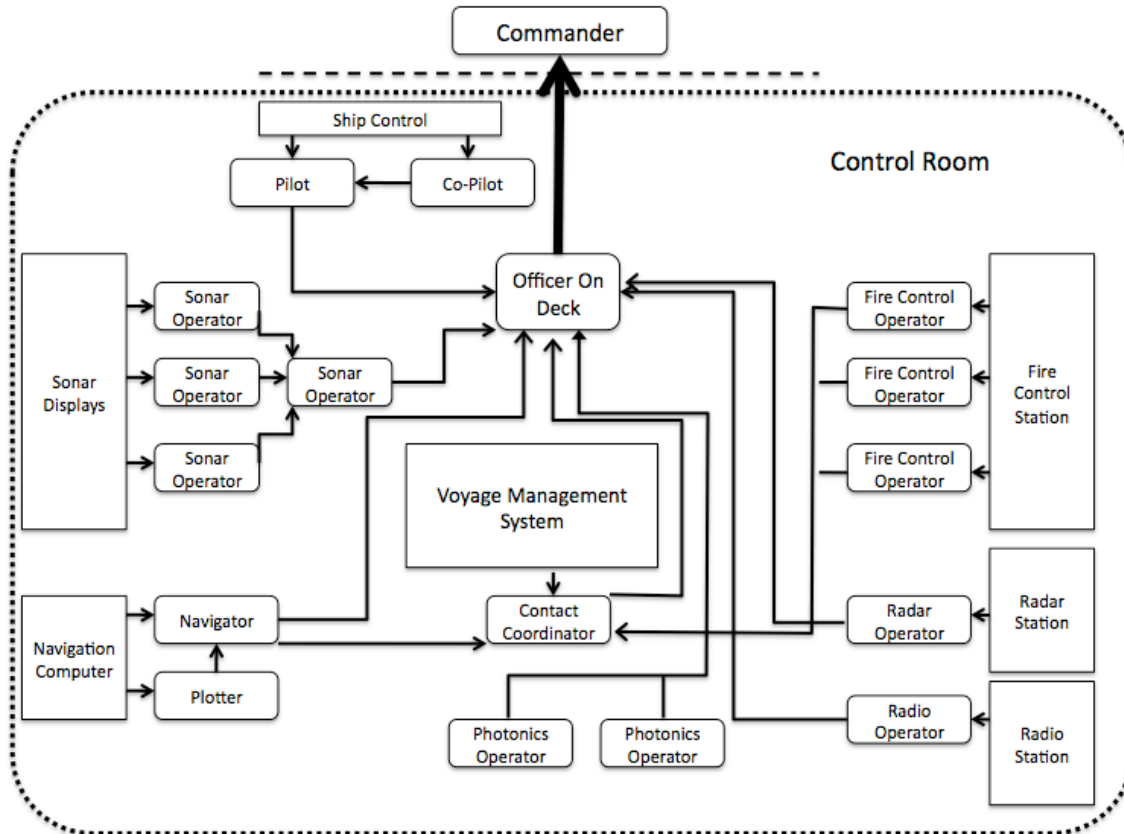
**Figure 4: Information Flow in the Control Room**

2.1.1 Shortcomings

This section describes some of the problems within the submarine community addressed through this research. First, a discussion of recent submarine crashes is presented, followed by some of the problems with current navigation processes. Operations are discussed with respect to the crew, noting the need for officers to be mobile, and how this mobility can add difficulty to maintaining the flow of information. Finally, the design of the submarine is discussed with regards to the current problems of adding new technologies.

Over the past few years, there have been various accidents that highlight difficulties in submarine navigation. Two specific examples are the Los Angeles Class USS *Greeneville* and the USS *San Francisco*. The USS *Greeneville* surfaced into a Japanese fishing vessel in 2001, and the cause of the accident was the inadequate interaction and communication among senior members of the combat systems team (NTSB, 2001). Problems with the

equipment used to track contacts led to the eventual incomplete contact picture, with missing information on the position of one of the neighboring ships (NTSB, 2001). The USS *San Francisco* also suffered from a collision, running into a sea mount southeast of Guam. This collision was the result of outdated paper charts, which were not accurate for the changing depths of the sea floor (Hamilton, 2005). For instance, the Notice to Mariners (a document used to update paper charts) including updates on this sea mount was over 58 pages long, covering hundreds of changes. This update was also only one of fifteen given during the calendar year, making it very difficult to stay current.

More recently, three accidents have occurred in the military maritime community, bringing added attention to the current safety of operations. On February 5, 2009, the USS *Port Royal* ran aground off the coast of Hawaii, while navigating in shallow water (Riley, 2009). The *Port Royal* is a Ticonderoga-class guided missile cruiser, with a cost of $1 billion to build and a crew of 360 (Riley, 2009). Less than two weeks later, the British HMS *Vanguard* and the French *Le Triomphant* collided in the Atlantic Ocean. Both were operating in the same area and were unable to detect each other. After the crash, the French submarine did not realize what it had hit, and determined it was the British submarine only after returning to port (Burns, 2009). The third accident was a collision between a submarine, the USS *Hartford*, and another Navy ship, the USS *New Orleans,* which collided when the submarine was surfacing in April, 2009 (Raphael, 2009). The full details of the collisions have not yet been released, but the frequency of these incidents highlights the need to increase the safety of maritime navigation operations.

These accidents illustrate that outdated technologies, and also poor workflow processes contribute to navigation problems. Typical submarine workdays are 18 hours long, with 12 hours on and 6 hours off. This leaves little time for sleep or rest, and also means many shift changes and position switches. In a submarine, the information needs to be constantly passed to shift replacements, and the crew must maintain constant vigilance to prevent information from being lost between shift changes. The CO is also very active, moving around to different parts of the ship, always ready to be contacted by the control

room if a situation arises. Although the Virginia Class is only about 100 yards from end to end, the series of turns and hatches inside a submarine separate the compartments, and slow movement. This can make it difficult for the CO to get up-to-date information, depending on where on the ship he is. Even if there is an intercom system, the amount of information that can be transferred through broadcasting is limited. It is also difficult to present information clearly without a visual picture, which keeps the intercom from being used if it can be avoided. Moreover, broadcasting over the intercom is infeasible when silence is needed for operations.

The flow of information itself can also be limiting, due to the rank hierarchy used in the submarine, the flow of information is typically from bottom to top, with limited horizontal communication. For instance, in the straits of Hormuz, the attack submarine USS *Newport News* collided with the Japanese merchant vessel *Mogamigawa* in 2007 when crew members, who were assembling the contact picture, did not pool all of the information, resulting in the collision of the two vessels (Scutro, 2007). Each operator saw only a small part of the information, and rather than comparing data, each member disregarded it as noise. This lack of information sharing can also be seen in the system design as well, as the relatively new Automatic Identification System (AIS), an automated system used to track and identify nearby ships, has been added to submarine control rooms without changing the information on the fire control displays. This means that rather than sending the contact information automatically into the rest of the system, AIS information stays on a separate screen unless manually entered into the fire control displays.

This lack of information integration is a general trend in the submarine community, where new technologies are added without re-designing the surrounding systems. Although the submarine community has started to integrate new commercialized products such as Furuno Radar© and AIS, which simplify the tasks of monitoring and tracking contacts, these systems are often added as afterthoughts. Designing the system as a whole would allow the full functionality to be achieved, incorporating AIS data and radar positioning across all stations from contact coordinator and fire control to the plotter.

### 2.1.2 Virginia Class Updates

The Virginia class comes with many technological advancements, such as photonic masts that replace the standard periscope with an electronic camera, and a reactor that lasts the life of the submarine (Pike, 2008). Although there are many improvements over older submarine classes, there are still shortcomings. For one, atmospheric levels must be tracked hourly by hand, and this task is done using a mobile handheld device. This device is then synchronized with a computer before the information is actually entered in the system, and even then, trend analysis is not available in any visual form. There are also problems with the warning systems, as there is no ability to set custom warning levels. Only pre-programmed levels can be used, which is sometimes not when the commander wants the actual alarm to go off. These and additional shortcomings will be discussed in Chapter 3, which details the results of a cognitive task analysis.

### 2.1.3 Voyage Management System

One important update seen on the Virginia class is the Voyage Management System (VMS). Until the emergence of the Voyage Management System, the Navy required all navigation to be performed using paper charts. The VMS is the system used by the US Navy to replace the old paper and pencil navigation methods. The VMS is an ECDIS that takes information from the Navigator, radar, GPS, and Fire Control and incorporates information into a single view. This view shows the ownship location and heading, as well as other contacts and their courses. It also leverages the strength of automation to perform electronic dead reckoning and sound alarms when limits are breached. The VMS is a powerful tool and has greatly simplified the task of navigation by reducing the work for the human and presenting a refined picture of surroundings. However, the VMS still has problems. Through interviews discussed more in detail in Chapter 3, issues with redundant warnings and system lockups are still present.

### 2.2 Previous Research

One question within this research is how to increase safety and efficiency for surface operations. Surface operations were chosen as a focus area due to the increased complexity that comes with operating a submarine on the surface, i.e., there are many

more contacts on the surface than under the water. In addition, the focus on surface operations allows for greater generalizability to other maritime settings. The following sections contain information on current research and developments relating to submarine navigation operations and the use of automation in support of these tasks.

2.2.1 Automation

As maritime technology continues to advance, tasks previously conducted by the human can now be automated. This can equate to long-term cost savings, reduced manning, and more consistent and predictable outputs. With any use of automation, it is important to define roles to keep the right balance of workload and decision making power. When task allocation is done well, the system is able to leverage the strengths of the human mind with the power of automation to minimize human weaknesses (Cummings & Bruni, 2009). It is also important for the user to understand what the automation is doing and why, which leads to predictable outputs regardless of the level of automation (Billings, 1997). In general, research has shown that intermediate levels of automation that keep the user involved work well in situations allowing for human in the loop control (Endsley & Kaber, 1999).

For the crew on a submarine, automation can provide many benefits. Sensors that will warn the crew if critical levels are reached can do many of the monitoring tasks that are currently done by hand, such as checking pressure gauges and monitoring air levels. Automation can be especially useful for path planning, where automation performs skill and rule based tasks such as mapping and connecting waypoints so humans only have to focus on knowledge-based reasoning (Rasmussen, 1983). Previous research has shown that leveraging computer-generated paths can lead to more efficient paths when compared to human generated paths (Marquez et al., 2005). This research points to the benefits of using automation for path planning when there is a clear set of rules for the computer to follow. This is the case with maritime navigation, where obstacles, constraints, and navigation rules dictate the possible solutions. Automation can quickly search possible paths to determine the most efficient based on the user's needs.

Other research has shown that automation is especially helpful for time critical situations (Johnson et al., 2002). On a submarine navigating through the littoral regions where contact density is high, time plays a major role in route planning. In addition, further studies indicate that automation should propose solutions, not just check the feasibility of a user's input (Chen & Pritchett, 2001). By providing submarine officers with possible path choices, navigation decisions can be made quickly, while still keeping the human operator involved in the decision making. Following these guidelines in the maritime navigation setting can lead to a successful path planner that creates efficient paths in a short amount of time.

When designing automation, one key factor that must be considered is how trustworthy the automation is. When humans offload work to a computer, they are doing so under the premise that the computer system can be trusted to perform the task as expected. When developing a decision support tool, it is essential that the design facilitates trust, so that the user is willing to use the tool to its full potential (Muir, 1987). In particular, users are more likely to trust a system that proves reliable in complex situations (Lee & See, 2004). Distrust may lead to system disuse and over-trust may lead to over-reliance on automation (Parasuraman & Riley, 1997). As a user increasingly uses automation, one negative trend is a decrease in the user's self confidence (Moray, Inagaki, & Itoh, 2000). If a system is unreliable, and presents poor information, this is also a problem, as operators will avoid the automation. With previous research in mind, it is important to design a decision support tool that presents the user with reliable automation, in a timely manner, while keeping the user involved in the final decision. This can help to build trust and self-confidence, as the user can continue to be part of the decision making process. Chapter 4 addresses these issues in more detail.

2.2.2 Collision Avoidance

Many researchers have built on the strengths of automation to aid in collision avoidance (Lebkoswki et al., 2005). Over the years, the number of accidents in the maritime community, both collisions and groundings, have decreased (Tiblin, 1990). Many changes have been implemented to aid in navigation safety, from new licensing programs

and increased traffic separation zones to harbor traffic control systems that moderate congestion (Tiblin, 1990). However, one of the largest contributions to maritime safety is likely be the electronic revolution at sea (Tiblin, 1990).

The benefit of systems that can automatically track and plot collision situations has been popular for nearly 20 years, with some of the first research published in 1990 discussing Predicted Areas of Danger (PAD) (Tiblin, 1990). This research, which expanded on dead reckoning observations to add uncertainty around each ship, showed a clear benefit for ships that used Automatic Radar Plotting Assist (ARPA). ARPA could predict where possible collisions would occur, based on current course and speeds. ARPA and similar systems are in many ships today, where radar is used to predict contact locations over time and notify the user if he or she is on a collision course. ARPA was then expanded to incorporate an evolutionary algorithm to aid in collision avoidance that accounts for other variables in the navigation picture, such as water currents, weather, and the size of each vessel (Smierzchalski & Michalewicz, 1998). This evolutionary algorithm for navigation was then tested, and it successfully accounted for other contacts and obstacles to present a safe trajectory in collision situations using sample data inputs (Lebkoswki & Dziedzicki, 2008; Smierzchalski & Michalewicz, 2000). The test used a small setup, with remote control boats, but is not yet operational on full size vessels.

One approach that has gone to simulator testing comes from Poland, and has performed well in aiding decision making by presenting safe trajectories to the CO as a standalone tool. This system currently operates as a simulator, testing collision avoidance algorithms against poor hydro and meteorological conditions (Lebkoswki et al., 2005). This is important for any operational system, as currents and weather must always be accounted for to keep a ship on track. The challenge with using any of these algorithms or automation is how best to guide the commander of the ship to make the right decision. It is important to present information in a display that can quickly illustrate the surrounding hazards. The next section discusses some of the displays that have come out of current research in navigation aids.

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2.2.3 Navigation Displays

From broad research that focuses on the principles of display design to the specific designs for collision avoidance, there is an abundance of research on display design (Rasmussen, 1986; Rasmussen, Pejtersen, & Goodstein, 1994; Smallman & St. John, 2005; Wickens, Gordon, & Liu, 1998). In any interface, it is important to present the information needed for decision making in a logical and easily understandable fashion (Rasmussen, 1986). To this end, researchers at Pennsylvania State Applied Research Laboratory (ARL) have developed a collision avoidance display that displays information on PADs in a unique way (Rothgeb, 2008). This display is shown in Figure 5.
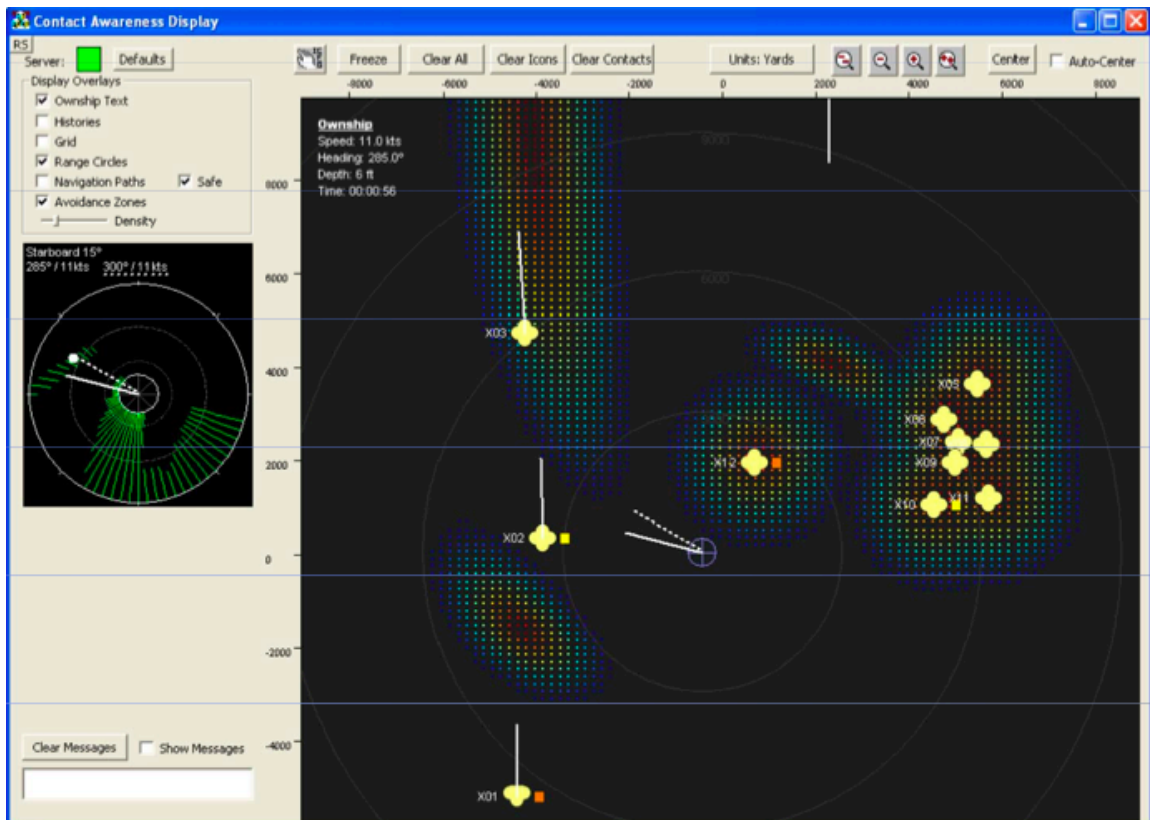


**Figure 5: ARL Display with Multiple Contacts (Rothgeb, 2008)**

The goal of the research conducted by ARL is to develop a course and contact advisory agent system that provides threat awareness, prioritization, and automated recommendations to maintain tactical control (Rothgeb, 2008). The purpose of the display is to help reduce workload by reducing the time it takes to make a decision, while

improving the quality of decisions and providing help for less experienced operators (Rothgeb, 2008). This is achieved by fusing data from multiple sensors to accommodate for uncertainty and form a model representing the surrounding contact picture. This information is then displayed in aggregate groupings, showing yellow, orange, or red based on the safety of an area. Figure 5 shows a situation with multiple contacts, and how the PAD is presented based on where contacts would be in the future.

The ARL display is helpful at showing a general picture of which areas are clear, and the small window on the left provides a constant recommended trajectory, but there are still some weaknesses in this display. For one, geographical information such as land and water depth is not displayed. This can make it difficult to maintain spatial orientation, and also requires operators to mentally integrate and synthesize information from multiple separate sources. Further, there is no compass information, and tracks of future positions are only displayed for some of the contacts. This means that the display cannot be used as a stand-alone option, but must be used in addition to other systems. Introducing a new display without integrating it with other displays may simply increase clutter in an already overwhelming environment, as discussed previously. Another weakness of this display method is that it only provides the next course of action, by presenting a direction that is safe to travel in. It does not offer full routes, which makes long-term planning difficult.

2.2.4 Decision Support for Health and Status Monitoring

The overwhelming amount of information flowing to the commander in the control room has led to a difficulty in maintaining SA. This was the case with some of the recent submarine crashes, most notably the USS *San Francisco* and USS *Greeneville*. One way to aid commanders in this monitoring is to develop better health and status monitoring systems, and extensive research has been performed in this area. A general list of requirements has been developed for decision support systems by Guerlain (2000), which are directly relevant to health and status monitoring decision support design.

The first is interactivity, the ability for the system to interact with the databases involved, and also with the user. Secondly, it should be simple to detect new events or changes. The system should also aid the user in representing the data, and provide error detection and recovery. With the vast amount of data taken in, the system must also have a method for turning the data into useful information. Finally, predictive capabilities are an added benefit, allowing users to prevent off-nominal situations (Guerlain et al., 2000).

There is a large body of work regarding decision support systems in process control environments, where operators and supervisors must monitor large amounts of information in real time for any unexpected changes (Guerlain, 2000; Guerlain & Bullemer, 1996; Guerlain et al., 2002). The case of a nuclear submarine is not much different from other process control activities. In both settings, a supervisor is needed to monitor a set of automated activities, using both current data and predictive modeling to prevent hazardous situations. Often times, the difficulty is not in gathering the relevant data, but rather in displaying the data in a way that promotes the most efficient interface with the user.

One previous design project that addresses such data fusion was the re-design of a display for a process control model-based predictive controller (MPC) (Guerlain et al., 2002). The original display, used in refining, pulp and paper manufacturing, and grinding operations worldwide, provided all the necessary information to the user in a manner that was difficult to understand. Researchers performed a cognitive task analysis to determine what information was needed for timely decision making. The display was then re-designed, and using the new display, operators were able to obtain information that previously took much longer (Guerlain et al., 2002). This research pointed to many key factors for display design. For one, information should be easily accessible, without the user having to navigate between many different screens and sub menus. Also, a system that can predict future states is helpful in aiding decision making. Trend displays, for example, show values over time that can help the user to predict future values based on the currently observed trend. Another lesson learned was that visual representation of data can help users to quickly reference whether systems are functioning at an acceptable

level. There were difficulties, however. For one, complex systems often have so many different systems and relationships that it is impossible to display them all on one screen. This is why it is important to understand the domain in its entirety before a new interface is designed.

Beyond simply creating an efficient display, further research has shown the importance of including user-initiated warnings in health and status (H&S) displays (Guerlain & Bullemer, 1996). User-initiated notifications allow the user to create certain rules for the automation, which will trigger alarms when set points are violated (Guerlain & Bullemer, 1996). Being able to set custom warnings simplifies the supervisory control task by adding automation into the monitoring task. Rather than analyzing the gauges, automation can be used, to a limited extent, to check for trends that the user defines. User-initiated notifications prevent unwanted warnings, which can be distracting to the user and further aids in real time monitoring by limiting the delay between the onset of a dangerous scenario and its recognition (Guerlain & Bullemer, 1996).

For an effective health and status monitoring tool, it is important to consider this previous research. Creating a tool that organizes its information into meaningful groupings, and aiding the user in building their situational awareness is key. Using visual representations and flagging key changes are also important. Not only must the tool meet the basic requirements discussed here for representing data, but it should also do it in a manner that is intuitive to the user. With a display that allows for quick checks of the system and the ability to set custom alarm points, a supervisor can manage a complex situation without being overwhelmed.

2.3 Mobile Tools for Expert Users

In many different arenas, mobile tools are growing in popularity. There is a growing desire to have the flexibility to retrieve information and execute tasks from anywhere (Perugini, 1996). As researchers from the University of Nebraska note, the coming mobile revolution will bring dramatic and fundamental changes to the world, assisting decision makers in real time (Siau & Shen, 2003). This can be seen in the emergence and

popularity of products such as the iPhone and micro PC's that offer the power to surf the Internet and email while still being completely portable.

The availability of cellular towers and wireless signals has allowed mobile technology to grow at incredible rates, keeping social class and geography from being limiting factors (Greengard, 2008). Wireless capability enables real time communication, collaboration, and even commerce in some cases (Sarker & Wells, 2003). However, there are some limitations to mobile technologies. One study into mobile commerce has shown that among the biggest constraints in mobile technology are slow CPUs, limited processing power, small screen size, low bandwidth and awkward input/output devices (Lee & Benbasat, 2003). In terms of the interface, for each mobile device, the actual display must be custom made. Simply shrinking a desktop interface will not work (Lee & Benbasat, 2003). However, previous research has shown that small handheld computers are comparable to larger tablet PCs with respect to usability (Bhattacharjee, 2007).

One example of a mobile technology that is used to both monitor information and execute tasks is a stock trading tool designed by Wiklund Research and Design (2005). This tool allows expert users the ability to trade stocks with the same efficiency as a traditional desktop computer, without having to be tied to a specific location. This allows traders to make quick decisions, while being presented with all of the relevant information, and beat competitors to the sale.

These mobile tools are seen in many different arenas. Another example, which has also gained popularity, is Cogon's mobile device for medical decision support. This device aids medical personnel in quickly gaining information on a patient and works seamlessly with the existing database to prevent redundant entries (Cogon Systems, 2007). Mobile tools are also found in the command and control domain. Because these tools can lead to life or death decision making, they must be much more robust in terms of error recovery and ease of use. The Commander, a tool designed by The Resource Group, is one example of a command and control tool (McEwan, 2009). This tool allows for mobile control of a UAV by an operator in the field. This tool is more than just a portable control

for basic functions; it provides advanced control operations for the user without size limitations

Because the operating environment of today's soldier is often removed from the office, mobile technology allows increased capability in field settings. One example is the handheld lie detector, developed by Lafayette Instrument Company (Dedman, 2008). This tool allows troops in the field to do basic questioning of non-U.S. personnel to aid in determining credibility at access points, as well as in gaining information following an attack (Dedman, 2008). Other examples of mobile military technology include handheld translators, mine detection systems, and several mobile PCs for commanders (Doheny, 2007; Krane, 2002).

One tool that reportedly supports ground-based commanders is called a Commanders Digital Assistant, first deployed in 2003 (Kempin, 2004). The purpose of this tool is to provide situational awareness capability to dismounted leaders by providing information on maps and troop location similar to what can be gained in a command and control station (Kempin, 2004). The tool also has the ability to aid in planning, and provides a map of the battle space, listing the location of known friendly forces. This information keeps commanders in the loop, without constraining them to the command center the way previous tools did. Thus, it embodies many of the same principles that apply to commanders of submarines. The main strength for many of these mobile technologies is that they free the supervisor from being constrained to a desk, while still giving access to needed critical information.

This review of previous literature has shown that there are clear benefits of mobile technology, collision avoidance systems, and well-designed health and status monitoring decision support systems. However, there is no decision support tool that incorporates these three characteristics in maritime settings. To fill this gap, this research effort proposes the use of a mobile command assistant, the Mobile Situational Awareness Tool (MSAT), to aid in surface collision avoidance and platform health and status monitoring,

embodied in a mobile device. The following chapters discuss the design, testing, and performance of the MSAT in more detail.

# 3. Design of the Mobile Situational Awareness Tool

3.1 Introduction

A common technique used to analyze a domain in order to derive interface design concepts and requirements is a cognitive task analysis (CTA) (Schraagen, Chipman, & Shalin, 2000). A CTA can involve a number of different methods, but the end goal is to learn more about a task by determining the cognitive processing involved. This includes mapping the decisions and processes, as well as gaining an understanding of the priorities and rules followed for a task. With a better understanding of the tasks and decisions involved, research can be focused on addressing shortcomings.

For this research, two different types of CTAs were performed. The first was a traditional CTA, which consisted of interviews with SMEs and a five-day cruise on the USS *New Hampshire*, a Virginia Class submarine. The second was a Hybrid CTA (HCTA). One limitation of traditional CTA processes is that they rely heavily on the existence of a predecessor system, which is problematic when designing for future systems that require some form of automated decision support. The HCTA was developed to address this shortcoming of traditional CTAs (Nehme et al., 2006), as this project involves the application of automated path planners in a mobile device, which is a revolutionary technology for the submarine forces.

The HCTA explicitly provides functional and informational requirements for futuristic systems by stepping analysts through a requirements-generation process, with an embedded analysis of tasks that may be appropriate for higher levels of automation. Each step in the HCTA is based on a structured methodology to make it repeatable and traceable, and it can be used when subject matter experts (SME) are not available. The outputs from the HCTA are functional requirements and lower level information requirements needed to support these functions and include SA requirements, display requirements, and areas for possible automation.

The traditional CTA, conducted for overall submarine operations focused on the health and status monitoring functions. Across the submarine, there are many systems that require constant monitoring. Interviews with submarine officers provided insight into what systems are monitored, how long tasks take, and where time is wasted. The HCTA focused on developing requirements for a decision support for the specific tasks of surface navigation and collision avoidance, which are frequently performed tasks and central to all submarine missions. The results from both CTAs are presented in the next sections.

3.2 Traditional CTA results

From the onset of this research, many submarine officers were interviewed about the submarine environment, navigation, and possible shortcomings. These interviews were conducted at shore-based facilities, as well as during a five-day cruise on the USS *New Hampshire,* where operations were observed in person. In addition to loosely structured interview questions, a subset of ten highly experienced submarine officers were given a set of written questions to gather information on different tasks. Only officers were used because the interest was in supporting health and status monitoring for officers. These questions formed the basis of a time and motion study, and are discussed in further detail in Chapter 4. These question and answer sessions provided a great deal of information on current submarine operations, and some of the highlights are discussed here.

One of the first trends that surfaced during interviews was the fact that submarine designers often do not understand submarine life. For example, some personnel referenced valve placements that were dangerous, because the crew has to reach between hot pipes in order to make adjustments. Some of the officers that worked in the control room also stressed the difficulty with staying informed once out of the control room. Only basic information on submarine heading, course, and depth can be seen in other areas, and so it becomes difficult to maintain situational awareness. Other comments dealt with the difficulty of maintaining a regular sleep schedule, as the lighting and shared living spaces make it difficult for peace and quiet. This is further complicated by

the 18-hour workdays. Once the crew is underway, everyone works a twelve-hour shift, and then has six hours off.

Many of the officers who just recently returned from sea mentioned the new AIS system. As mentioned in Chapter 2, this system tracks the information of all commercial vessels using it, broadcasting the ship name, position, course, speed and destination. This information can simplify the tracking process, but the officers said that it was added on as an afterthought, and does not connect well with the other systems already in place. These comments proved true during the five day cruise. The AIS display was tucked in a corner above one of the operator's normal display. The information was rarely used as a primary source, and only a few times was it used to check information gained from one of the other sensors. Since AIS provides accurate course and speed information provided from the actual ship in question, it seems unreasonable to not use this information as the starting point for building up the contact picture.

Other new systems have also found their way into the control room, but are also not integrated in any permanent manner. The commercial radar, for example, must be hand carried to the bridge every time the vessel surfaces and be manually mounted to the deck, which takes two crew members approximately 30 minutes. The bridge is the tall part of the submarine, which rises above the water, and is where lookouts stand while navigating on the surface. During the times when the submarine was on the surface, it was clear that the stress level for all personnel was much higher, with many more people in the control room and an additional set of lookouts on the bridge. During such a busy time, the task of setting up an additional radar dish is overly burdensome.

In current submarine operations, the transition from paper to electronic charts has been slow. Until the Virginia class, electronic charts such as those in the Voyage Management System were not allowed as a primary means of navigation. Although the paper charts have their benefits, there are still disadvantages to plotting courses by hand. The process is very tedious, requiring various tools and a large amount of space. This difficulty was observed during a charting demonstration by a Navy submariner. If re-planning is

necessary, plotting a new path by hand can become time intensive, as it is difficult to compare the options available in a timely fashion. Also, as each successive path is plotted and erased from a chart, the picture becomes faded and worn from use, and the chart can become difficult to read. Many of the officers interviewed saw the potential benefits of the VMS, but acceptance was not unanimous.

The addition of the VMS has helped to pool information, but when underway, many complaints were also raised. Although the VMS works towards combining and condensing information, there are still limitations. First, the VMS is still not technically very reliable. During the five-day cruise, the VMS froze multiple times, requiring it to be restarted each time. This delayed information flow and causing a break in mission execution in the control room. Also, the information coming from the VMS is only helpful to those who are within sight of it. It is hard to get the necessary information to a commander who is anywhere but in the control room. Thus, if the VMS information were placed on a mobile device, this would greatly aid in the flow of information.

Another finding from the interviews and the short cruise was that the number of systems onboard the submarine that must be continuously monitored is vast. From engine parameters and temperatures to atmospheric levels, weapons positions, and sensor strength, there are many things that the commander must constantly watch. The typical process involves delegating these monitoring tasks to someone else, and only being notified in an off-nominal scenario. This can be problematic, as the information is very disjointed, and is logged in many different areas with no easy way to keep track. These shortcomings are what inspired the need for a health and status monitoring function of the MSAT. Giving the commander constant access to these key system parameters can aid in safety as well as helping to keep the commander in the loop.

The information gained from these interviews helped to frame current problems in terms of information the commanding officer needs to know. The Hybrid CTA, discussed in the next section, focused on the specific areas that could benefit from automation, and the associated information requirements.

3.3 Hybrid Cognitive Task Analysis

The Hybrid CTA approach consists of the following components: 1) Generating a scenario task overview, 2) Generating an event flow diagram, 3) Generating situational awareness requirements, and lastly, 4) Creating decision ladders for critical decisions from which information and display requirements are extracted. An outline of these steps can be seen in Figure 6 (Nehme, et. al., 2006). Each of these steps is described in more detail below as they relate to the development of a display for collision avoidance.
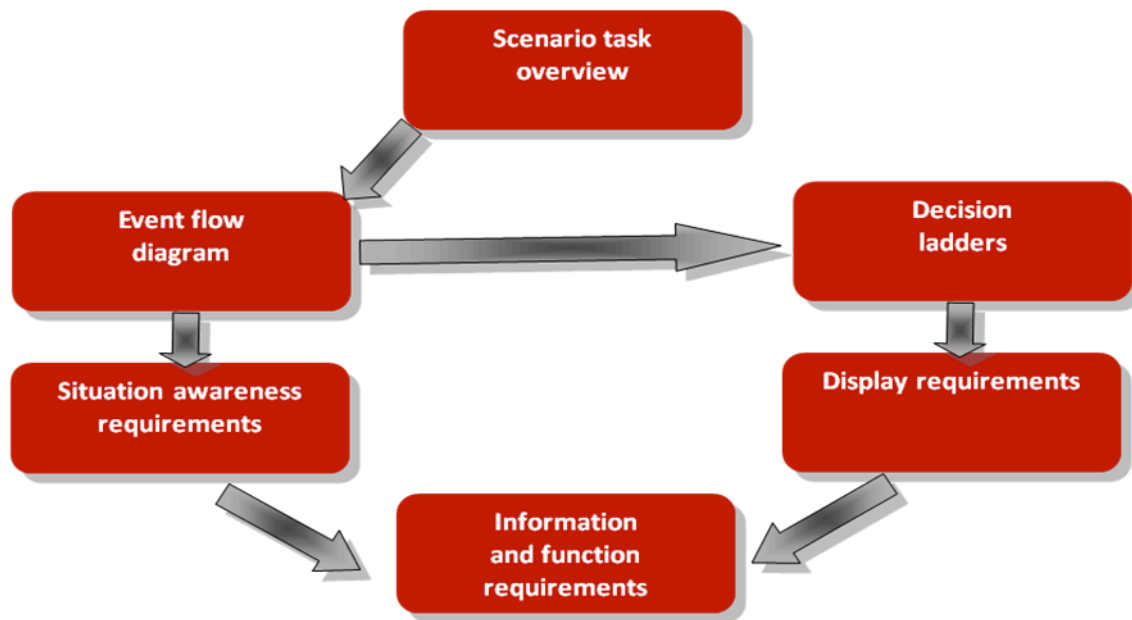


**Figure 6: Hybrid Cognitive Task Analysis Process (Nehme et al., 2006)**

In order to complete the HCTA analysis, some assumptions were made. In order to keep it task specific, it was assumed that the submarine had to stay at the surface during navigation. This is a realistic need since communication becomes very difficult for a submerged submarine, making surface transit a common choice, particularly in congested environments (Clancy, 1993). The analysis focuses on supporting a single decision maker monitoring the surface navigation picture (like a submarine commander). There are no a priori assumptions about crew size, and indeed, one possible application of the HCTA would be using the results to aid in estimating an overall manning model. The results of both CTAs are discussed in further detail below.

3.3.1 Generating a Scenario Task Overview

The Hybrid CTA begins with a scenario description of the overall mission. From there, the overall mission is divided into several phases, the boundaries of which are identified by the changes in expected operator tasking, both in time and sub-task groupings. For each phase, the sub-goals of that phase are enumerated, and the expected subtasks for each of these sub-goals are detailed. Further subdivisions can take place, resulting in a hierarchy, branching from the mission statement, to an individual subtask at the leaf level. The scenario task overview allows for later stage modification or revision of a phase goal or sub-task. A subset can be seen in Figure 7.

| | Phase Goals | Phase Breakdown |
|---|---|---|
| **Mission Execution** | Exit Harbor | - Cast off from docking position<br>- Orient craft to exit path<br>- Check for contacts in area<br>- Follow navigational aides to exit harbor while following rules of the road<br>- Determine whether to stall or change direction if path is blocked<br>- Determine whether to change path or wait for tides to change if depth is an issue<br>- Exit harbor phase is complete when the craft is outside the confines of the docking area |
| | Terrain Confined Navigation | - Set up possible course<br>- Determine potential obstructions both under and above water<br>- Determine whether stopping or slowing is better based on currents and navigation ability, if traffic is heavy<br>- Determine from the mission time constraint whether there is any ability to slow down passage<br>- Determine what contacts may cause interference based on realistic path prediction based on past experience<br>- Determine limitations on contact maneuverability<br>- Determine possible paths for burdened vessel to compare with actual path<br>- Phase completed when avoiding contact with terrain is no longer the primary concern |

**Figure 7: Partial Scenario Task Overview**

Based on the given scenario of surface collision avoidance during navigation, the nominal tasks were grouped into four main phases: Exit Harbor, Restricted Water Navigation, Unrestricted Water Navigation, and Return to Port. These phases cover surface collision avoidance in all areas, each of which contains its own unique challenges. From these phases, a list of all the possible subtasks was developed through

research and interviews with current submarine crew members, while focusing on the tasks of surface navigation. The entire list of tasks expected for each of the four phases is listed in Appendix A.

3.3.2 Generating the Event Flow Diagram

The next step of the HCTA involves generating event flow diagrams for each phase. While the scenario task overview determines what tasks and subtasks are needed to execute the mission, the event flow diagram demonstrates the temporal constraints, i.e., when the events must occur in relation to each other. There are two basic event types used in the event flow diagram:

- o Decisions, which could be simple decisions (yes/no) or could be ones that require knowledge-based input from the operator, represented by diamonds, and
- o Processes that require human-computer interaction to support a mission subtask, represented by rectangles.
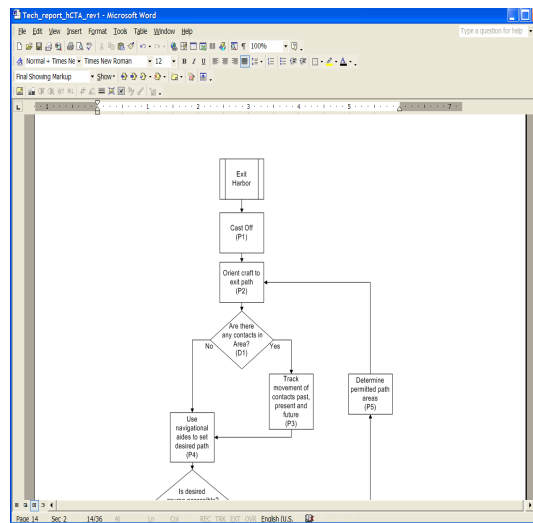


**Figure 8: Partial Event Flow Diagram for the Exit Harbor Task**

The first event flow diagram covers the Exit Harbor phase (Appendix B1). A portion can be seen in Figure 8. This phase starts as the vessel casts off and ends when the vessel is outside the bounds of the harbor. Some of the key subtasks in this phase are determining areas that are open to travel, identifying contacts in the area, and observing the tide and currents. This event flow covers the different decisions an operator may face, such as

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whether to delay movement or change path, as well as processes such as determining the right of way with any surrounding contacts.

The next event flow diagram represents Restricted Water Navigation (Appendix B2). With the exception of entering and exiting port, this phase represents any navigation where avoiding terrain is a factor. This phase increases in complexity when contacts are in the area, especially when collision is possible. This event flow also represents the need to account for structural limits of the craft and variances in the paths of surrounding contacts.

The Unrestricted Water Navigation event flow represents any navigation in open water where terrain avoidance is not an issue (Appendix B3). The important tasks here include locating any surrounding contacts and mapping their paths. Collisions must be avoided through obeying the rules of the road, which dictate who has the right of way in different navigation scenarios. Any craft not displaying Automatic Identification System (AIS) data must also be tracked in order to prevent collisions. This phase ends when the ownship craft enters any area where terrain becomes an obstacle.

The final stage, Return to Port, starts when the harbor pilot is picked up and ends when the craft is safely docked (Appendix B4). The harbor pilot is a person who is familiar with the specific area and its navigation rules, and is used whenever a submarine enters a port to aid in navigation. The event flow represents the series of events that must occur before transiting to port, such as securing systems and determining the status of tides and currents. It also allows for tug boat assistance, depending on whether tugs are available and whether their help would make the port accessible when external factors prevent normal transit. The tasks listed in these event flow diagrams show the key processes and decisions made during navigation, and are used to generate the SA requirements and decision ladders.

3.3.3 Generating SA Requirements

Situation awareness is a critical aspect of human supervisory control, particularly time-sensitive command and control operations. In order to account for this, the third step of the HCTA involves the generation of SA requirements for each of the mission phases and associated subtasks identified in the first two steps. Because SA, by definition, is inherently linked to temporal constraints, the SA requirements cannot be generated until the event flow diagram is constructed. The SA requirements generated in this step are divided into the three SA levels, perception, comprehension, and projection (Endsley, 1995). For each SA level, situational awareness requirements are specified for the mission phases and associated subtasks derived in the scenario task overview, keeping in mind the temporal constraints of the event flow diagrams.

In Level 1 SA, perception of information, is essentially obtaining the correct mental picture of the situation. Level 2 SA, comprehension, is the integration of multiple pieces of information and a determination of their relevance to the mission goals. Comprehension also means deriving operationally relevant meaning and significance from the Level 1 SA data. Level 3 SA, Projection, requires operators to forecast the future situation events and dynamics. Operators who have this ability can anticipate future events by projecting from current events, allowing for timely and accurate decision-making. Figure 9 shows a segment of the SA requirements for the Exit Harbor Phase.

Each SA requirement for the task of navigation is linked to a decision and/or process to which it relates, allowing traceability from each output to its source. The requirements are also grouped by phases, as some phases have different needs in order to complete tasks. SA requirements such as contacts positions, geo-spatial boundaries, and contact paths are seen multiple times, as this information is needed in many phases. Most of the Level 1 requirements are necessary to inform the operator of his or her surroundings. Displays that meet Level 3 requirements give operators a deeper understanding of what is going on around them, promoting the ability to forecast the outcome of their decisions.

The complete list of SA requirements for the task of collision avoidance is in Appendix C.



**Figure 9: Partial Situational Awareness Requirements**

3.3.4 Generating Decision ladders

Each decision in the event flow diagram represents a critical event that requires detailed understanding of what information and knowledge is needed to support the operator's decision-making process. By generating decision ladders, the states of knowledge and information-processing activities necessary to reach a decision can be captured (Rasmussen, 1983).

In a decision ladder, human behavior is represented using a three level hierarchy. The first and lowest level is skill-based behavior, generally characterized by volitional sensory motor acts, where performance takes place without conscious control. At the middle level is the rule-based behavior. This level works on stored rules, which are selected from previous learning in similar circumstances. The third and top-most level is knowledge-based behavior. In this level, behavioral responses of individuals are based on the analysis of cues within the environment and also on the goals of the particular individual (Rasmussen, 1983). Figure 10 shows the three levels of the hierarchy.

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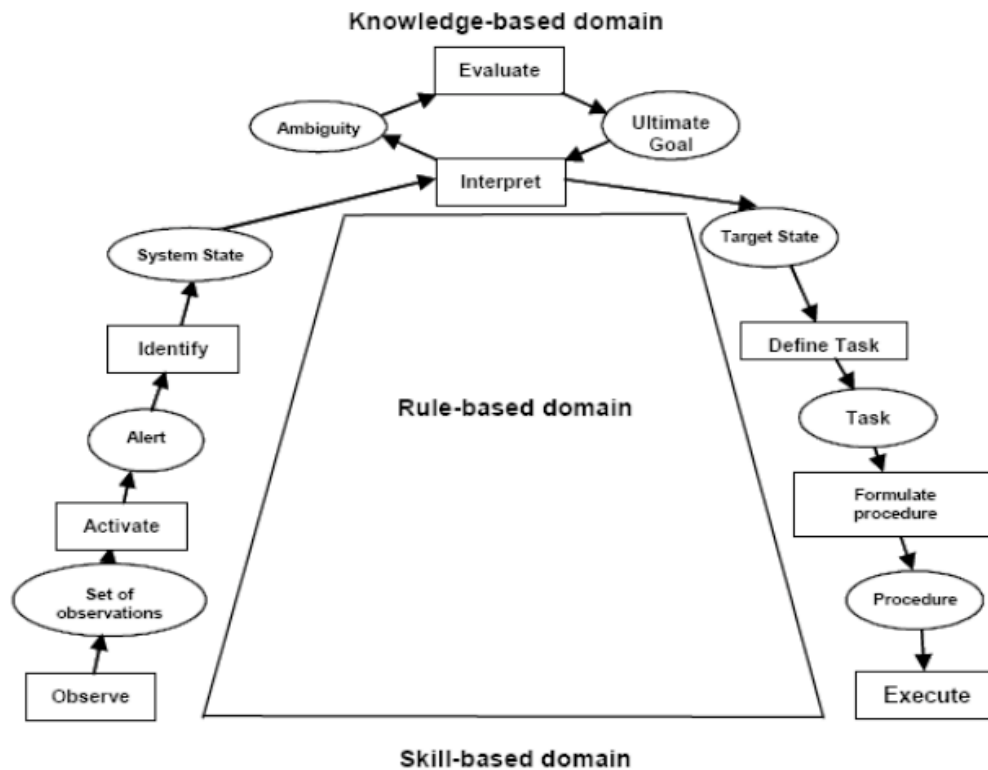
**Figure 10: Decision Ladder with its Hierarchy (Rasmussen, 1983)**

As illustrated in Figure 10, the decision ladder depicts relationships among the levels of causal reasoning (human behavior) and states of knowledge. The figure has two different shapes: boxes and circles. Boxes illustrate the information processing activities involved in each decision phase, and circles represent the information or knowledge produced, which feeds into the next decision phase. In general, after observing the data from the environment, the evaluation and interpretation of the data becomes possible and accordingly, an action is executed (Rasmussen et al., 1994).

In the HCTA, the complex decisions embedded in the scenario phases are explained in detail with the help of a decision ladder. Complex decisions are those characterized by many variables with often dynamic constraints, as well as significant uncertainty in the environment. A scenario can have multiple complex decisions embedded in it, and each of these decisions is depicted with a decision ladder. A feature of the HCTA process is that each decision ladder includes overlaid display requirements.

In generating decision ladders, the various steps are as follows:

- Develop a traditional decision ladder for each critical, complex decision
- Construct two variations of each decision ladder
  - In one, the corresponding display requirements are added.
  - In the other, the possible levels of automation are added.

Decision ladders were completed for each of the critical decisions found in the event flow diagrams, and can be seen in Appendix D. The four critical decisions are:

1. "Is desired course accessible?"
2. "Would tug boat assistance make course possible?"
3. "Are there any contacts in the area?"
4. "Is collision possible?"

The goal of the first decision, determining if the course is accessible, is to see if there are any external factors preventing navigation, such as tides, current, weather, etc. This is a complex decision due to the diverse set of problems that can arise. Also, the question of whether the course is accessible does not always have a binary answer, as different obstacles are not necessarily static. For example, a land mass is impassable, but if the obstruction is another vessel, simply waiting may clear the path. Observations from available sensors help determine how obstacles affect the path, and the decision ends when the status of the path has been determined as either passable or blocked. This decision ladder can be seen in Appendix D1.

The second is a follow-on decision to determine if using tug boats is an option when the desired path appears to be inaccessible, for example, in the presence of a strong tide. The complexity of this decision prevents a simple answer, as there are many factors that must be taken into account. First, information about the external conditions is needed, followed by an evaluation of whether the tug boat capabilities can overcome the problem. Once the path is finalized, and depending on whether tug boats will be used, the necessary steps are taken in order to continue with navigation. This decision process is in Appendix D2.

The third decision ladder, looking for contacts, is entered whenever the ownship craft moves into an area with unknown possible contacts. Since various sensors are used in order to determine what contacts are in the area, the resulting information is complex, with different levels of reliability. This makes the decision complex, with multiple steps. Again, sensor data are taken in and analyzed to determine what is in the surrounding area. This information is then used to update the display with the surrounding contacts, along with their predicted paths. If there are no possible contacts, the craft continues navigating and monitoring until new information is received. The full decision ladder is in Appendix D3.

The final decision deals with navigation when contacts have been discovered in the area, raising the possibility of a collision. This occurs when a contact has been detected in or near the operating area. Since the course of each ship is constantly changing due to tides, currents, and traffic patterns, this is a complex decision. The contact's current course and relative speed must be known (or at least estimated), and then the likelihood of collision is determined based on the current paths and possible variations. If a collision is possible, the rules of the road are applied, and a new course should be planned, if necessary. This decision ladder is shown in Appendix D4.

Once completed, each step in the decision ladder is then assessed to determine what display information is required to support the actions and knowledge-based reasoning, as well as identify what processes could be automated. The display requirements, as seen in Figure 11 and Appendix D, are contained in the shaded callout boxes. The display requirements do not assert a specific "how" in terms of information needed for a decision but only "what". It is left to the designer to determine which mode (i.e., visual, aural, or haptic) in which to present this information, as well as how to combine it with other relevant data, etc. The specific design of the MSAT, guided by these requirements, is discussed in more detail in section 3.4.
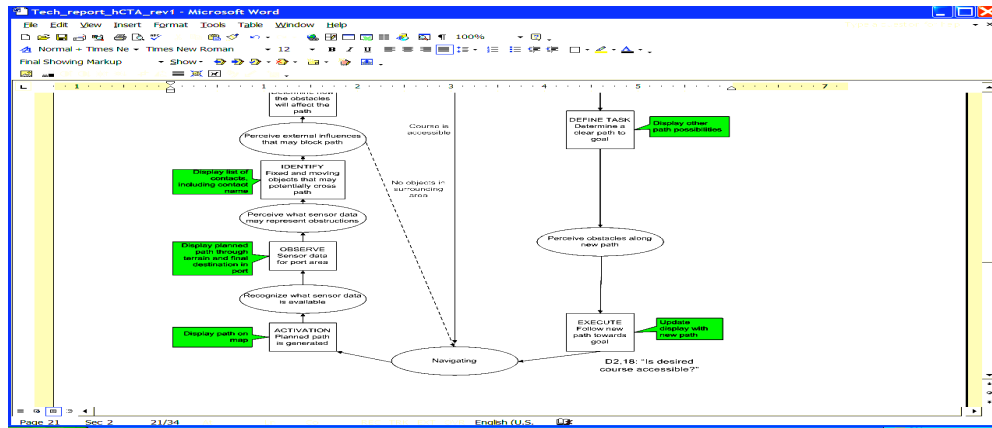
**Figure 11: Partial Display Requirements**

Finally, the levels of possible automation are added to the decision ladders in order to show which steps are *possible* candidates for automation, with the ultimate goal of reducing mental workload of the operator. Each action block on a decision ladder is assessed to determine if it is an action that can be done with some level of automation, and if so, it is marked as a candidate for automation. One example is in the decision of changing the path when the craft is on a collision course. One of the steps requires re-planning the path to avoid a conflict, given the rules of the road. Because this task is rule based, and can be completed without knowledge level decision making of a human, automation may be able to help. This is an area where automation can be applied through a tool such as an automatic path planner.

Figure 12 shows how automation can decrease operator workload by removing one of the steps in the decision making process. With computer assistance, all of the obstacles and possible paths can be checked against each other, and a possible solution can be presented to the operator. This reduces the mental workload on the operator, which can lead to decreased manning and more efficient collision avoidance. Automation possibilities for all the ladders are shown in Appendix D, depicted in the callout boxes.

50
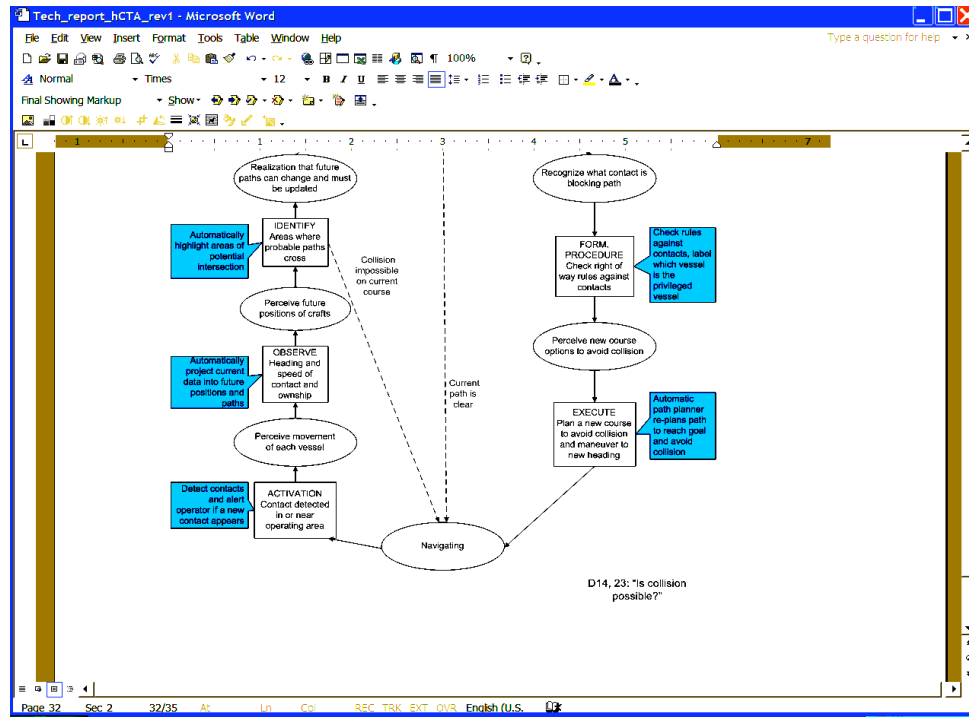
**Figure 12: Partial Possible Automation Diagram**

### 3.3.5 Information and Functional Requirements

Fifty-two information requirements were defined for the function of collision avoidance, broadly categorized in geo-spatial information, contact information, alerts and feedback, and data/miscellaneous groupings. These requirements are shown in Appendix E. Each requirement can be traced back to either the SA requirements and/or the display requirements, as indicated in the requirements list.

### 3.4 Specific Display Requirements for Design of a Decision Support Tool

Of the submarine functions listed in Chapter 2, a subset was chosen for illustration in the MSAT, highlighted in Figure 13. Because of the path planning automation, a special focus was put on navigation in the littoral regions, where contact and obstacle presence is highly likely. With this in mind, representative functions were chosen to demonstrate how such a mobile tool would integrate the information, as well as due to their critical, central role (i.e., navigation, collision avoidance, and health and status monitoring represent the most common tasks aboard a submarine). Also, these tasks represent

continuous activities for the commander to follow, and the tasks are broad enough to keep the results generalizable to other maritime settings.
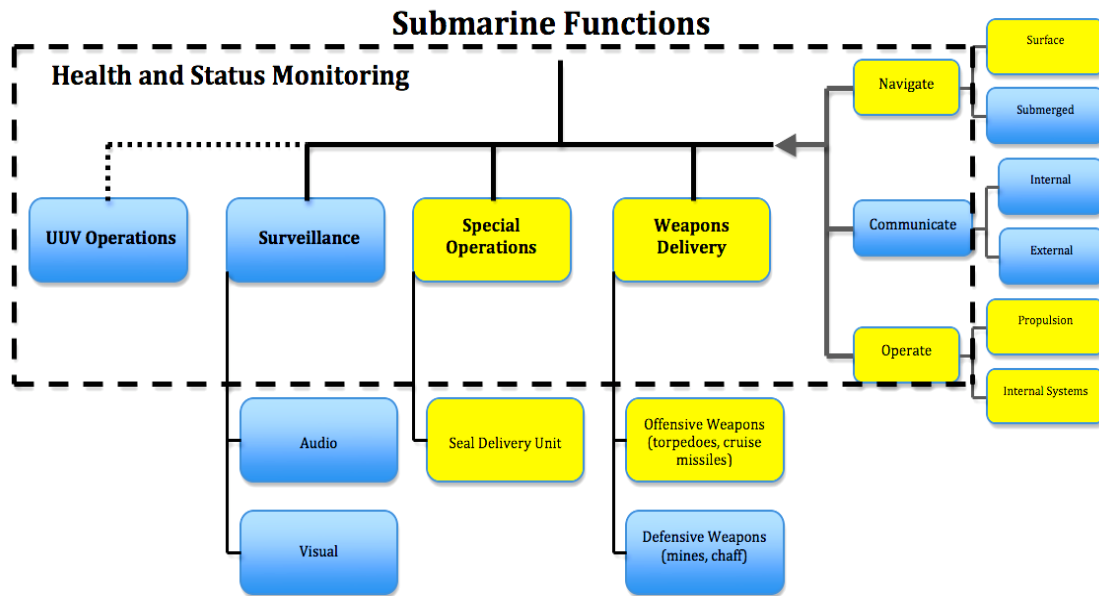


**Figure 13: Submarine Function Focus**

3.5 Mobile Situational Awareness Tool

The next paragraphs describe the resultant display that was designed, given the previously discussed requirements. Throughout the design process, guiding principles were followed to ensure that the information presented was shown in a clear fashion. One set of principles used were Jakob Neilsen's heuristics (Nielsen, 1994). Some of the more notable items are giving the user control and freedom, having a match between the system and the real world, being able to simply recover from errors, and following standards (Nielsen, 1994). These design principles are important, because following them will lead to a simple system, from the user's perspective, and also easier to learn. Other general principles were followed with regards to basic visual perception, such as keeping similar buttons together, and having the interactions represent real world movements (Ware, 2000). The design is discussed is more detail in the following sections, keeping these principles in mind.

Due to the large amount of information that must be monitored, as well as the functional grouping of the different information types, the display was developed with different

tabs. With the limited screen space on a mobile tool, a tabbed display allows for increased information without overwhelming a single display. Based on the requirements, three natural groups of information emerged. The first is general information viewed most often. The second group under the Navigation tab provides all the information for navigation and path planning. A third grouping include all of the health and status monitoring information, and finally a fourth option is included to show how such a tool could be extended to include additional functionality such as a 3D visual environment for increased SA. The information is broken down into the following four tabs: Overview, Navigation, Health and Status and Rite View, and the sections below discuss how these tabs meet the display requirements identified through HCTA. The complete User's Manual for the display can be found in Appendix F.

3.5.1 Overview Tab

The first tab in Figure 14 is the Overview tab. For most commanders, there is a constant need to see the geospatial representation of the surroundings, the obstacles, and basic information such as course, speed, and depth. As a default, this information was grouped together into the Overview tab, which also contains contact management information for the closest point of approach (CPA) of each surrounding contact. For some users, this may not be the primary display, but it was placed in the primary position because it covers general overarching information required by a submarine commander. This tab gives basic navigation information and helps to build the picture of the surroundings and current path, as can be seen in Figure 14.

This interface provides various pieces of information to support the commander. The map portion in Figure 14 shows the current position (blue U shape) (1), current path (black line) (2) with waypoints (triangles) (3), and a hazard that has shown up on the map (red area) (4). The colors were selected to match what is used in conventional paper charts, and the hazards are shown in red to draw the user's attention. Contacts are shown as light blue circles (5), with numbers on the circle, and a vector showing their movement direction. This matches the military standard for friendly contacts (U.S. Department of Defense, 1999). The goal position is shown in yellow (6).
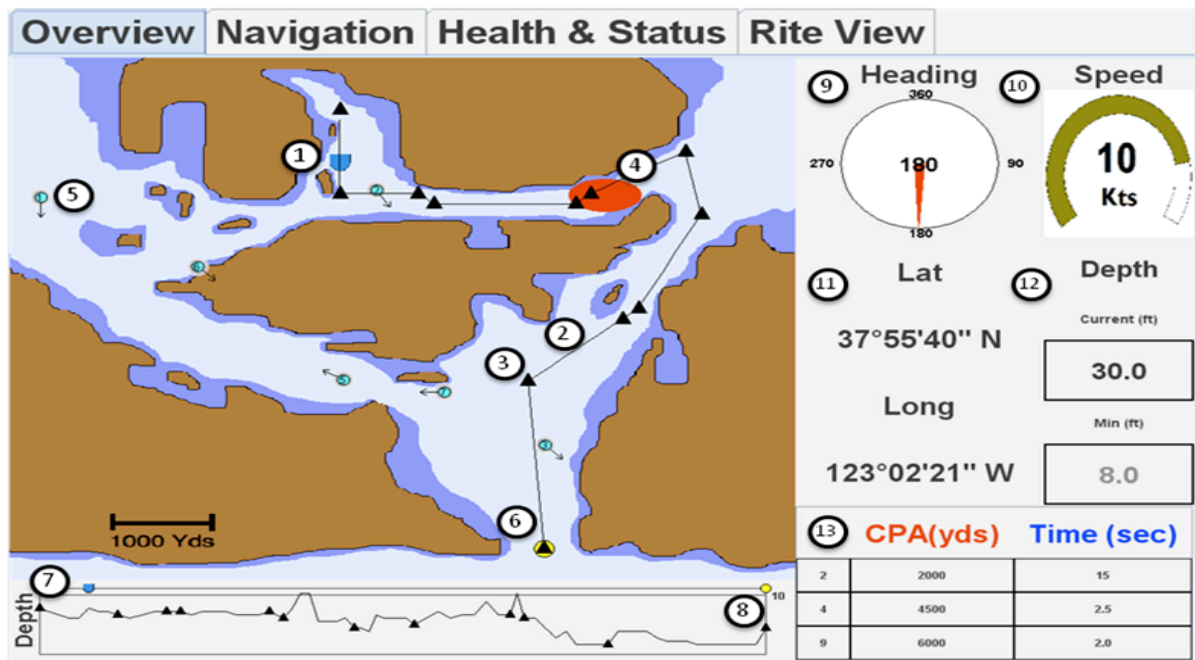
**Figure 14: Overview Tab**

At the bottom of Figure 14, the depth track along the course is shown (7), including the entire course and waypoints, with the distance between the top and the plotted line representing the depth. This helps the user to see a profile view of the depth along the course, something that is not typically available on charts. A second line (8) shows the user-specified minimum depth requirement. This can be changed using the navigation tab.

On the right side, the compass shows the current heading of the ship (9), indicated by both the red arrow and the digital readout in the center. Both methods are used for redundancy, and also to give quick information through the pictorial display as well as the specific heading for navigation purposes. To the right of the compass is the speedometer, which is dual-coded with shading and a digital readout in the center (10). Below these are updated latitude and longitude coordinates (11) (which, while not critical for SA, are a feature insisted upon by users), as well as the current depth and the minimum depth along the path (12). Finally, a table of contact information is shown at

the bottom right corner (13). This table can be sorted by contact number, CPA, or time to CPA by clicking on the column heading.

Many of the geospatial requirements from Appendix E are met in this tab, such as providing a map, current location, and the position of surrounding obstacles. Information on contacts, including their closest point of approach (CPA) is given in the bottom right, and the information can be sorted by contact number, CPA distance, or CPA time by clicking on the columns. Also, the chart on the bottom shows the current position of the submarine and the depth track from the current location to the goal. The map shows the position of ownship, as well as contact positions and headings.

3.5.2 Navigation Tab

The navigation tab contains the information needed for the task of navigation and collision avoidance. This view is shown in Figure 15.
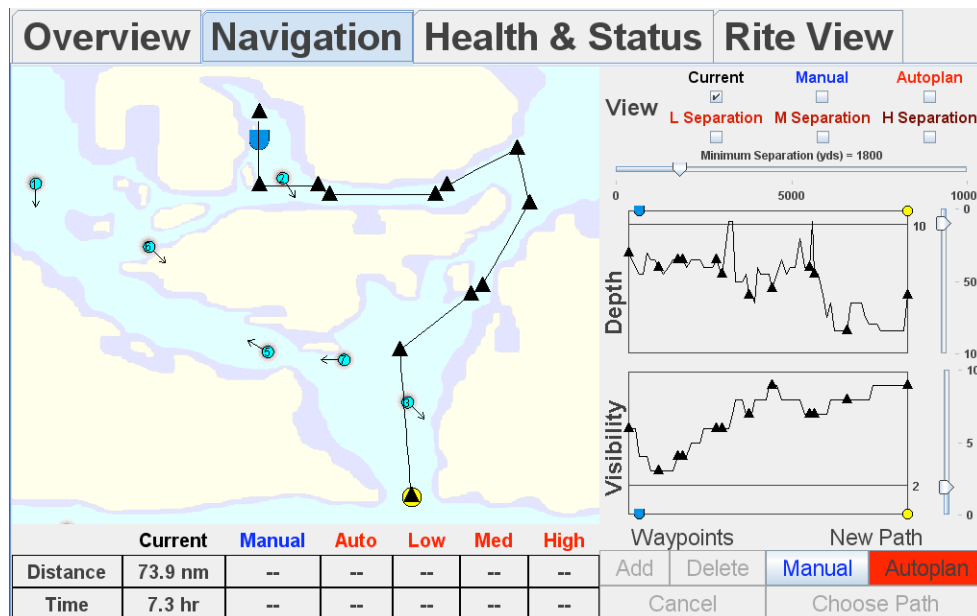


**Figure 15: Navigation Tab**

Contact location, current position, goal, and different path options are displayed on this tab. This information is presented on a separate tab from the overview information because it allows for changes to the current path, and so more space is needed for the planning tools. The map area is also displayed in lighter colors to prevent mode

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confusion with the Overview tab and prevent users from accidentally changing the path (Wickens & Hollands, 2000). The navigation tab is designed to aid the commander in quick decision making by giving assistance during path planning. From this tab, the current path can be modified, updated, or changed completely using either a manual or automation-based method called Autoplan.

When using the Autoplan feature, the automation determines this path using an A* Algorithm, which is a heuristic search algorithm that looks for the best path by optimizing the constraints set by the user. This algorithm takes into account the minimum depth, visibility and separation level, and finds the shortest path from the current location to the goal that meets all of these requirements (Buchin, 2009). Figure 16 shows a sample output for the Autoplan paths.
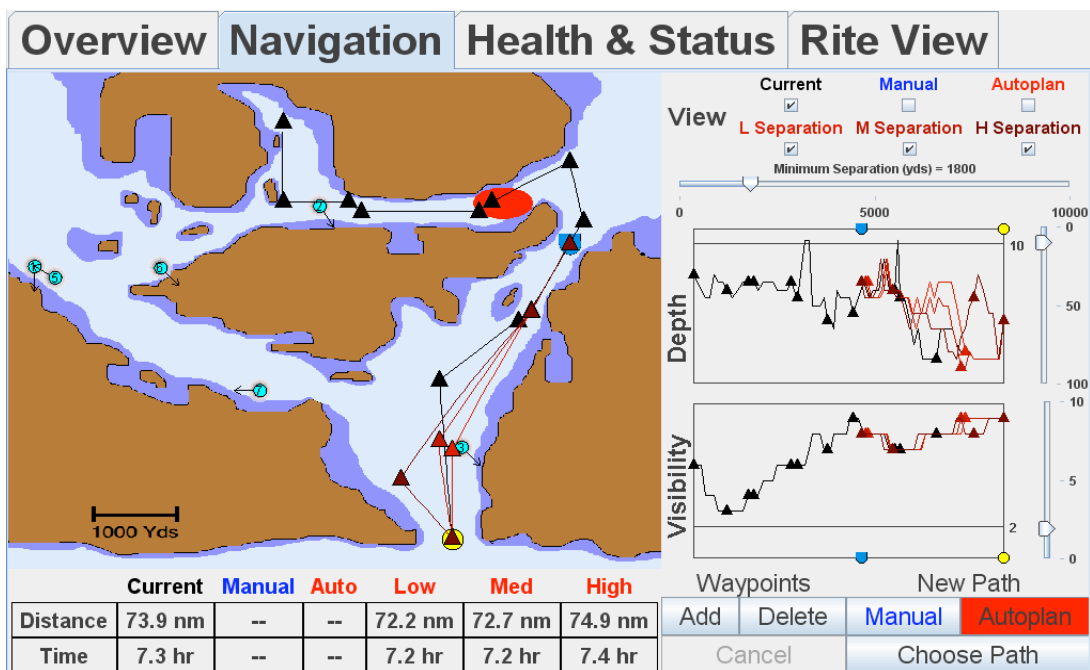


**Figure 16: Automated Paths**

As shown in Figure 16, there are three different automation paths presented. These paths represent different levels of risk the CO is willing to take. As the automation predicts where a contact will be in the future, the three paths account for different levels of uncertainty in each contact's path. The low separation path is used when there is low

uncertainty in a contact's path, which means the path is much closer to the contact. For high uncertainty, a much more risk adverse path is developed, leaving more room between the submarine and any contacts. This functionality was built into the system to allow users to choose a path based on the level of risk they find acceptable. For example, if most of the contacts were sailboats, which are less predictable, a high separation path would be safer. However, if most of the contacts were merchant vessels, which follow very fixed courses and speeds, then a low separation path could be a more efficient way to reach the goal.

Figure 17 shows an expanded view of the navigation tab. Along the bottom of this tab, proposed paths can be compared by distance and time (1) (these will be described in more detail below). On the right, checking the corresponding boxes (1) can change the view of different paths, created either by the human or the automation. The L, M and H Separation section represents the low, medium and high separation paths made by the automation. Low separation paths allow for movements closer to the contacts, and high separation paths leave more space between ownship and contacts. If the Autoplan button is used, all of the L, M, and H paths are created, and then the user can compare them with the graphs and the navigation map to choose the one that best fits his or her needs.
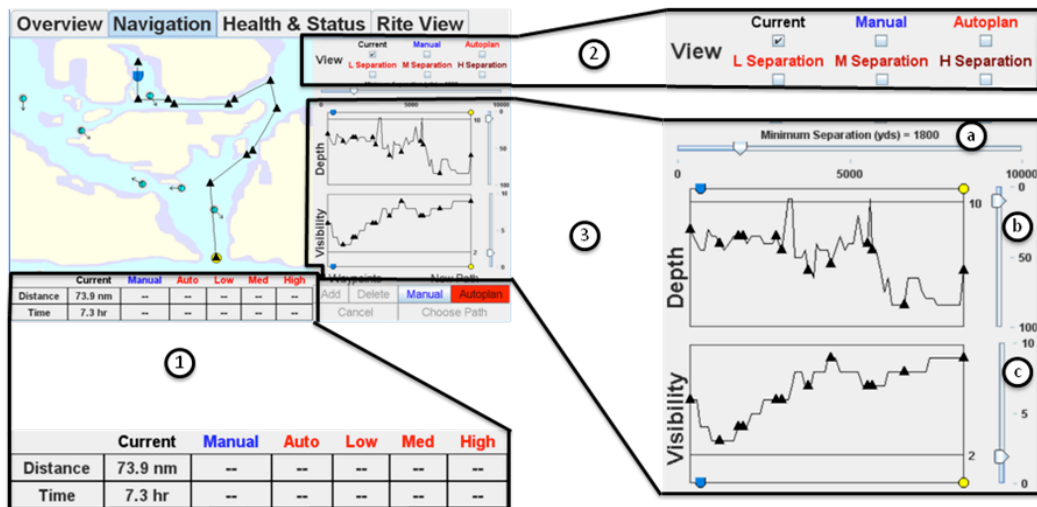


**Figure 17: Navigation Tab Expanded**

Below the checkboxes are the three different inputs for the automation, each with a slider bar. These slider bars are shown on the right, denoted as (a), (b) and (c). The first is minimum separation from obstacles (a). This user-generated setting means that all proposed paths will have at least this amount of distance between ownship and any surrounding contacts or shoal water. Next is the minimum depth setting (b) and minimum visibility setting (c), which also must be set by the user. These sliders were designed to show both relative position and a digital readout, so that the user can quickly plan a path or be more specific with inputs. For depth and visibility, the cutoff point can also be compared across the current path, to filter out undesirable paths through a simple movement of the slider. Only paths that meet these requirements will be considered by the automation. The two graphs show a comparison of depth and visibility by the paths that are created (3). The view in Figure 16 shows only the current path, but manual and automation paths are added to the view as they are created. Thus, a maximum of six paths can be shown at the same time (the current, one proposed manual, and four proposed Autoplan routes). Finally, the controls at the bottom right are used to create these manual or computer-generated paths.

Once the path is developed, it can be modified by either moving, adding or deleting waypoints. When performing any of these path planning tasks, the underlying automation prevents the user from violating any of the pre-set conditions. For example, paths cannot be plotted through land, and warnings will display in the manual mode if users create a path that violates the input depth, visibility, or separation distance. The system also warns users before a path is deleted, to prevent accidental loss of information. Before changes to the current path can be finalized, a final confirmation box appears, ensuring that the user is ready to update the current course. When any changes are made, the graphs on the right update automatically to show depth and visibility along the track.

3.5.3 Health and Status Tab

The Health and Status (H&S) tab provides information on many systems across the ship. For submarine commanders, health and status monitoring is an important task during all operations, whether on the surface or submerged. With so many different functions on the

submarine, it is a constant burden for the commander to monitor subsystems such as air, weapons position, and sensor strength. The health and status display runs parallel to the operational missions, ensuring that everything is working properly. Since one of the key components of this research is determining how to assist a submarine commander in surface operations, the health and status tab was added as one of the necessary outputs because of the direct benefits that come from knowing the status of systems across the submarine. For the purposes of this research, the systems that were the most difficult to monitor were chosen to be represented in this display.

There were many considerations in designing the H&S tab. One problem seen on the Virginia class submarines is with the alarm systems. The various stations in the control room are set up to monitor everything from possible collisions, shallow water, low air pressure, reactor problems, and more. All of these alarms go to different stations with different people monitoring each. Critical alarms are passed on to the commander when realized by the primary monitors of all different subsystems, over 7 in all. If the person monitoring a system does not think an alarm is critical, that information flow stops, and the commander is not informed. It is important to prevent commander information overload, but critical alarms can be dropped before reaching the commander, as well as not communicated to other members. This communication problem with alarm states can be addressed with a more robust H&S system that automatically provides some of these alerts to the commander.

Other alarm systems are poorly designed. The high-pressure air, for example, has a set point that once reached, causes the alarm to sound. In order to prevent this from happening, commanders typically assign someone to monitor the system and set an artificial alarm at a higher value. This wastes resources and is potentially dangerous. One way to address this workaround is through user-initiated notifications, which allow the user to set an artificial alarm at a higher or lower value. This can be in the form of a simple warning rather than a full-blown alarm, and can still keep the commander in the loop. The MSAT H&S tab acts as a funnel for many of these alarms. This way, the most important alarms would go directly to the commander, and other alarms can be set to

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desired points based on the commander's risk for various alerts, warnings, and alarms. The first view for the H&S tab gives high-level information across many systems, based on what the CO might be most interested in viewing. This information is presented similar to its placement on the actual submarine to aid in quick searches for information, and help with pictorial realism (Figure 18).
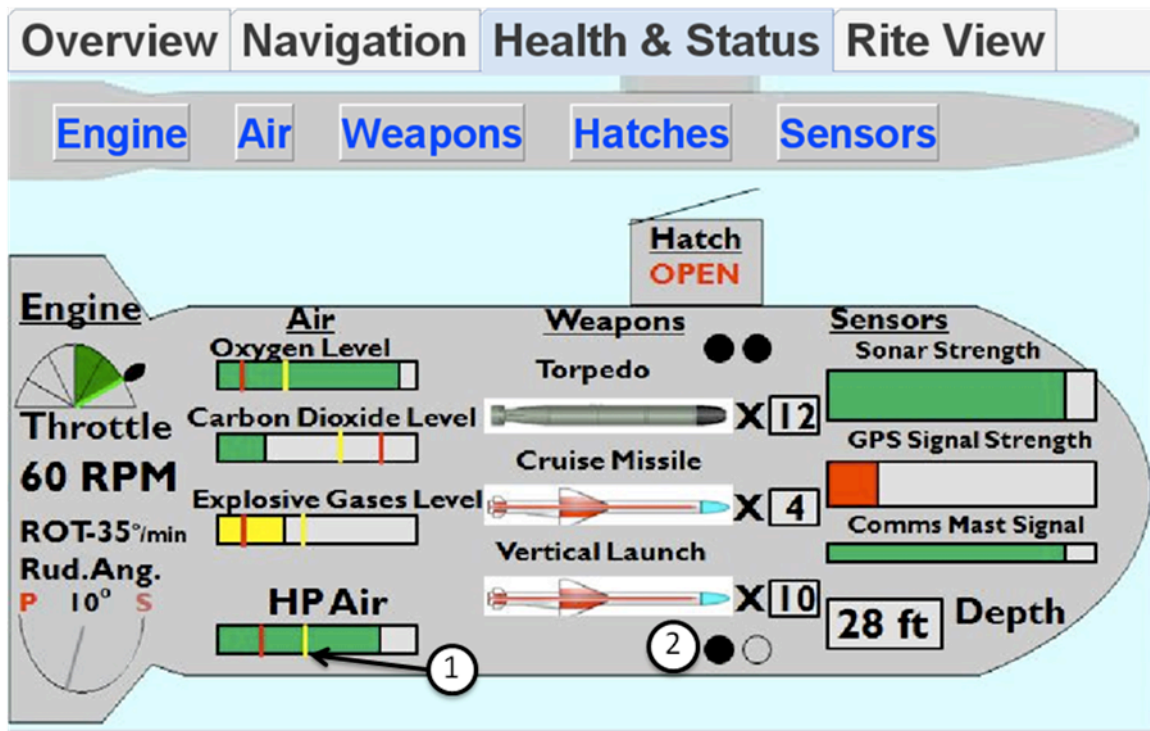


**Figure 18: Health and Status Tab**

This view uses a standard color scheme, where red is danger, yellow is caution, and green is acceptable. Also, for the rudder angle (Rud. Ang.), red and green are used to match the port and starboard (P and S) lights, conventional for maritime lighting schemes. From this view, the user can change the warning levels for different atmospheric levels by moving the yellow line to a new set point (1). The red line represents the fixed warning level that is built into the system. These user-initiated notifications serve many purposes. First, they give control to the user, helping to build trust in the system. Next, they provide added flexibility on warnings, as the commander can set the warnings so that he can be notified long before a critical situation is reached. They also allow the warnings to be personalized for each user.

The user can also gain more specific system information by clicking the buttons on top. For example, if the Air button is clicked, the display changes to show a detailed picture of the atmospheric levels over time. For weapons, the detailed position of each weapon on the rack is shown, as well as what is currently in each tube. From the basic view above, the user can see that three of the four torpedo tubes are full, but there is no indication here of what is in those tubes (2). The full H&S range of displays is shown in Appendix G.

3.5.4 Rite View Tab

The final tab is the Rite View tab. This tab uses a 3-D simulation environment currently in development by Rite-Solutions, Inc, and is seen in Figure 19.
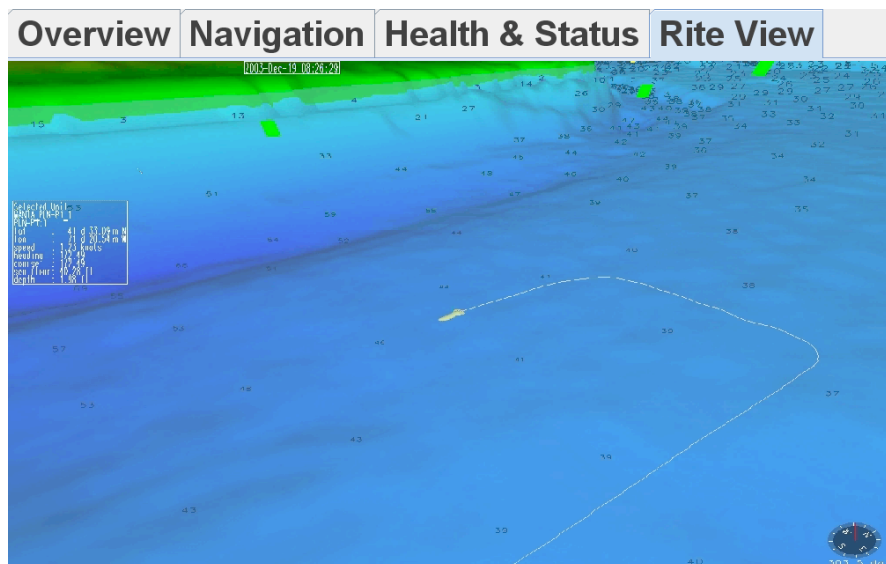


**Figure 19: Rite View Tab**

This tab helps to meet many of the situational awareness requirements, by providing an exocentric view of the surroundings. One of the problems with highly realistic displays is the assumption that people can accurately extract information from these 3-D interfaces (Smallman & St. John, 2005). People often perform worse with a 3-D display for tasks involving finite measurements (Smallman & St. John, 2005). So while 3-D environments are not the best for making specific course adjustments, they do provide a simple visualization to aid in overall situational awareness. This environment has the ability to

show and hide many different layers of information, which can be used to assist the commander in determining his geospatial location and surroundings. Also, it provides a quick overview at the surrounding contacts and hazards that may affect future navigation. The supporting overview and navigation tab can provide the more specific information for making exact judgments, while the Rite View tab gives the overall picture. Thus the navigation and Rite View tabs are complementary

3.6 Flexibility

The MSAT was designed to allow flexibility in the information displayed. Using the tabs, new information can be added, or current information can be removed, allowing the tool to be customized for each user or mission type. By customizing the display, other members of the submarine could make use of the MSAT, such as the executive officer (XO), navigator, or any other member that desires updated information on a mobile device. Displays such as dive controls and checklists can also be included, along with any existing display across the submarine. In the reverse, MSAT views could be put on a larger display in the control room for quick checks among the crew. Beyond the submarine, this same device can also aid surface ships, both civilian and military. Because the MSAT was designed based on many of the tasks that occur in other commercial and military vessels, the results are generalizable to other maritime vessels as well.

3.7 Summary

The overall design of the MSAT provides a unique interface that brings together information from across the submarine and presents it to the user in a simple interface, meant to be highly intuitive. This display also provides a flexible interface that can benefit other surface operations. By designing the interface based on a formal, principled set of requirements, the process ensures that all of the key information needed for decision making is available to the user. A final list of the requirements met in the MSAT is shown in Table 1, listing the original requirement as well as the display tab where the requirement is met.

**Table 1: Fulfilled Requirements**

| Requirement Description | Display location(s) |
| --- | --- |
| Geo-spatial boundaries | Overview, Navigation, Rite-View |
| Hazardous/restricted areas | Overview, Navigation, Rite-View |
| Tide, current, weather, marked on display | Navigation |
| Planned course, highlighted red if blocked, green if clear | Overview, Navigation |
| Visual indication of allowable paths when helpful | Navigation |
| Mark final destination or goal location on map | Overview, Navigation |
| Ability to determine range from ownship to other points of interest | Navigation |
| Geo-spatial location of all surrounding contacts | Overview, Navigation, Rite-View |
| Contacts course and speed | Overview |
| Specific sensor data available for review | Health and Status |
| Highlight sensor data that most likely represents a contact | Overview, Navigation |
| Contact path: past, present and future | Overview, Rite-View |
| Contact location on path | Overview, Navigation, Rite-View |
| List of contacts, with name, bearing, speed, and whether course is opening/closing | Overview |
| When craft is on a collision course with a contact | Navigation |
| When planned course violates limits or set restrictions | Navigation |
| Current speed and heading | Overview |
| Ability to compare different routes | Navigation |

# 4. MSAT Evaluation

4.1 Introduction

After any design process comes to completion, it is important to use sound testing methods to rate the quality of the tool developed. The MSAT was designed around the problem of improving decision-makers' situation awareness, focusing on both presenting high-level health and status of systems, while also being able to assist in the various functions carried out by submarine commanders. In order to test the tool against the objectives laid out in Chapter 1, two separate methods were employed. The first was a time and motion study, which used interviews with SMEs to determine how the MSAT compares with current monitoring methods. The second was a navigation experiment, which was performed to determine how well users can interact with automated planning tools. The navigation experiment also provided a platform to test users to determine their trust in a mobile automated planning tool. The following sections describe these methods in more detail.

4.2 Time and Motion Study

The first test performed was the time and motion study. A time and motion study is used to study a method or process to determine how the process can be simplified or improved (Robbins et al., 2003). Although the process can vary in its specifics, there are general steps followed in each case. First, the process itself is chosen, in this case the monitoring of a nuclear submarine. Next, all the relevant data is collected for the process. Following this, the process can be evaluated to determine where efficiency is lacking, or where improvements can be made. After determining the shortcomings in the current methods, new methods can be developed to fix these problems.

The interviews discussed in the CTA chapter formed the basis of the time and motion study. During these interviews, ten submarine officers from different classes of Navy submarines were questioned to determine trends in task time, and see how often tasks were performed. These results were then compared with the MSAT, by estimating how

long it would take to perform the same task using the handheld tool. These results will be discussed in the next chapter.

## 4.3 Navigation Experiment

The second test performed was a navigation experiment. The goal of this test was to evaluate how the MSAT performs as a navigation aid when compared with current paper and pencil methods. Since the navigation tab also allows for user interaction, the test also provided insight as to how easy the display was to use for complex tasks.

### 4.3.1 Experimental Design

For this experiment, participants were tested with two navigation scenarios, one using a paper chart and one using the MSAT. Two different counterbalanced scenarios were used to control for learning effects. Users from both military and civilian maritime backgrounds were recruited to assess trends in trust and performance based on training and job experience. A 2x2 mixed factorial design was used with user experience (military or civilian) as a between-subject variable and decision support (MSAT or Paper chart) as a within-subjects variable. Each user performed the experiment using the same map, and used one tool to navigate from top to bottom, and the other tool to navigate from left to right.

Results were compared by both path length and the time it took to complete planning. The path length was measured as the total distance between the start position and yellow goal position (see Figure 15), which was measured automatically on the MSAT and by hand using paper charts. A stopwatch was used for all the subjects to record how long it took from the time planning was started until the path reached the goal position. After completing the path, a questionnaire was administered to gauge users' trust levels.

### 4.3.2 Participants

Eight military personnel from both Coast Guard and Navy, and eight civilians from the MIT sailing pavilion and the Massachusetts Maritime Institute with experience in navigating in open waters were recruited. The average age of the military personal was

31 years old, with a standard deviation of 7 years, and a range of 23-47 years. The average age of the civilians was 41 years old, with a standard deviation of 10 years, and a range of 27-59 years. Only male participants were employed in the experiment since the submarine community is only composed of men.

4.3.3 Apparatus

For this experiment, two different sets of tools were used. The first was the MSAT, which runs based on a Java executable file. This file was run on a Sony *Vaio* Micro PC, model number UX390N, with a 1024x600 screen resolution. The second set of tools used was for the paper and pencil navigation task. Each participant was given a map and a printout of the expected visibility (a representative weather map), using the same values as those used by the MSAT. Each participant was also given a set of navigation tools, including a compass, ruler, parallel plotter, rolling ruler, pencil, and eraser, with which they were all familiar. Each participant plotted their path on tracing paper used by the Navy, which was covering the map. Times were recorded using a stopwatch, and distances were measured using a standard ruler and converted to nautical miles using the same scale as the MSAT.

4.3.4 Procedure

All participants were first given a practice scenario with both the paper tools and the MSAT. These scenarios were set up exactly like the actual test scenarios, with the exception of the map used. For the practice scenario, a different map was used to prevent learning effects with route planning. For the experimental scenarios, participants were randomly assigned to one of four combinations of scenario and navigational tool groupings listed below.

- MSAT left to right navigation followed by paper top to bottom navigation
- MSAT top to bottom navigation followed by paper left to right navigation
- Paper left to right navigation followed by MSAT top to bottom navigation
- Paper top to bottom navigation followed by MSAT left to right navigation

The same map was used in all scenarios, with the left to right navigation moving across the screen from the top left to the top right, and the top to bottom navigation moving from the top center to bottom center. Participants completed the task using either the MSAT, with time starting once the system was given to the participant, and ending once a new path was created and chosen, or with paper and pencil, with time stopping once the participant reached the goal. Following the experiment, a trust questionnaire was administered (Appendix I). The complete experimental protocol for the navigation experiment can be found in the thesis by Buchin (2009).

4.3.5 Dependent Variables

Table 2 shows the performance dependent variables.

**Table 2: Performance Dependent Variables**

| Metric | Interpretation |
| --- | --- |
| Path length | Length from start to goal, converted to nautical miles for consistency between paper and MSAT map and normalized based on the absolute shortest path |
| Obstacle avoidance | Avoiding collisions with other obstacles, including both land and other contacts (a binary yes/no value) |
| Time to generate path | Time from when the obstacle was presented to when the new path was submitted |
| Trust variables | Trust, accurateness, reliability, usability, and robustness were all assessed using a post experiment questionnaire |

4.4 Summary

The design of the MSAT is based on addressing the shortcomings seen in previous systems. In order to evaluate the MSAT to ensure that it is, in fact, an improvement, two tests were performed. The first test measured the MSAT's ability to perform health and status monitoring functions. By performing a time and motion study, the possible time savings that can be gained through using the MSAT were determined. To address the benefits of using the MSAT for navigation, a second experiment was performed. The goal was to determine, based on task time and task efficiency, whether the MSAT is a better tool for navigation. The results of these tests are discussed in Chapter 5.

# 5. Results and Discussion

5.1 Time and Motion Study Results

After the time and motion study questions were asked to a field of ten submarine officers, the results were recorded for evaluation (questions in Appendix H). The responses for each task time were then compared with an estimate of how long the same task would take with the MSAT. Due to the limited pool of submarine officers with different operational experience, there was large variability in the responses. The estimates for the MSAT were single point estimates, since they are based on users locating and selecting the correct data, which has little variability for expert users. The MSAT estimates were determined based on the time needed to both cognitively process a task, and then to carry out the task using the MSAT. The results for the time and motion study are broken down into the following three categories: physical movement, navigation, and health and status monitoring.
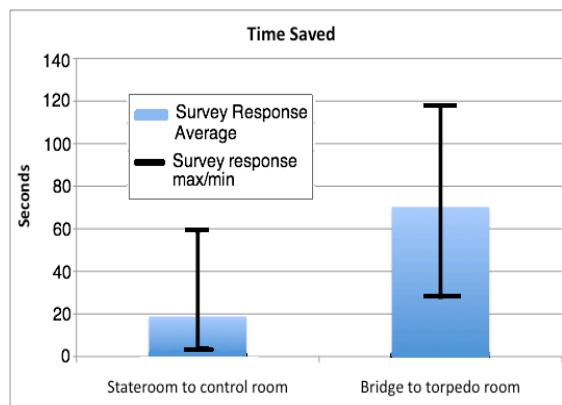


**Figure 20: Movement Time Survey Responses for Physical Movement**

The survey results in Figure 20 show the average response time and variability for the first two questions. The first set of questions was a simple comparison of the two main trips carried out by a submarine commander. The first is moving from the stateroom to the control room. The stateroom is the living quarters of the CO, and so movement between the two locations occurs often by the CO so he can seek out information and

keep a high level of situational awareness. Movement from the bridge to the torpedo room represents another movement the CO might need to make. Since the MSAT presents information without requiring movement into the control room or torpedo room, the graph represents time that can be saved using the MSAT.

Because the MSAT would allow commanders to obtain the information needed from the control room or weapons room without having to be physically present, there is no need to make these trips anymore. Currently, the commander needs to move from his stateroom to the control room to get information, but with the MSAT, this information is available wherever the commander is. Since these movements are no longer necessary to gain information, the time to gain this information is simply the time it takes to click through to the navigation tab. These time savings would occur every time the commander would have previously moved. Throughout a typical day, these time savings could add up to be a much more significant amount of time.
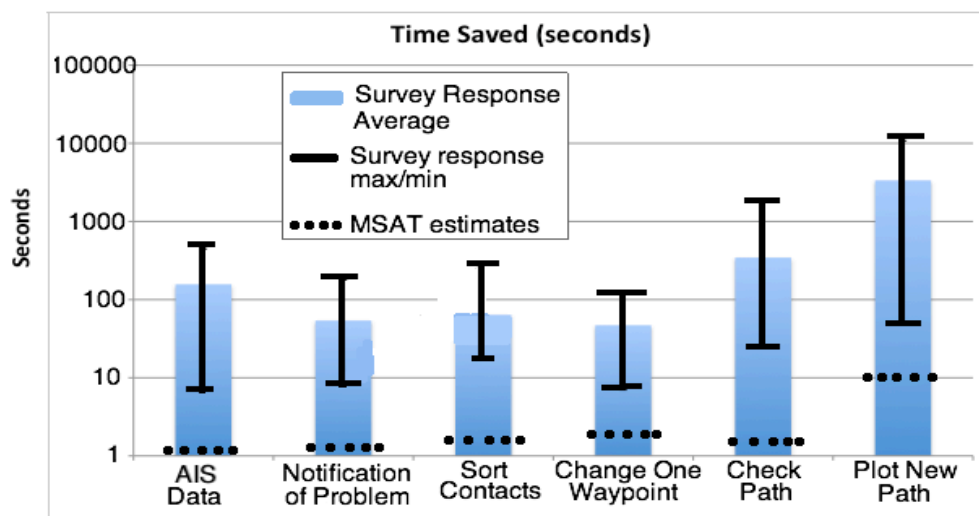


**Figure 21: Navigation Time Responses**

The second set of questions dealt with time saved for the task of navigation. There are many processes involved in navigation, and the tasks used for the time and motion study are shown in Figure 21. The questions ranged from simply gathering AIS data to more

difficult tasks such as plotting an entire new path. The responses for each of these tasks using the current methods are compared to the MSAT estimates in Figure 21.

The range in Figure 21 shows a great deal of variability for these responses, likely due to the personal experiences of each submariner. Comparing the average time with the MSAT estimates shows the large potential savings. This is because plotting a new path takes a significant amount of time using conventional methods, due to the large amount of information needed and the difficulty in plotting each leg. With the MSAT, which takes in this information automatically, a new path can be plotted in seconds using the Autoplan feature.

The final grouping of questions addressed health and status monitoring. These questions dealt with the checks and measurements performed by the commander to ensure that the overall submarine is functioning within normal limits. The responses for the time it takes currently to perform these tasks are shown in Figure 22, along with the MSAT estimates.
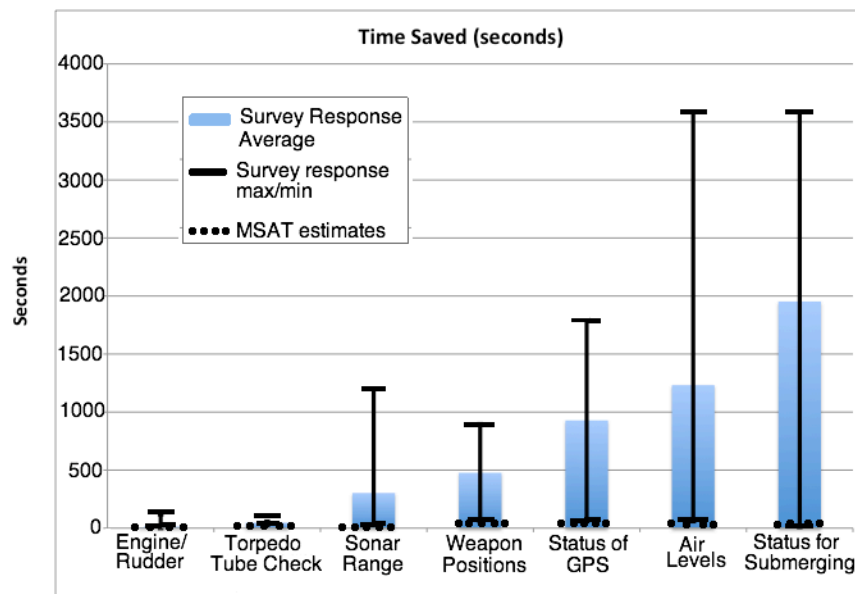


**Figure 22: Health and Status Survey Responses**

The average time savings given the MSAT are clear. The MSAT has the ability to track many of the submarine's systems in real time, which would prevent waiting for rounds to

be made, and also give the information in its entirety in one central display. However, not all tasks here show large savings. Some of the monitoring tasks, such as checking the engine/rudder positions and torpedo tubes, are currently performed in an effective manner, and so the MSAT simply matches this value rather than improving it. The MSAT excels with the more complex tasks, such as monitoring air levels due to the aid of automation.

The MSAT affects many roles, as it shifts work previously done by the crew over to the automation. Many of the monitoring tasks, such as checking gauges for air levels, can be done automatically by a computer, and that information can go directly to the MSAT. Since many of these time savings are relatively small, it may be difficult to simply cut manning. Instead, re-allocation of resources can help to improve workflow by changing roles and responsibilities. A shift in roles can allow for more evenly distributed work, or even just more sleep, while also giving the commander more rapid access to information. Beyond simply reducing task time, the variability of tasks can also decrease.

Using the MSAT to decrease time on task can be related to a cut in costs. Based strictly on the cost of various crew involved, and an estimate of how many times per day a task is performed, an estimate was made for the total cost savings. This estimate takes into account who is involved in each task, what the pay rate is for each of these members, and how many times the task is performed each day. An example would be plotting a new path. Not only must the commander dictate a new path, but the navigator and plotter must also work to create the actual path. The time taken by the navigator and plotter can be converted to a cost using the formula shown in Equation 1.

$$\frac{Money\ Saved}{Task} = \frac{Time\ Saved}{Task} * \frac{Pay\ (dollars)}{Time} \qquad (1)$$

This equation uses the average time saved per task based on the survey results, and the pay is based on current submarine pay scales including allowances. Since some tasks require multiple people of different ranks, these tasks are handled separately, and a cost is calculated based on the time each task takes to perform. These time savings for each task

are the amount of time that would be saved using the MSAT versus current methods, and Table 3 shows a summary of the time saved for many of the common tasks performed during daily operations.

**Table 3: Time Savings**

| Task | Average Time (sec) | | Frequency /day | Time saved /day (sec) |
| --- | --- | --- | --- | --- |
| | **MSAT** | **Current** | | |
| *Movement Tasks* | | | | |
| Stateroom to control room | 1 | 19.8 | 6 | 118.7 |
| Bridge to torpedo room | 1 | 72.2 | 4 | 288.9 |
| *Navigation Tasks* | | | | |
| Input AIS Data | 1 | 158.0 | 50 | 7850.0 |
| Notify CO of problem on path | 1 | 55.0 | 10 | 540.0 |
| Sort contacts by CPA | 2 | 65.9 | 40 | 2554.3 |
| Change one waypoint | 3 | 50.0 | 10 | 470.0 |
| Check parameters of path | 2 | 347.1 | 4 | 1380.6 |
| Plot a new path | 10 | 3365.0 | 1 | 3355.0 |
| *Monitoring Tasks* | | | | |
| Engine/rudder | 2 | 15.8 | 75 | 1033.3 |
| Atmospheric levels | 2 | 1234.3 | 24 | 29574.9 |
| Munitions position | 3 | 480.0 | 4 | 1908.0 |
| Contents of torpedo tubes | 3 | 50.0 | 4 | 188.0 |
| Status check for submerging | 3 | 1955.7 | 2 | 3905.4 |
| Status check for GPS | 2 | 930.0 | 4 | 3712.0 |
| Sonar Range | 3 | 306.0 | 4 | 1212.0 |

Based on the time savings shown in this chart, the average time saved in a typical day that could be gained from using the MSAT is over 16 hours. This is across the whole crew, but on a mission that lasts over six months, this can add up quickly. Similarly, if broken down by cost based on pay rates, the money saved during a six-month mission is nearly $35,000 dollars (Defense Finance and Accounting Service, 2009). This amount is based on a members pay (including average housing and food benefits) broken down by

time, assuming a 40-hour workweek[1]. While not a drastic savings, it shows that there is room for improvement in the current methods of carrying out these tasks, and that new methods can aid in increasing efficiency through better resource allocation or changes in manning. The MSAT is not a fully functional tool, but the methods used can lead to improved operations.

Table 4: Comparison of Means for Different Tasks

| Task (Parametric t tests) | Mean Difference | t-value | p-value |
| --- | --- | --- | --- |
| Move from stateroom to control room | 19.8 | 3.16 | .01* |
| Move from bridge to torpedo room | 72.2 | 5.44 | .00* |
| Gather AIS data | 157.0 | 1.88 | .13 |
| Plot new path | 3668.0 | 1.63 | .18 |
| Check atmospheric levels | 1232.3 | 2.09 | .08 |
| Determine weapon position on rack | 477.0 | 1.14 | .46 |
| Check contents of firing tubes | 47.0 | 4.70 | .04* |
| Check status for submerging | 1952.7 | 3.52 | .01* |
| Check status of GPS | 928.0 | 1.07 | .48 |
| **Task** (Non-Parametric Responses) | | | |
| Notify commander of problem on path | 54.0 | -- | .00* |
| Sort contacts by CPA | 63.9 | -- | .13 |
| Change one waypoint | 47.0 | -- | .03* |
| Check path parameters | 103.0 | -- | .02* |
| Check engine | 0.8 | -- | .00 |
| Check sonar range | 303.0 | -- | .06 |

*Note: Values with * represent significance at $\alpha=.05$

As a final means of comparison, one-sample t-tests were conducted, comparing the responses to the estimate for the MSAT to determine if there was a significant difference (Table 4). For some tasks, the distribution of responses was highly skewed. Thus, the

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[1] The pay rates were taken from http://www.dfas.mil/militarypay/militarypaytables.html, which provides military pay information for different ranks.

responses to these tasks were analyzed using non-parametric statistics, specifically a single sample sign test. Type I error was set at $\alpha=0.05$.

These values show that in many different areas, the MSAT offers both a statistically and a practically significant advantage over current methods. For those tasks that are not significantly different, there may still be advantages. For one, the graphs for survey responses show that variability with current methods is high, and the MSAT may offer more consistent results. Also, high variability and limited responses make it difficult to show significant differences. The variability for each task can be seen in Appendix J.

Based on the results of the time and motion study, there are many tasks that can benefit from use of the MSAT. Time savings are seen for each of the tasks associated with the time and motion study, and using automation can also help to reduce the variability in task times. The overall benefit of the MSAT can be seen in the time savings across all of the tasks, which can lead to a shift in responsibilities or possibly reduced manning. These results show areas where automation can aid current users across the submarine. From these responses, navigation and its subtasks seem to benefit from the aid of automation. In order to see what time savings and efficiency increases may be seen, a more specific navigation test was also performed. These results are discussed in the next section.

5.2 Navigation Experiment

The results of the navigation experiment also revealed many benefits of MSAT. Based on the 2x2 ANOVA results for task duration, it can be seen that the time taken to plot a path is significantly less using the MSAT as opposed to paper charts for both military and civilian users ($F(1,14)=92.47$, $p<.0001$). There was also no interaction effect ($p>.05$). The supporting ANOVA tables can be found in Appendix K. The factor mean time spent using the MSAT was just over 1.5 minutes, with the average time used for the paper charts nearly 4 minutes. These results are separate from the time and motion study, which focused on real world scenarios which can be much more complicated. The navigation experiment was a very basic navigation scenario, so it was expected that task times would be shorter than those cited in the time and motion study. The experiment also provides

objective results, unlike the subjective answers provided for the time and motion study. Figure 23 shows that there were slight differences in time between military and civilian users, but that the overall time was much less for the MSAT. Because these results are based on actual experimental data, they are far more realistic, and should be weighted more than the time and motion study estimates.
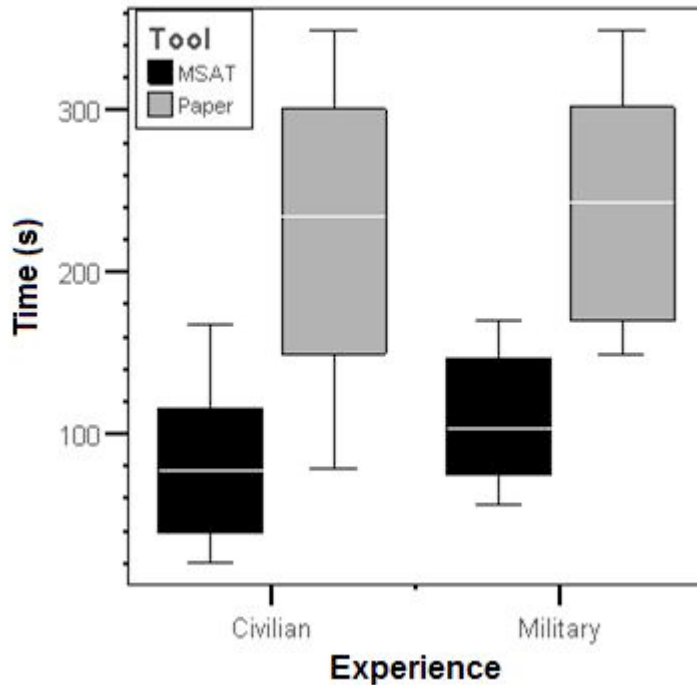


**Figure 23: Total Time for Plotting a New Course**

Similarly, there was also a significant difference between the MSAT and paper charts for the length of the paths ($F_{(1,14)}= 13.21$, $p=.003$). These lengths were calculated by subtracting the most direct path length that avoided obstacles from the length of the user created path (Figure 24). This scaled the results so that they could be compared across the two scenarios. On average, the MSAT planned paths were approximately five nautical miles shorter, which is about 7% of the total distance. Also, it was noted that for path length, there was a significant difference between military and civilian users ($F_{(1,14)}=18.26$, $p=.001$). The military members planned longer paths, which tended to be more conservative near contacts. The shorter paths created by the MSAT were overall more efficient, leading to both time savings and decreased operating costs. Again, there

was no interaction effect (p>.05). The ANOVA tables can be found in Appendix K. With regard to obstacle avoidance, there was no difference. None of the participants plotted paths that intersected obstacles on the MSAT or on the paper charts.
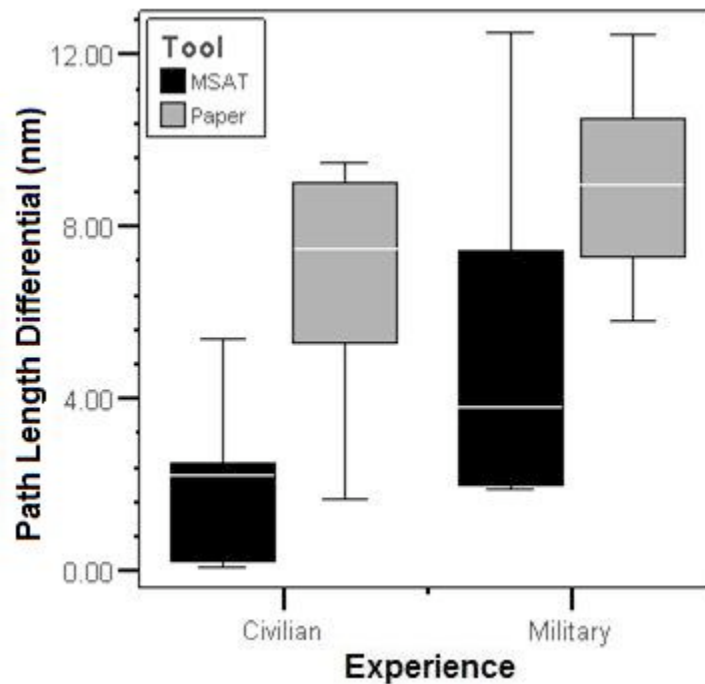


**Figure 24: Path Length Comparison**

After the navigation experiment, a trust questionnaire was administered. The primary focus of this questionnaire was whether participants were willing to trust the MSAT. The overall results were positive. Responses ranged from 1 (no trust) to 5 (complete trust), and most subjects reported having some amount of trust. Although only one participant reported having complete trust, the general trend was that the tool was trusted, as only two participants reported having less than an average amount of trust in the MSAT. Based on a Mann-Whitney test, there was no significant difference between military and civilian responses for trust (U=25.5, p=.50). These results are shown in Figure 25.

Other analyses were performed to determine if there were additional trends in the data. Based on the HCTA and interviews with SMEs, it was expected that the military users would be more likely than civilians to use the manual MSAT method, rather than trusting

the automation. A marginal correlation was seen (Spearman's ρ=.39), but there was no significance (p=.13, 4/8 military subjects used the manual method, 1/8 civilians used manual method).
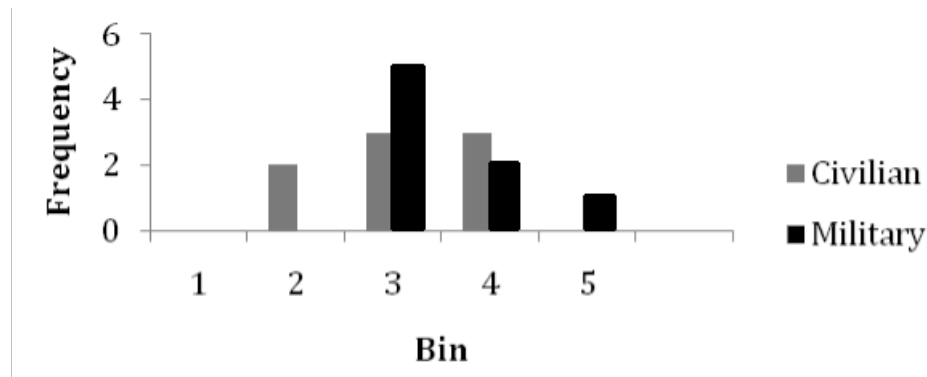


**Figure 25: Overall Trust in System**

The next comparison investigated whether there were any correlations among subjects who used low, medium or high-risk paths (based on separation). Four different factors were checked using the Spearman rank test to see if there was a relationship among the following: age, civilian or military background, maritime experience, and charting experience. After checking for significant correlations, none were found (supporting statistics in Appendix K3). The Spearman rank test was used because the assumption of normality was not met by any of the predictor variables. The lack of significance could simply be due to the relatively low number of subjects, but could also indicate that a subject's willingness to accept risk is not strongly tied to factors such as age, experience, and training.

The next test checked to see if there was any relationship among users' responses on the trust questionnaire and their risk level for the path used. The assumption was that users who had higher trust in the automation would be more willing to accept high-risk paths, and vice-versa. The responses for questions regarding the trust, reliability, and accurateness of the MSAT (Appendix I) were assessed for a relationship between the different risk levels, using the Spearman Rank correlation. All values were based on a five point scale, and based on this test, none of these responses showed significant

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correlations (Appendix K3). Based on these results, there does not seem to be a significant relationship between how much someone trusts the MSAT and the level of risk they are willing to take. A table showing some of the descriptive statistics for this test is shown in Appendix K4.

Finally, the last set of tests performed was a regression analysis, to see if there were any significant predictor variables for high performance. Age, years charting and risk were all checked for significance for both path length and time while controlling for tool type, background, and their interaction. A mixed linear model was built with the following factors: tool type (MSAT/paper), background (civilian/military), and tool type and background interaction, as well as the following covariates: age, charting experience, and risk level. None of the covariates were found to be significant ($p > .2$). Overall, it appears that the subjects' performance was not significantly dependent on age, charting experience or level of risk. While the lack of significance may be due to the relatively small sample size, it may also indicate the robustness of the MSAT, suggesting that MSAT was simple and intuitive enough that people were able to use it regardless of past experience. While age has been seen to have a significant tie to performance in a mission planning study (Cummings & Guerlain, 2007), the fact that age did not affect performance with the MSAT could be a beneficial result, indicating the ease with which users were able to learn the system.

# 6. System Implementation

Based on the results of the time and motion study and navigation experiment, it is clear that the MSAT can provide advantages to submarine, and more generally, maritime crews. However, there are still many issues for system implementation that must be addressed before the MSAT can become operational. This chapter raises many of these questions by looking at the MSAT through several different lenses of human-system integration (HSI). Many of the human factors issues were addressed in previous chapters, but the other areas of HSI will be discussed here, including but not limited to manpower, personnel, training, habitability, and survivability. Finally, other issues specific to the MSAT will be discussed with regard to how they will effect system implementation.

6.1 Manpower

Across the military, an important question being asked is how to reduce manning and shift responsibility to automation (Frost, 2008; Roth, 2004). Reducing manning and shifting the crew component to a more technologically sophisticated workforce can allow the Navy to cut costs without losing capability (Roth, 2004). In the submarine environment, manning must be determined as early as possible, because space is a driving factor. With such a high demand for space, crew size is very important, as each person means an additional bunk, more room for food, more oxygen, and possibly even additional facilities such as showers and bathrooms. If the MSAT can aid in manning reduction, this means overall cost savings in the design process. Space can be set aside for new technologies, increased facilities, or even extra food storage.

The difficulty in determining manning requirements, especially in the submarine environment, is that the tasks are dynamic. When in a typical monitoring scenario, personnel requirements are minimal. This is often the case during peacetime, when the needs are very repetitive and well defined. During wartime, operational tempo increases and most people on the submarine become inundated with tasks, which also occurs in emergency situations. Manning is normally determined in the conceptual design phase with the wartime tasks in mind, which often prevents designers from making cuts to

personnel. The MSAT can help to perform tasks that are necessary for both war and peacetime, such as decreasing the amount of physical movement needed and speeding up the processes of navigation. These savings could potentially lead to a reduction in the number of people needed for both war and peacetime operations.

An alternative to reducing crew is to shift responsibilities. Based on the changing task times using the MSAT, legacy task allocation may leave gaps for some members of the crew whose tasks have been automated. Shifting these gaps through task re-allocation can mean a more constant workload. For example, the navigator can spend more time monitoring unknown contacts, rather than planning future paths for example, or engage in more mission-specific tasking. By increasing the efficiency of workflow, a tool like MSAT could help to balance manning for different operation tempos.

6.2 Personnel

Originally designed for the CO of the submarine, it was quickly realized that this tool could aid other members in doing their job as well. The executive officer (XO), the Officer on Deck (OOD), and the lookout on the bridge could all benefit from the information the MSAT provides. With the flexibility of the tabbed display, many others can also benefit from this type of mobile tool. The capabilities of the MSAT also raise further questions.

For one, the cost-benefit ratio would need to be determined to see who should have the tool. Although everyone on board might find it useful, it may be an unnecessary cost to give one to every member of the crew. However, with advances in computing power, a similar display design could be put into a smaller platform, such as the new touch screen mobile phones. At the very least, the software needs for each crew member may differ. The CO and XO might want to use the same original design, which shows a very broad and shallow view of systems across the ship. The OOD might want the same views, or he might want to see additional tabs to represent sonar or radar displays. For the Engineering Duty Officer (EDO), the requirements might be very different. The EDO, who spends his time monitoring the nuclear reactor on board, may want more information on turbine

generators and valve positions. Determining the right mix of applications as well as security issues for various echelons of personnel on a vessel is an area that needs further exploration.

6.3 Training

The benefit of designing a simple to use, intuitive tool like the MSAT is that the training process may be less intensive than current paper and pencil methods. The users' manual seen in Appendix F is short, and the tool has few hidden functions, allowing easily access to most of the interactions. In order for users to obtain the knowledge, skills, and abilities necessary to operate the MSAT, users would face a straightforward process of instruction, learning, and application. After becoming familiar with the users' manual and the tool itself, users can then learn how to use the tool with demo scenarios. Once comfortable with these scenarios, they can begin to transition the abilities to the operational environment.

Another additional benefit of the MSAT is that this training process can take place with minimal costs, by simply giving the tool to a person and allowing them to try out the interface. Simulated data can be used, showing realistic output on the MSAT to train for specific scenarios. Because the MSAT is designed to share information with the other displays on the submarine, crews can be trained individually without having to bring the whole control room together. Once the member is ready, he can easily transition to working with the team using the MSAT in the same way. Based on the navigation experiment, users were able to learn how to use the navigation interface in just one short ten minute training session. To learn the entire tool could take as little as one hour. After this initial training, the member would be ready to use the MSAT to aid in current responsibilities.

The added training for the MSAT is fairly minimal, and it is possible that other training changes may result. For one, training for other systems can be accomplished using the MSAT as a training interface. Since a great deal of training for the Navy is computer based, these programs could be incorporated into the MSAT so members can stay current

with training during downtime. In addition, with the ability to plan and plot a path with just the click of a button, certain tasks such as paper navigation become less useful. Although important to have in case electronic systems go down, the time spent teaching crews how to plot on paper charts can be reduced to leave more time for other training. Crews can also be trained in recognizing off-nominal situations, so that the Health and Status monitoring tab in the MSAT can further aid in providing quick warnings.

6.4 Habitability

The impact of the MSAT to habitability is fairly straightforward. Because the MSAT allows increased mobility and gives up-to-date information on many systems, the MSAT provides a greater quality of life for supervisors of submarines. The CO can stay up-to-date while not engaged in a specific task by simply keeping the MSAT nearby. The OOD can have increased flexibility of maintaining situational awareness even if he has to leave the control room. Of course, the MSAT only provides high-level information, so it is still necessary to be in the control room during major operations.

The quality of work could also increase with the MSAT. Beyond normal functions, further capabilities such as video monitoring of different locations on the submarine could help the commander stay involved. The display could be updated with a new tab to display this video feed information, if desired. Although the small screen size prevents complete control capability, the commander can use the information to determine whether or not movement to the control room is necessary or simply use the information to start thinking of solutions en route. There are many more opportunities to increase quality of work through the MSAT. As mentioned in previously, there are many functions on the submarine. Not all of these were addressed in the current version of the MSAT, but following the design process outlined in Chapter 3 can lead to additional tabs that can support all functions across the submarine. Any or all of these additional capabilities of the MSAT would aid in habitability through the resulting increase in quality of work.

## 6.5 Survivability

The MSAT will also do a great deal to increase survivability through the health and status monitoring abilities. This tool allows for user-initiated warnings for items such as atmospheric levels and air pressures, which keeps commanders in the loop by allowing them to set levels with which they are comfortable. Also, the aggregation of information keeps the commander up to date on the system status throughout the ship, allowing for quick actions if something begins to go wrong. This constant access to updated information can prevent gaps in the commander's situational awareness.

## 6.6 Other Issues

Many of the other issues with implementation of the MSAT deal with the hardware and software required to support such a tool. Hardware and software implications are not a part of the typical HSI model, but because of the significant implications of the MSAT, they are discussed here. These issues range from security issues such as using wireless communications to software integration with current systems. There is also the issue of adding a server to support the MSAT, which brings with it another set of issues entirely.

The first question is how to support the MSAT via a wireless network. With the need for information security at a constant high, wireless is always a risk because of the lack of network security. The fear is that the wireless signal might "leak out" when the submarine is surfaced, and someone nearby might be able to gain privileged information. Although wireless will never be as secure as wired communication, research has shown that it can work within the steel hull of the Virginia Class (Wilkins, 2001). During the short cruise on the USS *New Hampshire*, wireless access was possible through a series of repeaters. While surfaced, crew members were able to check e-mail and even outside websites. If for some reason the MSAT cannot utilize this same system, there are other options.

One possibility is to use a shorter-range signal such as Bluetooth. This would prevent information from leaking beyond the immediate hull, as the signal strength is very low. Bluetooth range is also not entirely limited, so within the submarine the commander can

remain mobile. A different option would be to use one of the new technologies such as magnetic induction. This system has approximately a range of six feet, which is short but still unwired. Stations could be set up across the submarine where information can be received, which would still provide more areas outside the control room than the current configuration. If no wireless signal will work, the last option would be to provide Ethernet hookups at various locations, where the user can plug in to access up-to-date information. Similar to the repeaters that are currently on board, this will still benefit users due to the greater amount of information provided in remote areas away from the control room.

Another important issue to consider is the thermal impact of a new system. Because all of the heat on board the submarine must be expelled, it is important to limit the amount generated. Although the MSAT has a small heat signature, a server would be needed for support, and could potentially generate a significant amount of heat. The server would take in information from different systems and compile that information before sending it to the MSAT. Contact information, speed and heading, and all of the health and status information would need to be taken from other systems before being sent to the MSAT. This server must also be designed to interface with all of the other submarine systems. Because the MSAT takes in information from across the submarine, the server must be able to connect with each system to share information. With different designs for fire control, radar, and sonar, the MSAT must be able to connect with each and pass that information to the commander. This would be no simple task, as many of the systems on board were designed at different times, using different underlying codes.

One of the hardware issues specific to the MSAT is battery life. The current Sony *Vaio* has a battery life of approximately 4 hours during normal operation. Ideally, this duration would be increased to last the length of a normal 6-hour shift. Through upgrades such as solar powered charging and lithium ion batteries, this may be possible. It would also be important to provide many charging stations, so that the tool is ready to use for the next person. Other options include changing the supporting hardware, as new platforms such as the iPhone[©] boast a battery life up to six hours with continuous wireless use.

The software for the MSAT would also need to be continually upgraded to account both for software improvements but also new task applications. In addition, other abilities such as increased viewing capability and electronic dead reckoning would also be important to incorporate.

The need for further work on the MSAT is clear if it is going to have any future aboard the submarine. However, this initial research shows many clear benefits. The crew can benefit from an increased quality of work, training can be streamlined, and information becomes accessible across the submarine. Identifying the hurdles that still need to be overcome is an important step in the process of implementing a mobile system onboard.

# 7. Conclusion

Recent news shows an alarming number of avoidable maritime accidents, especially within the nuclear submarine community. These accidents have occurred even with new advances such as the Virginia class and the Automatic Identification System for tracking ships at sea. The fact that these collisions are still occurring indicates the need for help. Based on a cognitive task analysis of current submarine operations, including a five-day cruise and interviews with various Naval officers, the existing shortcomings were identified. One central problem is how information is gathered and presented to the commander, due to disjointed sources and lack of communication between certain operators. Other problems relate to the difficulty of monitoring systems across the submarine, as there is no convenient way to track all of the different subsystems. Finally, the bulk of information lies in the control room, and so it is difficult to maintain an accurate mental model and still have mobility across the submarine.

After recognizing these shortcomings, design requirements were generated and a mobile decision support tool was designed to aid the commander in operations. The goal was to design a tool to aggregate information and increase the situation awareness of a submarine commander. In addition, inserting automation via an automated path planning tool was a primary design focus, which could be especially helpful in the littoral regions, where contact density and the number of obstacles becomes high. The design of the tool followed many key design heuristics to integrate the information in an easy to use interface that would require minimal training. Once the display was designed, a two-pronged evaluation approach was used.

The first method was a time and motion study, meant to measure the capabilities of the MSAT against current health and status monitoring procedures. The second was a navigation experiment, comparing the MSAT and its automation against current paper and pencil methods. Both experiments showed positive results. For the monitoring tasks, the MSAT decreased the expected task time, and also removed certain tasks requiring movement across the submarine. The time savings are estimated at 16 hours per day

across the crew, based on the average time of the MSAT versus current methods. As for navigation, the benefits are also clear. Use of the MSAT resulted in significantly shorter planning times, as well as significantly shorter paths. In addition, a trust questionnaire administered after the test showed positive results from both military and civilian test subjects, indicating a willingness to trust mobile devices in the context of navigation.

The addition of the MSAT into the submarine environment affects more than just physical movement, navigation, and monitoring tasks. There are many other changes that may be seen in MSAT implementation. Training may change due to the new methods available for path planning, manning might decrease, and the quality of both work and life may increase on the submarine. Other more challenging effects deal with the design of a server to support the MSAT, and the additional heat signature of supporting one or more MSATs.

Although there are still hurdles that must be addressed before the benefits of the MSAT can be fully realized, the need for improved decision support for the commander is clear. Giving commanders the ability to offload tasks to automation, stay current on the surroundings anywhere on the submarine, and easily monitor systems on an intuitive device that fits in the palm of a hand is a possible solution to these problems. Based on the initial tests performed in this research, the MSAT can provide current and future commanders with the support needed to gain higher levels of safety and situation awareness.

7.1 Future work

The first steps towards the use of a mobile decision support tool have been taken, but further actions are required. Future work is broken down into the following three sections: MSAT design changes, system development, and additional uses.

The first step in moving forward with the MSAT in an operational environment is to complete the display design and add functionality as needed. For example, different information for health and status monitoring may be necessary based on new systems.

Also, more information can be added to the map display, and the Rite View interface, or some other 3D viewer needs to be incorporated to offer full viewing capability. The contact summary on the overview tab also needs to be updated, allowing the system to show all surrounding contacts and adding the ability to scroll through the information. One way to do this is with the aid of advanced automation. By aggregating information from different sensors on the submarine, contacts could show up automatically depending on whether or not a reliable signal has been detected. If the MSAT were to be used in a control setting rather then just an advisory took, further experiments should be conducted.

The next area is dealing with the design of the supporting hardware and software. In order to support the MSAT with the needed information, a server/client system needs to be created. The server size will vary based on the number of mobile devices used. Regardless of size, the biggest issue will be designing a system that can communicate with the current technology on the submarine to take information from the other systems and pass it to the MSAT. The current VMS system can compile this information, but further updates are needed to combine contact information from sonar, radar, and visual inputs to determine the most likely surrounding contact picture. Once a server is designed, a method for passing this information must be chosen. Wireless is the recommended method, but based on the issues with security, other options such as Bluetooth and short-range magnetic induction systems may need to be considered.

Finally, there is an opportunity to modify the MSAT to work in other areas. The transition to surface ships is likely the first update, but other operations can also benefit from the idea of the MSAT. Beyond the Navy, commercial ships could also use the MSAT, with a few design changes. Commercial ships would especially benefit from the mobility, as many of the large tanker ships operate with very small crews. Outside of the maritime environment, other tasks that require mobile information and monitoring could potentially benefit from the MSAT. Hospital staff, police, and fire fighters are just a few professions that may be able to use a tool like the MSAT.

The MSAT is not yet ready for implementation in all respects, but through this research, the opportunities and issues available are better understood. With the continuing problems in the submarine community in navigation and collision avoidance, the need for safer operations is more than apparent. The MSAT is just one aspect of a solution, but based on the results of this research, it adds a clear benefit to the operational picture. Through the implementation of a mobile decision support tool, submarine commanders can increase their situational awareness, make decisions more quickly, and operate from all areas of the submarine to improve both the efficiency and safety of operations.

# Appendix A: Scenario Task Overview

## Collision Avoidance during Surface Operations

<table>
<tr>
<td rowspan="2"><b>Mission Planning</b></td>
<td colspan="2">It is assumed that the following issues will be resolved in this phase:

- Objectives for mission will be determined
- Path desired will be set
- Traffic patterns in navigation area will be known
- Expected contacts list generated
- Land map is known and accurate
- Known current and predicted weather
- Restricted areas defined
- Force Protection level</td>
<td>Helpful information for resolving these issues includes:

- Start and ending locations
- Possible paths provided, allowed variance
- Shipping routes that might be crossed
- Current traffic in the area
- Terrain map in all possible travel areas
- Up-to-date weather and current information
- Military operations or wildlife restrictions
- Coastal maps
- Assistance that comes along with each FP level, such as high speed patrol boats to intercept vessels</td>
</tr>
</table>

<table>
<tr>
<td rowspan="5"><b>Mission Execution</b></td>
<td><b>Phase Goals</b></td>
<td><b>Phase Breakdown</b></td>
</tr>
<tr>
<td>Exit Harbor</td>
<td>
- Cast off from docking position
- Orient craft to exit path
- Check for contacts in area
- Follow navigational aids to exit harbor while following rules of the road
- Determine whether to stall or change direction if path is blocked
- Determine whether to change path or wait for tides to change if depth is an issue
- Exit harbor phase is complete when the craft is outside the confines of the docking area
</td>
</tr>
<tr>
<td>Terrain Confined Navigation</td>
<td>
- Set up possible course
- Determine potential obstructions both under and above water
- Determine whether stopping or slowing is better based on currents and navigation ability, if traffic is heavy
- Determine from the mission time constraint whether there is any ability to slow down passage
- Determine what contacts may cause interference based on realistic path prediction based on past experience
- Determine limitations on contact maneuverability
- Determine possible paths for burdened vessel to compare with actual path
- Phase completed when avoiding contact with terrain is no longer the primary concern
</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</table>

| | Phase Goals | Phase Breakdown |
|---|---|---|
| **Mission Execution** | Open Water Navigation | - Set desired path<br>- Check contact list<br>- Get Automatic Identification System (AIS) information for crafts when available<br>- Generate predicted path for contacts<br>- Set desired speed and possible checkpoints<br>- Determine what variance is allowed in the path, what time restraints must be met<br>- Be alert to other contacts in the area, predicting their courses and possibilities of collision, while ensuring terrain is not a factor<br>- Determine maneuvering limitations for other contacts<br>- Understand who the privileged vessel is<br>- Understand structural and human limits on turning and course change maneuvers<br>- Open water navigation phase is complete when entering port or coming in range of shallow water where land contact is possible. This range is determined by the size and speed of the craft |
| | Coming to Periscope Depth | - Determine most likely current position and possible surface area<br>- Prepare craft for surfacing<br>- Set desired ascent rate and speed<br>- List purposes for surfacing (navigation, communications, maintenance, etc.)<br>- Check sea state and environmental conditions<br>- Brief all sensor operators of plan<br>- Perform all required tasks |
| **Mission Recovery** | Return to Port | - Once no more mission execution phases are scheduled, the return to port mission recovery stage begins<br>- Ensure all systems are in final position, no weapons systems are still active<br>- Path is displayed to commander<br>- Possible traffic hold ups determined<br>- Tide issues are checked to see if they will change plans<br>- If crew is fatigued or near shift change, then check whether docking should be pushed forward or delayed<br>- Check for harbor restrictions based on craft size, type, and space<br>- Determine the loiter time available outside the harbor<br>- This phase is complete when the craft is secure and propulsion mode is off |

# Appendix B: Event Flow Diagrams

## B.1 Event Flow Diagram: UUV Exit Harbor
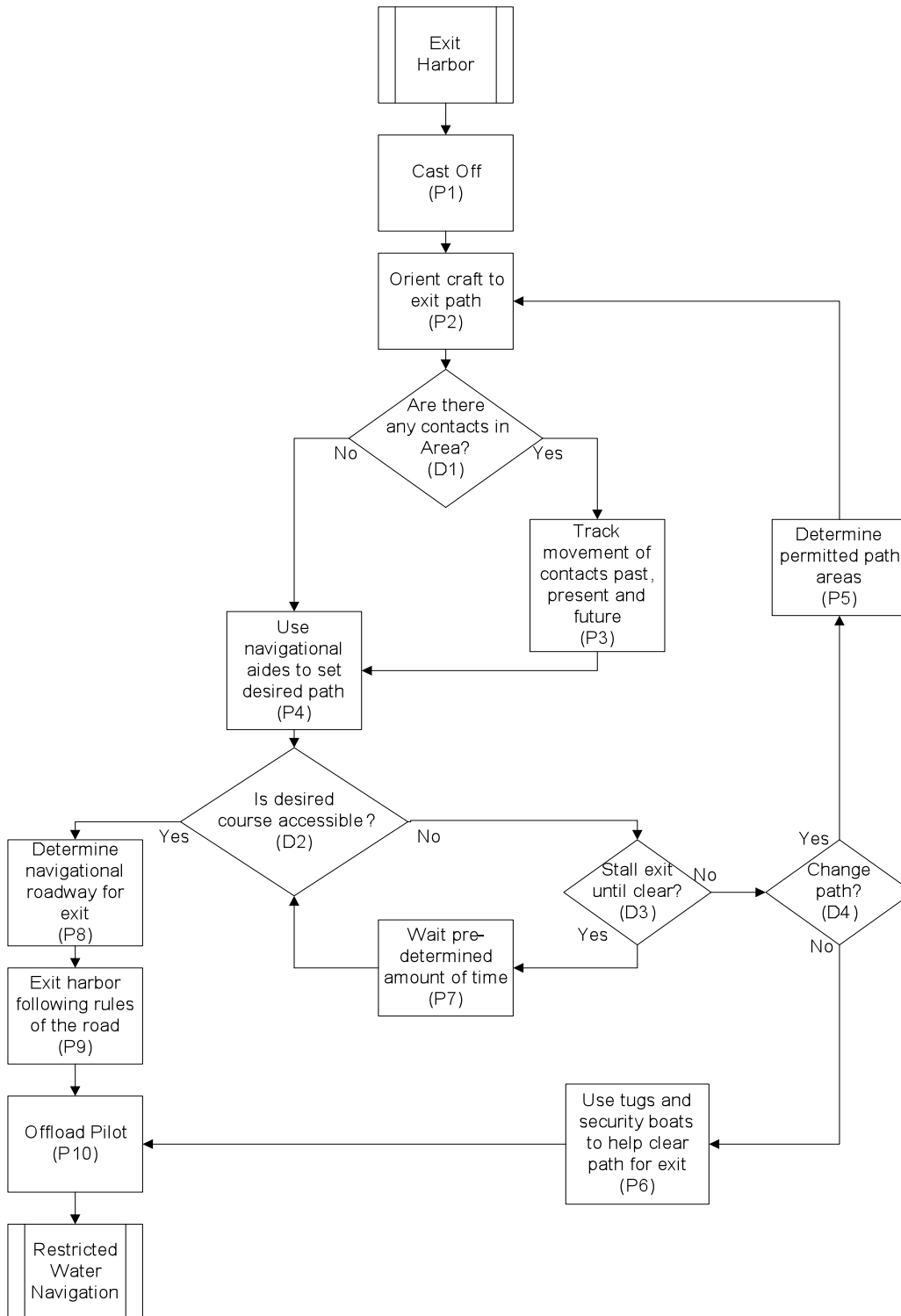
# B.2 Event Flow Diagram: Restricted Water Navigation
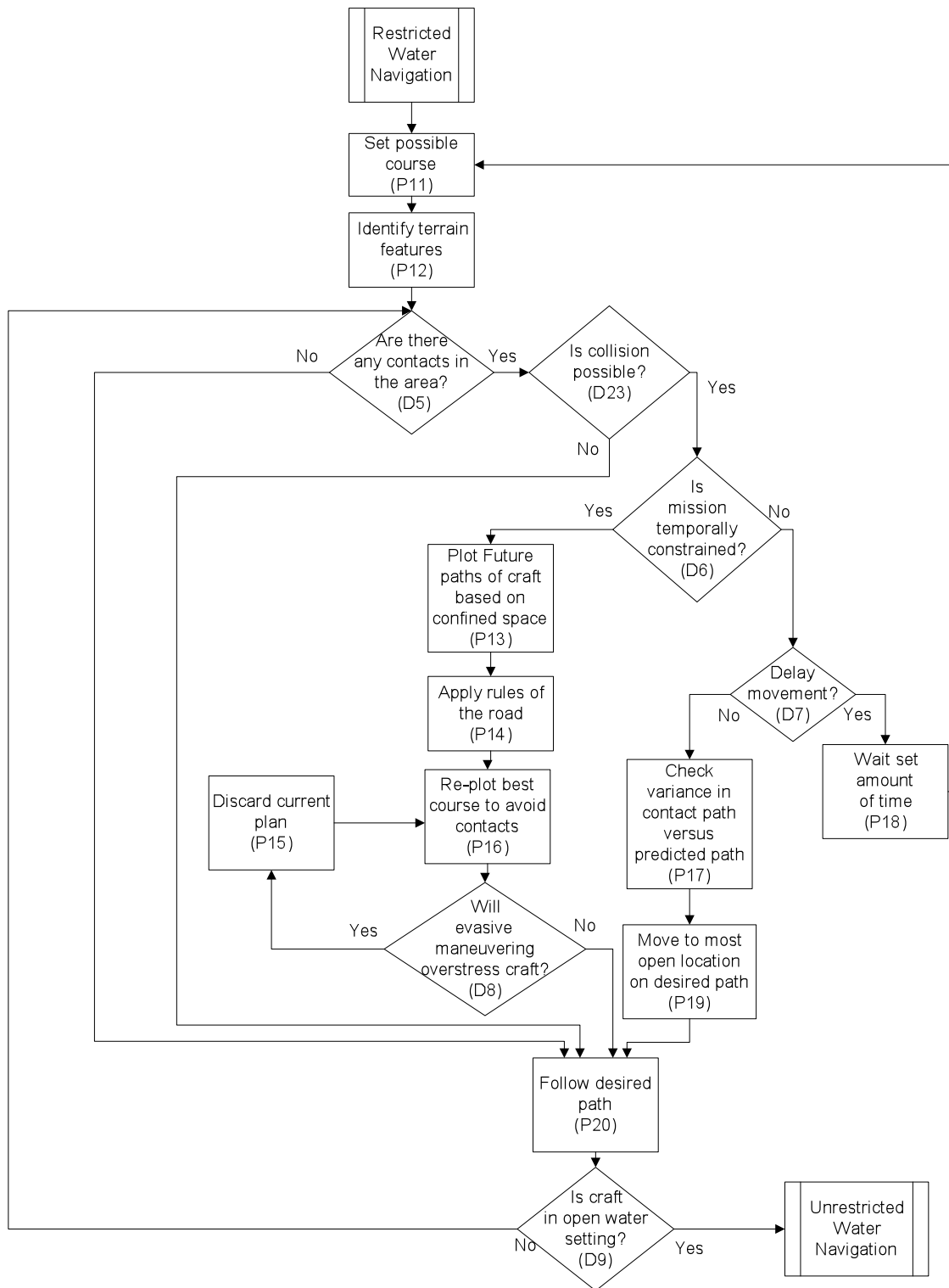
## B.3 Event Flow Diagram: Unrestricted Water Navigation
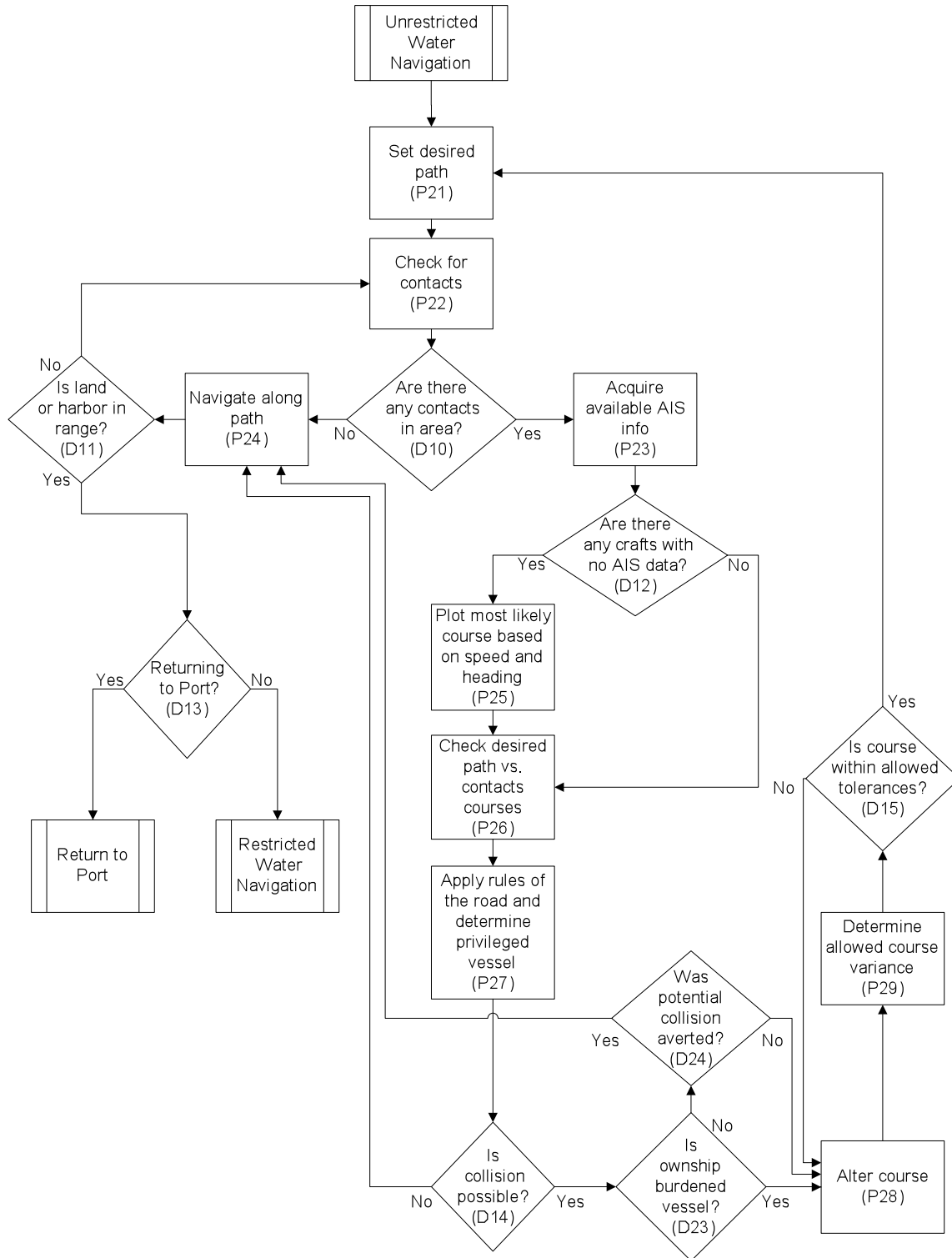
## B.4 Event Flow Diagram: Return to Port
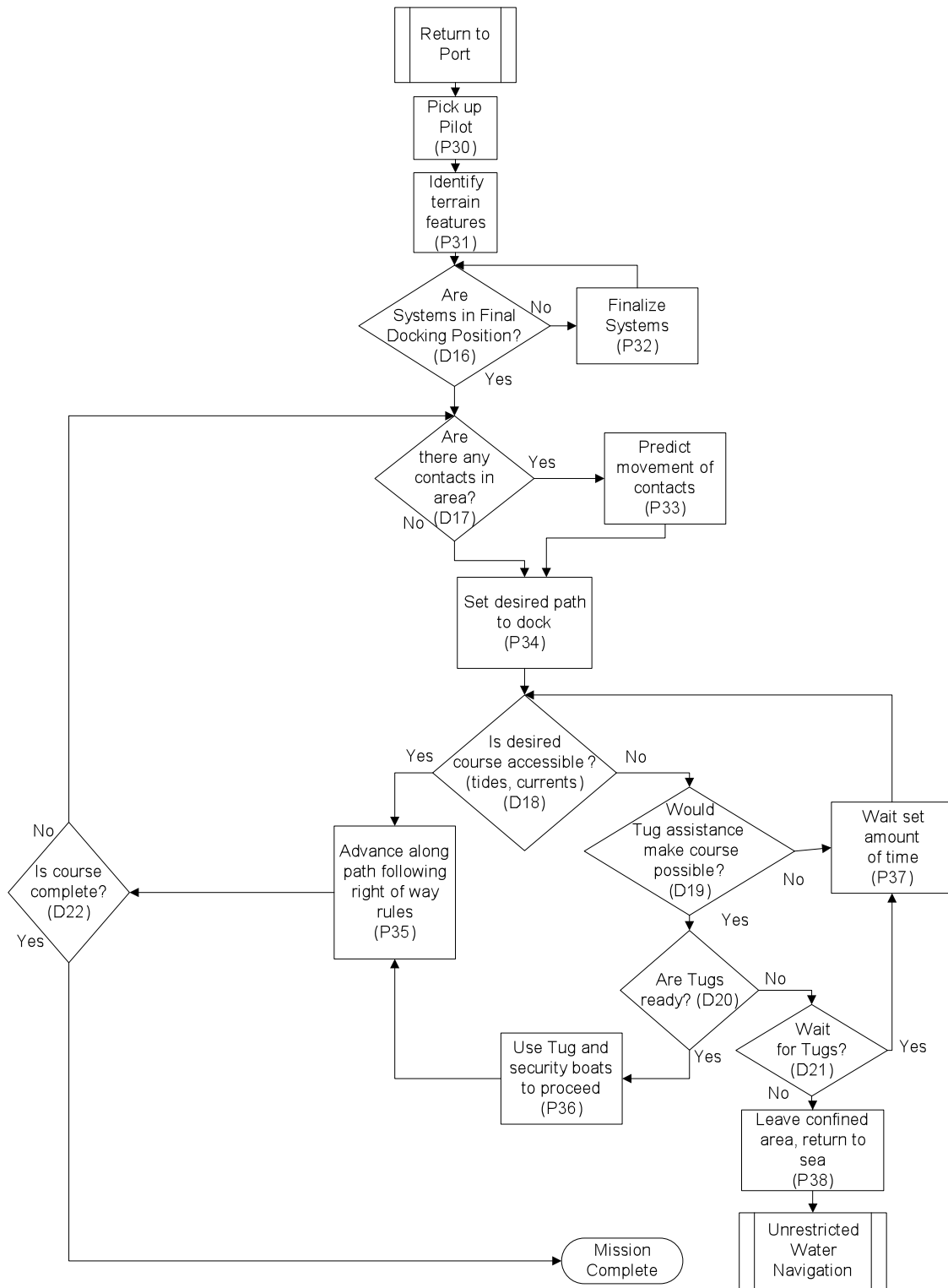
# Appendix C: Situational Awareness Requirements

| Phases /Events | Level 1 (Perception) | Level 2 (Comprehension) | Level 3 (Projection) |
|---|---|---|---|
| Exit Harbor | - Geo-spatial boundaries (P1, P2, P4, P5)<br>- Alert of when craft is free from dock (P1)<br>- Visual information of navigational roadway (P2, P4, P8)<br>- Hazardous area (D2, P5)<br>- Indication of thrust/direction status (P2, P9)<br>- All contacts positioning information (D1, P3)<br>- Current position/velocity information (P20)<br>- Indication of privileged vessel (P9)<br>- Tide and current information (P4)<br>- Sensor data on surrounding objects (D2)<br>- Current time and mission timeline (D3)<br>- Indication of maneuvering ability of craft (D4)<br>- Flag status of all contacts (restricted maneuvering, etc.) (P9) | - Visual location of craft on path (P2)<br>- Possible dangerous areas based on tides/currents (P4)<br>- Visual information on contact position/direction with relation to operator (D1)<br>- Visual warning if path is blocked (D2)<br>- Warning if time constraints are not being met (D3)<br>- Where mission status is temporally with respect to plan (D3)<br>- List recommended course changes if path is blocked (D4)<br>- Indication of status of pilot (onboard/off) (P10)<br>- Indication of status of escorts (active/disengaged) (P6)<br>- Readiness of security and tug boats (P6) | - Predict future path of contacts (P3)<br>- Predict possible collision courses (D2)<br>- Future tide and current information (D2)<br>- Timeline with predicted success/failure of meeting time constraint (D3, P7)<br>- Ability to compare possible route options ("what if") (P4, D4)<br>- Predict privileged vessel for future collision courses (P9)<br>- Visual indication of current route in geo-spatial context (P8, P9)<br>- Indicate expected offload location for pilot (P10) |
| Restricted Water Navigation | - Visual information of navigational roadway (P11)<br>- Visually represent initial course (P11)<br>- Geo-spatial boundaries (P12)<br>- All contacts positioning information (D5)<br>- Current time and mission timeline (D6, P18)<br>- Current contact path (P17)<br>- Tide and current information (P13)<br>- List rules of the road (P14)<br>- Flag status of all contacts (restricted maneuvering, etc.) (P14)<br>- Indicate privileged vessel (P14)<br>- Visual indication of available paths (P16, P19)<br>- Visual indication of current path (P20)<br>- Sensor data on proximity of surroundings (D9)<br>- Current position/velocity information (P20)<br>- Warning if path would overstress craft (D8) | - Incorporate path with geo-spatial information to show danger areas(P12)<br>- Add contact data (position, heading) (D5)<br>- Indicate temporal position on mission timeline (D6)<br>- Visually represent actual contact paths vs. predicted paths (P17)<br>- Current structural stress on craft vs. limits (D8)<br>- Indicate open areas for navigation (P19)<br>- Updated path information for craft (P16, P20) | - Visual indication of current route in geo-spatial context (P11, P12, P20)<br>- Ability to compare possible route options ("what if") (P11, P16, P19)<br>- Predict contacts future position using previous area data for confined space (P13)<br>- Predicted structural stress on craft following set path (D8)<br>- Timeline with predicted success/failure of meeting time constraint (D6, D7, P18)<br>- Predict privileged vessel for future collision courses (P14)<br>- Actual path of contacts compared with predicted paths, noting major discrepancies (P17) |
| Unrestricted Water Navigation | - Visual information of desired final location and planned course(P21)<br>- All contacts positioning information (P22, D10)<br>- Current position/velocity information (P24)<br>- Range to land/harbor (D11)<br>- Contacts heading, speed, and status (given or predicted based on availability of AIS data) (P23, P25)<br>- Identify privileged vessel (P27, D23)<br>- Warning if collision is possible (D14)<br>- Warn if planned course falls outside of allowable limits (D15)<br>- List variance from original path (P29) | -Visual representation of contact data (position, heading) (P22, D10)<br>- Incorporate Automatic Identification System (AIS) data (ship status) (P23)<br>- Indicate potential path crossings (P26)<br>- Display tolerable variance (P29)<br>- Provide information noting allowable courses (D15) | - Visual indication of current route in geo-spatial context (P21, P24)<br>- Visual indication of contacts predicted paths using AIS data (P25)<br>- Ability to compare possible route options ("what if") (P21, P28)<br>- Indicate possible collision courses (P26, D14)<br>- Alert if current path is outside of limits (D15) |

| | Level 1- Perception | Level 2- Comprehension | Level 3- Projection |
|---|---|---|---|
| Return to Port | - Information on pilot location (onboard, offboard) (P30)<br>- Visual representation of Geo-spatial information (P31)<br>- System status (D16, P32)<br>- All contacts positioning information (D17)<br>- Current position/velocity information (P33)<br>- Navigational roadway information (P34)<br>- Tide and current information (D18)<br>- Right of way/privileged vessel information (P35)<br>- Current time and mission timeline (D21, P37)<br>- Tug availability status (D20)<br>- Docking status (D22)<br>- Position of escort boats (D20, D21)<br>- Indicate privileged vessel (P35) | - Status of each system (ready/wait) (D16)<br>- Indicate contact position and heading (D17, P33)<br>- Tide and current status along with go/no go limits(D18)<br>- Indication of whether Tug boat assistance makes docking possible (D19)<br>- Estimated time of arrival of escort boats (D20, D21) | - Indicate expected pick-up point for pilot (P30)<br>- Predicted path of contacts in area (P33)<br>- Visual indication of current route in geo-spatial context (P34)<br>- Future tide and current information (D18)<br>- Timeline with predicted success/failure of meeting time constraint (D21, P37)<br>- Future weather in area (D21)<br>- Ability to compare possible route options ("what if") (P34)<br>- Predict privileged vessel for future collision courses (P35) |

# Appendix D: Decision Ladders

**DL 1: "Is desired course accessible?" (D2, D18)**



EVALUATE
Determine whether the path is passable

Understanding of how the existing path is impacted

Recognize need to change path

INTERPRET
Determine how the obstacles will affect the path

DEFINE TASK
Determine a clear path to goal

Perceive external influences that may block path

Course is accessible

IDENTIFY
Fixed and moving objects that may potentially cross path

No objects in surrounding area

Perceive what sensor data may represent obstructions

Perceive obstacles along new path

OBSERVE
Sensor data for port area

Recognize what sensor data is available

ACTIVATION
Planned path is generated

EXECUTE
Follow new path towards goal

Navigating

D2,18: "Is desired course accessible?"

# DL 1b: "Is desired Course Accessible?" with display requirements

# DL 1c: "Is desired Course Accessible?" with levels of possible automation

EVALUATE
Determine whether the path is passable

Possible Automation

Project planned path through time to see whether there are conflicts

Understanding of how the existing path is impacted

Recognize need to change path

Automatically highlight obstacles that are blocking path

INTERPRET
Determine how the obstacles will affect the path

DEFINE TASK
Determine a clear path to goal

Recommendation from computer based on proximity of obstacles to path

Perceive external influences that may block path

Course is accessible

Label all objects on display, either by color coding (terrain) or name (contacts)

IDENTIFY
Fixed and moving objects that may potentially cross path

No objects in surrounding area

Perceive what sensor data may represent obstructions

Perceive obstacles along new path

Show path and objects on path when leaving port

OBSERVE
Sensor data for port area

Recognize what sensor data is available

Possible use of automatic path planner

ACTIVATION
Planned path is generated

EXECUTE
Follow new path towards goal

Automatic path planner re-plans path to reach goal and avoid collision

Navigating

D2,18: "Is desired course accessible?"

**DL 2: "Would tug boat assistance make course possible?" (D19)**

EVALUATE
Time constraints and
ability of tugs to
perform desired
maneuvers

Understanding that problem
is constantly changing over time
and may fix itself

Perceive need to
use tug boat assistance

Decision
not to
use tugs

IDENTIFY
Capabilities of
tug boats in
area

DEFINE TASK
Finalize which
tugs will be
needed

Perceive whether problem
can be overcome

Knowledge of which tugs
are being requested

OBSERVE
Determine
what problem
is (current,
tide, contacts)

FORM
PROCEDURE
Determine how
to contact tug
boats

Perceive problem
with following path

Understanding of
communication

Tug
assistance
would not
help
overcome
problem

ACTIVATION
Path into port
is inaccessible

EXECUTE
Request tug
assistance

Waiting to enter port

D19: "Would tug assistance
make course possible?"

104

# DL 2b: "Would tug boat assistance make course possible?" with display requirements

Display Requirements

Visual indication if time constraints prevent tug use (highlight tug information if it can't arrive in time)

EVALUATE
Time constraints and ability of tugs to perform desired maneuvers

Understanding that problem is constantly changing over time and may fix itself

Decision not to use tugs

Perceive need to use tug boat assistance

Display any information available on local tug boats (contact info, number of boats, position, estimated time to arrive, etc.)

IDENTIFY
Capabilities of tug boats in area

DEFINE TASK
Finalize which tugs will be needed

List allowing user to add/ remove available tugs

Perceive whether problem can be overcome

Knowledge of which tugs are being requested

List what the problem(s) are with getting into port

OBSERVE
Determine what problem is (current, tide, contacts)

FORM PROCEDURE
Determine how to contact tug boats

Display contact information again

Perceive problem with following path

Understanding of communication

Display status of path (clear, blocked)

ACTIVATION
Path into port is inaccessible

Tug assistance would not help overcome problem

EXECUTE
Request tug assistance

Waiting to enter port

D19: "Would tug assistance make course possible?"

105

## DL 2c: "Would tug boat assistance make course possible?" with levels of possible automation

Possible Automation

Automatically check problem with possible solutions, using capability of tug boats available vs current or weather limitations, display whether course becomes passable

EVALUATE
Time constraints and ability of tugs to perform desired maneuvers

Understanding that problem is constantly changing over time and may fix itself

Decision not to use tugs

Perceive need to use tug boat assistance

Provide list of tug boats in port that are available

IDENTIFY
Capabilities of tug boats in area

DEFINE TASK
Finalize which tugs will be needed

Automatically select tugs that would be needed in order to make path possible

Perceive whether problem can be overcome

Knowledge of which tugs are being requested

Automatically update display with tide, current, and contact info, highlighting what may prevent arrival

OBSERVE
Determine what problem is (current, tide, contacts)

FORM PROCEDURE
Determine how to contact tug boats

Display the required tug contact information to operator

Perceive problem with following path

Understanding of communication

Tug assistance would not help overcome problem

ACTIVATION
Path into port is inaccessible

EXECUTE
Request tug assistance

Send automated message to tug boats requesting assistance

Waiting to enter port

D19: "Would tug assistance make course possible?"

106

**DL 3: "Are there any contacts in the area?" (D1, D5, D10, D17)**

# DL 3b: "Are there any contacts in the area?" with display requirements

Highlight on sensor data what information most likely represents a contact

**EVALUATE**
Determine possible contacts based on what information can support , adjust sensor settings or request additional sensor information if available

Display Requirements

Recognize that some sensor data can be ambiguous

Recognize need to track contacts

**INTERPRET**
Based on the given sensor data , determine if the information could represent active contacts

Display decision of whether to analyze data or continue monitoring

**DEFINE TASK**
Finalize which contacts are in the surrounding area

Display list of contacts, including contact name

Perceive what information may represent possible contacts

Perceive what contacts are in the area

**IDENTIFY**
Identify if data/ imagery is sufficient for identifying possible contacts

Highlight important information on data/ imagery

If there are no possible contacts in area , continue monitoring

Perceive data/imagery from sensor systems

**FORM. PROCEDURE**
Log contacts, including range and whether they are opening or closing

Update list with speed, bearing , and whether the course is opening or closing

**OBSERVE**
Sensor data from sonar , radar , GPS, Satellite and/or Automatic Identification System (AIS)

Sensor information must be available for review

Perceive state space locations and paths of all contacts in area

Recognize what sensor data is available

If data/ imagery is insufficient continue monitoring until situation can be perceived

**EXECUTE**
Plot the contacts location and most likely predicted path in state space with respect to the operator's vessel

Display position and direction of all surrounding contacts with respect to craft

Highlight on map what areas have not been checked for contacts

**ACTIVATION**
Moving into area with possible unknown contacts

MONITORING

D1,5,10,17: "Are there any contacts in the area?"

108

# DL 3c: "Are there any contacts in the area?" with levels of possible automation

EVALUATE
Determine possible contacts based on what information can support, adjust sensor settings or request additional sensor information if available

List the contacts whose paths differ from predicted path in order from highest to lowest deviation

Possible Automation

Recognize that some sensor data can be ambiguous

Recognize need to track contacts

Show initial guess at contacts, highlight which ones are uncertain, show what data is missing or questionable

INTERPRET
Based on the given sensor data, determine if the information could represent active contacts

DEFINE TASK
Finalize which contacts are in the surrounding area

Automatically list surrounding contacts

Perceive what information may represent possible contacts

Automatically go back to monitoring if no useful data is obtained, report no contacts

IDENTIFY
Identify if data/imagery is sufficient for identifying possible contacts

Perceive what contacts are in the area

If there are no possible contacts in area, continue monitoring

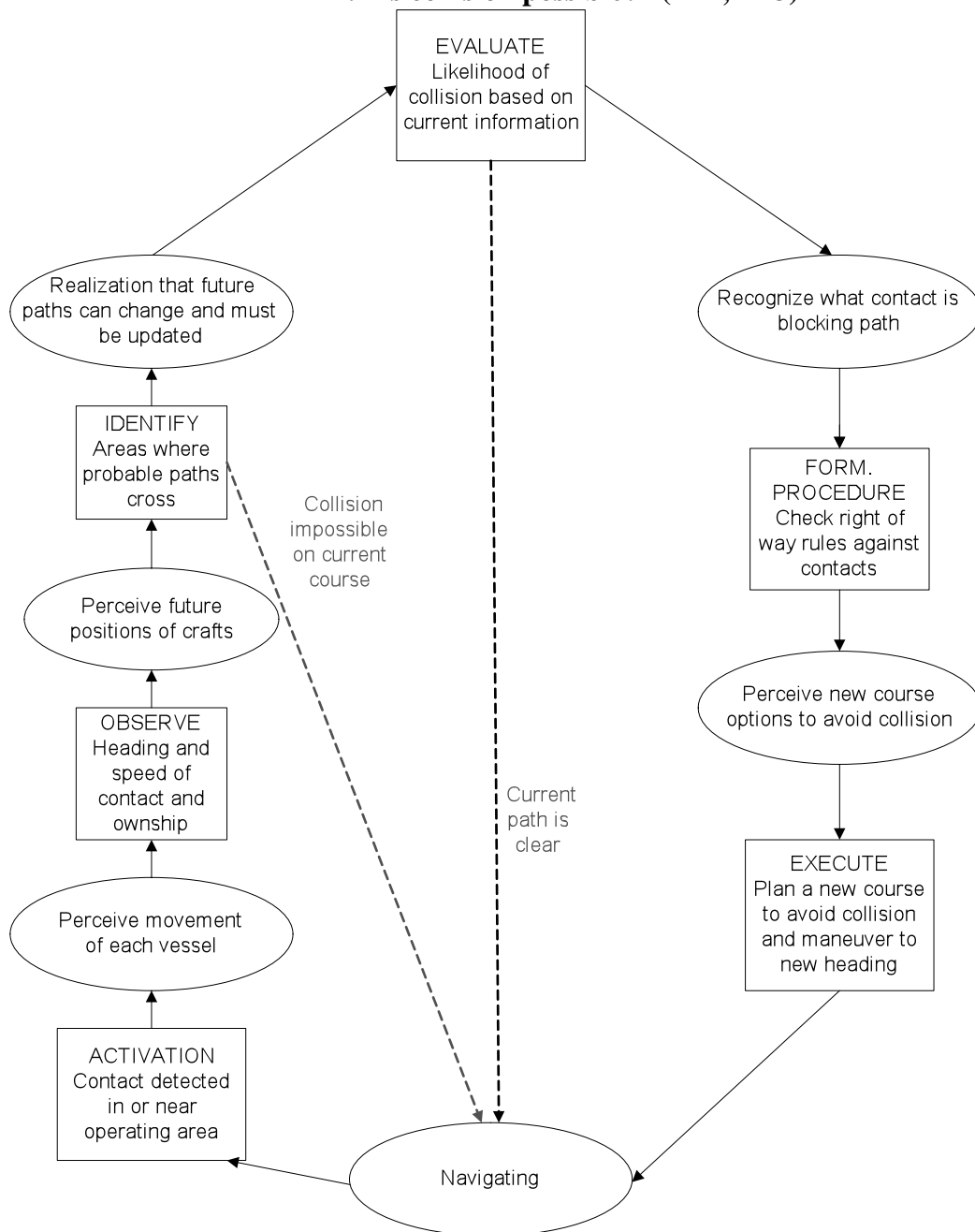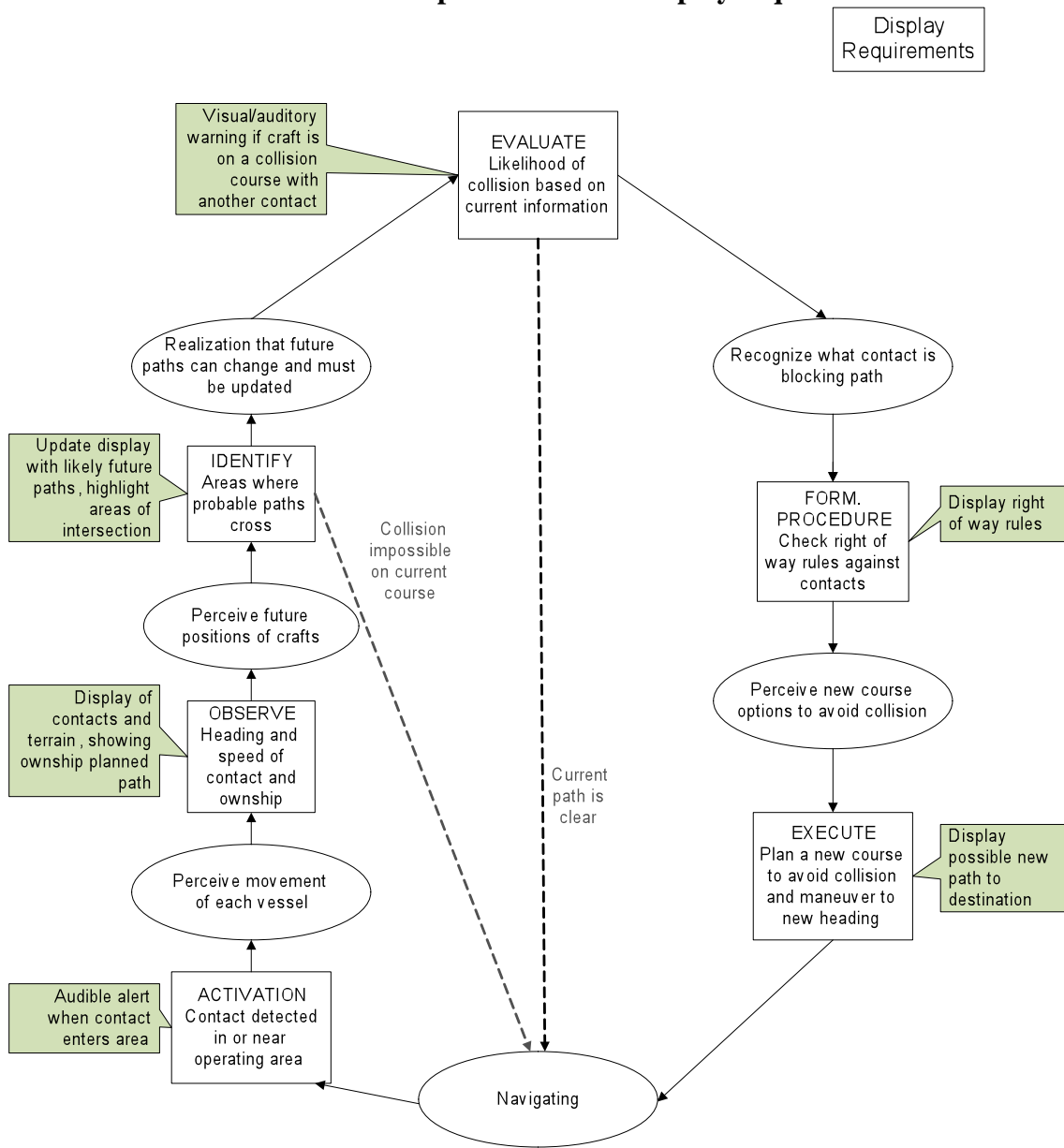Perceive data/imagery from sensor systems

FORM. PROCEDURE
Log contacts, including range and whether they are opening or closing

Automatically log this information for all contacts in the area

Scan sensor data to detect patterns that could represent a contact

OBSERVE
Sensor data from sonar, radar, GPS, Satellite and/or Automatic Identification System (AIS)

Perceive state space locations and paths of all contacts in area

Recognize what sensor data is available

If data/imagery is insufficient continue monitoring until situation can be perceived

Automatically export contact information to state space display, showing current and likely future position

Alert crew when part of surroundings is unknown

ACTIVATION
Moving into area with possible unknown contacts

EXECUTE
Plot the contacts location and most likely predicted path in state space with respect to the operator's vessel

MONITORING

D1,5,10,17: "Are there any contacts in the area?"

109

**DL 4: "Is collision possible?" (D14, D23)**

EVALUATE
Likelihood of collision based on current information

Realization that future paths can change and must be updated

Recognize what contact is blocking path

IDENTIFY
Areas where probable paths cross

Collision impossible on current course

FORM. PROCEDURE
Check right of way rules against contacts

Perceive future positions of crafts

Perceive new course options to avoid collision

OBSERVE
Heading and speed of contact and ownship

Current path is clear

EXECUTE
Plan a new course to avoid collision and maneuver to new heading

Perceive movement of each vessel

ACTIVATION
Contact detected in or near operating area

Navigating

D14, 23: "Is collision possible?"

# DL 4b: "Is collision possible?" with display requirements

Visual/auditory warning if craft is on a collision course with another contact

EVALUATE
Likelihood of collision based on current information

Realization that future paths can change and must be updated

Recognize what contact is blocking path

Update display with likely future paths, highlight areas of intersection

IDENTIFY
Areas where probable paths cross

FORM. PROCEDURE
Check right of way rules against contacts

Display right of way rules

Collision impossible on current course

Perceive future positions of crafts

Perceive new course options to avoid collision

Display of contacts and terrain, showing ownship planned path

OBSERVE
Heading and speed of contact and ownship

Current path is clear

EXECUTE
Plan a new course to avoid collision and maneuver to new heading

Display possible new path to destination

Perceive movement of each vessel

Audible alert when contact enters area

ACTIVATION
Contact detected in or near operating area

Navigating

D14, 23: "Is collision possible?"

111

**DL 4c: "Is collision possible?" with levels of possible automation**

Possible Automation

Automatically alert operator if current path is a collision course

EVALUATE
Likelihood of collision based on current information

Recognize what contact is blocking path

Realization that future paths can change and must be updated

Automatically highlight areas of potential intersection

IDENTIFY
Areas where probable paths cross

Collision impossible on current course

FORM. PROCEDURE
Check right of way rules against contacts

Check rules against contacts, label which vessel is the privileged vessel

Perceive future positions of crafts

Perceive new course options to avoid collision

Automatically project current data into future positions and paths

OBSERVE
Heading and speed of contact and ownship

Current path is clear

EXECUTE
Plan a new course to avoid collision and maneuver to new heading

Automatic path planner re-plans path to reach goal and avoid collision

Perceive movement of each vessel

Detect contacts and alert operator if a new contact appears

ACTIVATION
Contact detected in or near operating area

Navigating

D14, 23: "Is collision possible?"

# Appendix E: Information Requirements

| Type | Requirement Description | Source |
|------|------------------------|--------|
| **Geo-spatial info** | Geo-spatial boundaries (Overview, Navigation, Rite-View) | SA, DL 4 |
| | Visual navigation lanes | SA |
| | Hazardous/restricted areas (Overview, Navigation, Rite-View) | SA |
| | Highlight any areas that have not been searched for contacts | DL 3 |
| | Tide, current, weather, marked on display (Navigation) | SA, DL 1 |
| | Future weather information | SA |
| | Future tide/current information | SA |
| | Planned course, highlighted red if blocked, green if clear (Overview, Navigation) | SA, DL 1,2,3,4 |
| | Variance of actual path versus planned path | SA |
| | Visual indication of allowable paths when helpful (Navigation) | SA, DL 1,4 |
| | Mark final destination or goal location on map (Overview, Navigation) | SA, DL 1 |
| | Ability to determine range from ownship to other points of interest (Navigation) | SA |
| | Position of escort/tug boats | SA |
| | Areas where collision is possible or uncertain | SA |
| | Indicate allowed variance of ownship path | SA |
| | Mark location of pilot pick-up and drop-off | SA |
| | Most likely paths for commercial vessels (shipping lanes, port roadways) | SA |
| **Contact Info** | Geo-spatial location of all surrounding contacts (Overview, Navigation, Rite-View) | SA, DL 3,4 |
| | Contacts course and speed (Overview) | SA, DL 3 |
| | Specific sensor data available for review (Health and Status) | DL 3 |
| | Highlight sensor data that most likely represents a contact (Overview, Navigation) | DL 3 |
| | Popup asking whether to analyze current data for contacts or continue monitoring | DL 3 |
| | Indication of privileged vessel, flag status | SA, DL 4 |
| | Contact path: past, present and future (Overview, Rite-View) | SA, DL 4 |
| | Contact location on path (Overview, Navigation, Rite-View) | SA |
| | Marking to distinguish contacts with AIS data | SA |
| | List of contacts, with name, bearing, speed, and whether course is opening/closing (Overview) | DL 1,3 |
| | Alert when contact enters area | DL 4 |
| | Deviations of contact path versus what AIS data says | SA |

| | | |
|---|---|---|
| **Alerts and Feedback** | When craft is free from dock | SA |
| | When path would overstress vessel (maneuvering limitation) | SA |
| | When craft is on a collision course with a contact (Navigation) | SA, DL 4 |
| | When planned course violates limits or set restrictions (Navigation) | SA |
| | When systems are not in final position and heading for port | SA |
| | When path is inaccessible, also list why (Overview) | SA, DL 2 |
| | When time constraints are not being met | SA |
| | When Tug assistance is available/helpful | SA |
| | Rules of the road: ability to display when unsure | SA |
| | Highlight tug boat if it cannot arrive in time | DL 2 |
| | Status of Pilot | SA |
| **Data/Miscellaneous** | Current speed and heading (Overview) | SA |
| | Current time | SA |
| | Mission timeline | SA |
| | Predicted ability of meeting timeline | SA |
| | Availability of tug boats | SA |
| | Current structural stress on craft | SA |
| | ETA of escort/tug boats | SA |
| | Recommended course changes | SA |
| | Information on local tug boats (contact info, number of boats, position, ETA) | DL 2 |
| | List of tug boats allowing user to add/remove | DL 2 |
| | Ability to compare different routes (Navigation) | SA |

Note: Information requirements highlighted in gray are the ones chosen for implementation on the MSAT.

# Appendix F: User's Manual

**MOBILE SITUATIONAL AWARENESS TOOL
(MSAT)
USER'S MANUAL**

Geoff Carrigan

**Massachusetts Institute of Technology\***
**Prepared For MARS**

**HAL2009-01**
**February 2009**

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# USER'S MANUAL

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## 1.0    GENERAL INFORMATION

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## 1.0 GENERAL INFORMATION

### 1.1 System Overview

The Mobile Situational Awareness Tool (MSAT) allows submarine commanders to maintain situational awareness while being mobile across the submarine. This tool provides a variety of useful information, including basic submarine status information such as speed, position, and course, as well as more detailed health and status information from the air levels and weapons systems. In addition, the tool provides the capability to plan a path using manual inputs or an automated function that takes into account user inputs.

This system is currently run as a Java file. This program was written specifically for the Sony *Vaio* micro PC, and so the display size is set to widescreen mode but the Java file will work on any display. Because it is still in a beta version, the MSAT works as a standalone device, however in order to be fully functional, it would need to be set up with a server on the submarine that broadcasts data to populate the screens in the MSAT.

The system itself is designed for submarine commanders, but could be adjusted to fit the needs of a variety of users. Each tab can be modified, and additional tabs can be added to show the waterfall display for sonar operators, radar plots, contact information, etc. This flexibility was designed into the tool to allow for changing user requirements and to aid in a variety of mission types.

### 1.2 Project References

This tool was designed by students in the Humans and Automation Lab, MIT, under Professor M.L. Cummings. For more information on the product itself, see the completed thesis of Mariela Buchin (February 2009, MIT) or the thesis by Geoff Carrigan (June 2009, MIT). These can be found on the Humans and Automation Lab website, http://web.mit.edu/aeroastro/labs/halab/index.shtml.

### 1.3 Acknowledgments

This research was funded through a Small Business Innovation Research (SBIR) for the Combat System of the Future (CSoF) in partnership with MIKEL Inc., ASSETT Inc. and Rite-Solutions Inc.

### 1.4 Points of Contact

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## 1.5 Organization of the Manual

This user's manual is broken down into the following sections:

**1.0 General Information-** This section describes the overall tool, as well as the background information for the project including the designers and the SBIR "Combat System of the Future" through which the research was funded.

**2.0 Getting Started-** This section describes how to start the program and interact with the tool.

**3.0 Overview Tab-** This section describes the information provided in the overview tab as well as how to use the functions.

**4.0 Navigation Tab-** This section describes how to use the navigation tab and what information is provided.

**5.0 Health and Status Tab-** This section describes how to navigate through the various health and status information.

**6.0 Rite View Tab-** This section describes how the Rite View tab works and what information is provided.

## 1.6 Acronyms and Abbreviations

| | |
|---|---|
| CM | Cruise Missile |
| CPA | Closest Point of Approach |
| CSoF | Combat System of the Future |
| EMBT | Emergency Main Ballast Tank |
| Ft | Feet |
| GPS | Global Positioning System |
| HP | High Pressure |
| JRE | Java Runtime Environment |
| Kts | Knots |
| Lat | Lattitude |
| Long | Longitude |
| Min | Minimum |
| MSAT | Mobile Situational Awareness Tool |
| MT | Empty |
| PSI | Pounds Per Square Inch |

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| | |
|---|---|
| TH | Tomahawk Missile |
| TP | Torpedo |
| ROT | Rate of Turn |
| RPM | Revolutions Per Minute |
| Rud. Ang. | Rudder Angle |
| SBIR | Small Business Innovation Research |
| Sec | Seconds |
| VL | Vertical Launch |
| Yds | Yards |

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## 2.0   GETTING STARTED

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## 2.0   GETTING STARTED

### 2.1   Software Code

The software for the MSAT was developed using the Java programming language in the Eclipse integrated development environment. The code itself is highly modular, which allows any or part of the display to be edited, replaced, or modified. Background maps, controls, gauges, and information are representative of actual information that would need to be taken from sensor data, navigation maps, or other operational information sources. The executable Java Archive (JAR) file could be used to show how the MSAT looks in an operational capacity.

### 2.2   MSAT Hardware

The MSAT is designed for a mobile interface, specifically the Sony *Vaio* pictured below in Figure 1. Because of this, the screen is best viewed under wide-screen conditions. The specific *Vaio* model is *VGN-UX390N*. Since the executable is a separate JAR file, it can be run on any machine that supports Java with the Java Runtime Environment 6 or higher. This software can be downloaded for free at http://java.sun.com/javase/downloads/index.jsp.



**Figure 1: Sony Vaio**

On the Sony *Vaio*, the interface with the system works through the use of a stylus. For this reason, there are no right-click features. Navigating through the different tabs is done using either the stylus or the mouse, which is built into the *Vaio*.

### 2.3   Starting the Software

In order to start the MSAT software, double click on the executable file, Demo.jar. This program can be run from any file location, but it is typically run from the user's desktop. The User's Manual will refer to two different versions, the Demo version and the Operational version. The Demo version is the version that currently uses the .jar file. The operational version describes how the tool would work if implemented into the submarine fleet. In the demo version, the submarine starts at the top and has a goal position on the bottom. Once the file is open, maximize it to the screen (if using a Sony *Vaio* or widescreen interface), or manually change the size to a widescreen format (if using a normal monitor). From this view, any of the tabs can be used or interacted with by simply clicking on the tab name at the top. The four different tabs, Overview, Navigation, Health & Status and Rite-View tabs are described in more detail in the following sections. The initial startup screen is shown in Figure 2.

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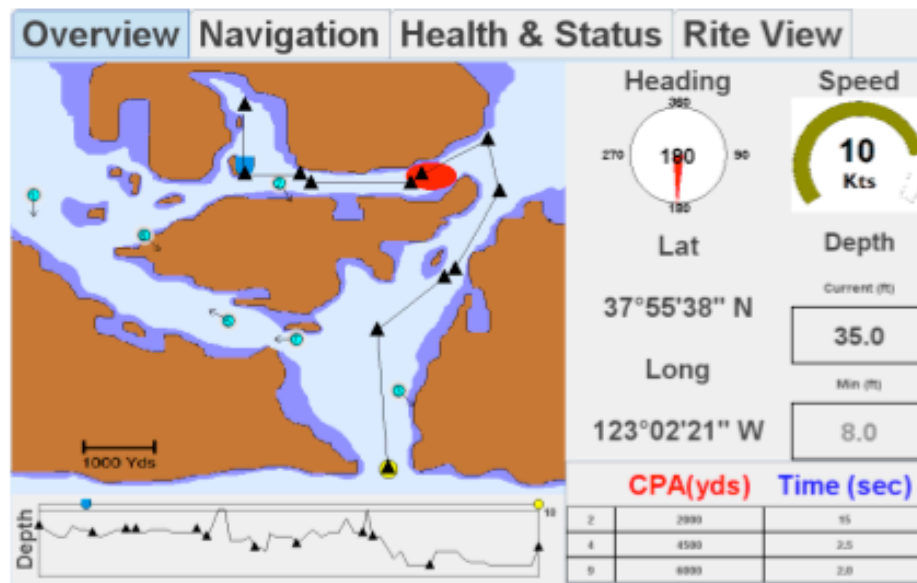
Figure 2: Start Screen

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## 3.0   OVERVIEW TAB

## 3.0   OVERVIEW TAB

### 3.1   Screen Layout

The overview tab is the default tab displayed when MSAT starts.  This tab is meant to show the general information a commander needs.  A screenshot of the overview tab is shown in Figure 3.
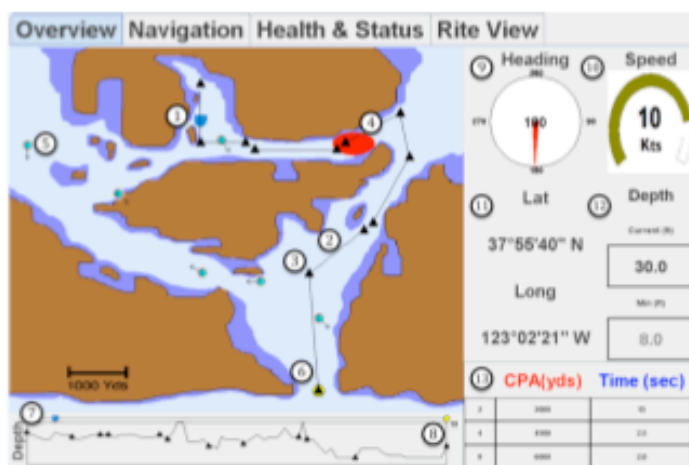


**Figure 3: Overview Tab**

This interface provides various pieces of information to support the commander.  The map portion shows the current position (blue U shape) (1), current path (black line) (2) with waypoints (triangles) (3), and a hazard that has shown up on the map (red area) (4).  Also, contacts are shown as light blue circles (5), with numbers on the circle, and a vector showing their movement direction.  The goal position is shown in yellow (6).

At the bottom, the depth track along the course is shown (7).  This shows the entire course and waypoints, with the distance between the top and the plotted line representing the depth.  A second line (8) shows the user-specified minimum depth requirement.  This can be changed using the navigation tab.

On the right side, the compass shows the current heading of the ship (9), indicated by both the red arrow and the digital readout in the center.  To the right of the compass is the speedometer, which is dual-coded with shading and a digital readout in the center (10).  Below these are updated latitude and longitude coordinates (11), as well as the current depth and the minimum depth along the path (12).  Finally, a table of contact information is shown at the bottom right corner (13).  This table does not automatically update in the demo version, but the final version would allow each column to be sorted by clicking on the column heading, and a scroll bar on the right could allow the commander to scroll through the entire list of contacts.

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## 3.2 Interaction

There are no interactive features integrated in the overview interface. Most of the information in this tab would be dynamically updated by a server located in the submarine's control room. Although the current version does not currently support any interactive features, the contact list could be designed to be sorted by **number**, Closest Point of Approach (**CPA**) or **Time to CPA** by clicking on their labels accordingly.

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## 4.0    NAVIGATION TAB

## 4.0   NAVIGATION TAB

### 4.1   Screen Layout

The navigation tab is highly interactive, and allows the commander to view the current path/hazards and compare them to other paths created either manually or by the automation. Figure 4 below shows the initial view.



**Figure 4: Navigation Tab**

On this tab, the same information is shown on the map as for the overview tab. In this view, the background map is faded to prevent mode confusion. One other difference is that on the Navigation tab, movement is frozen to prevent the settings from changing during path planning. In the operational version, movement could continue to allow the commander to plan in real time.

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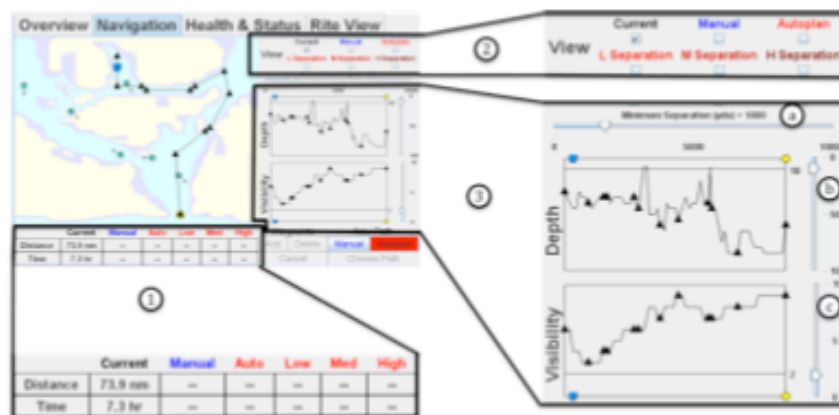
**Figure 5: Navigation Tab Expanded**

Figure 5 shows the key areas of the Navigation Tab.  Along the bottom, proposed paths can be compared by distance and time (1) (these will be described in more detail below).  On the right, the view of different paths can be changed by checking their corresponding boxes (2).  L, M and H Separation represent the low, medium and high separation paths made by the automation.  Low separation paths allow for movements closer to the contacts, and high separation paths leave more space between contacts.  If the Autoplan button is used, all of the L, M, and H paths are created, and then the user can compare them with the graphs and the navigation chart to choose the one that best fits his or her needs.  Below the checkboxes are the three different inputs for the automation, each with a slider bar.  These slider bars are shown on the right, denoted as (a), (b) and (c).  The first is minimum separation from obstacles (a).  This user-generated setting means that all proposed paths will have at least this amount of distance between ownship and any surrounding contacts or shoal water.  Next is the minimum depth setting (b) and minimum visibility setting (c), which must also be set by the user.  Only paths that meet these requirements will be considered by the automation.  The two graphs show a comparison of depth and visibility by the paths that are created (3).  The view above shows only the current path, but manual and automation paths are added to the view as they are created.  Finally, the controls at the bottom right are used to create either manual or computer automated paths.

## 4.2    Interaction

The navigation tab allows for complex user interactions.  This section will walk through a hypothetical situation using both manual and autoplan modes for a path.  Imagine the following scenario where a ship is past the hazardous area and wants to plan a new course from the current location to the goal (as seen in Figure 6a).  From here, either a manual or autoplan path can be made.  Starting with a manual path, the user would first set the parameters for the path using the slider bars in Figure 5.  These would restrict the points on the map where the user can add waypoints, to ensure that only waypoints that meet the user criteria can be created.  Next, the user would click on the **Manual** button, and then click on the map to create a series of waypoints (Figure 6a).  If the user clicks in an area that would violate the path rules for separation, visibility, depth or land, a warning will be displayed on the right and the user will have to click a new area, or click **Cancel** to stop the path (Figure 6b).
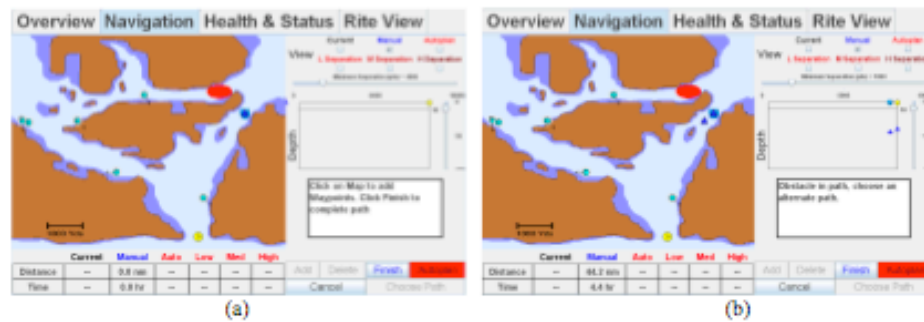
**Figure 6: Manual Path**

Once the user is close enough to the goal, the **Finish** button can be clicked to complete the path. Once the manual path is created, the waypoints can be modified. Clicking **Delete** will highlight all waypoints that can be deleted without causing the path to cross an obstacle. If no waypoints can be deleted, an error message will be displayed. This view is shown in Figure 7. Clicking a highlighted waypoint will delete it.
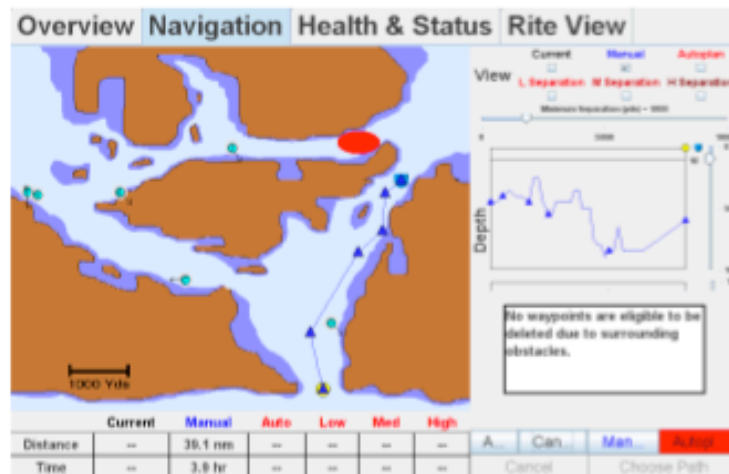


**Figure 7: No waypoints to delete**

To add a waypoint, click the **Add** button, and then click on a segment of the manual path. The waypoints can then be dragged to different locations to modify the path. This is shown below in Figure 8. Figure 8a shows a waypoint being added (highlighted in yellow) and Figure 8b shows that waypoint being moved, along with the graphs that update on the right.

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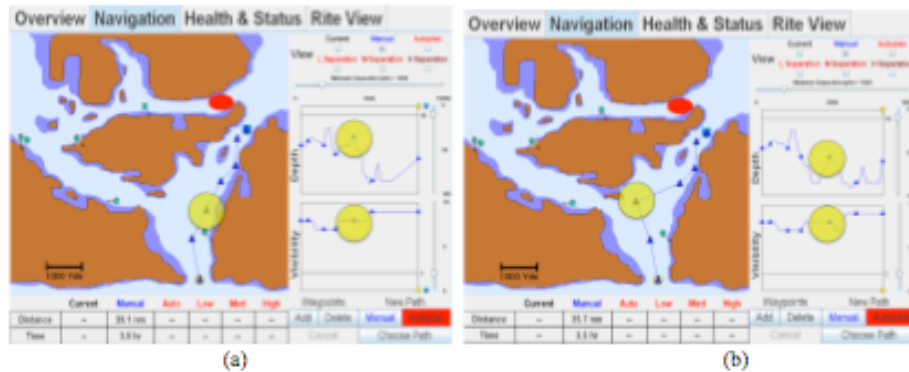
**Figure 8: Adding/Moving Waypoints**

In order to remove the manual path from the view (without deleting it from memory), simply un-check the **Manual** box on the top.

If the user decides to create an autoplan path instead, he or she must first set the requirements using the three slider bars for separation distance, depth, and visibility. The minimum and maximum values allowed by the slider bars represent typical ranges used, based on interviews with subject matter experts. After this, simply click the **Autoplan** button. This will create the following four paths on the screen:

1. Autoplan (red): Meets all of the requirements, does not account for contacts.
2. H Separation (dark brown): Meets all requirements, leaves extra room near contacts, best for high variability contacts.
3. M Separation (brown): Meets all requirements, leaves moderate room near contacts, best for medium variability contacts.
4. L Separation (light brown): Meets all requirements, leaves little room near contacts, best for low variability contacts.

These paths can be added/removed from the view space using the corresponding checkboxes. All four are shown in Figure 9.

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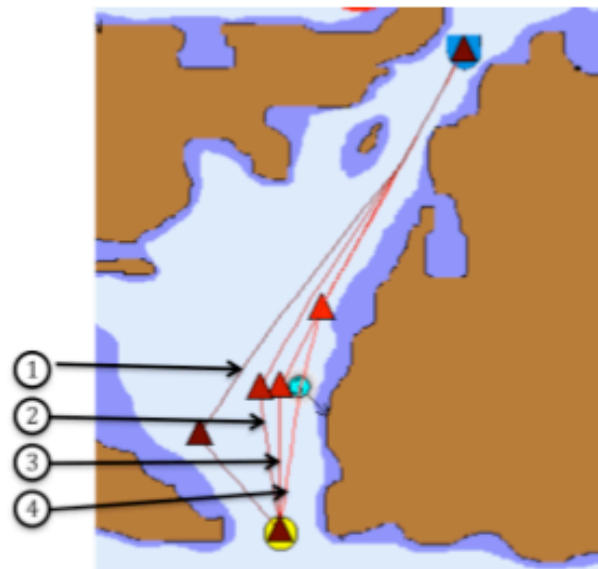
**Figure 9: Autoplan Paths**

Once the desired path has been plotted, it can be selected to replace the current path. To do this, click the **Choose Path** button, and select the radio button next to the path you want to use to replace the current path. Clicking **OK** makes this path the new current path, and the process can be repeated as many times as desired throughout the mission. This is shown in Figure 10.
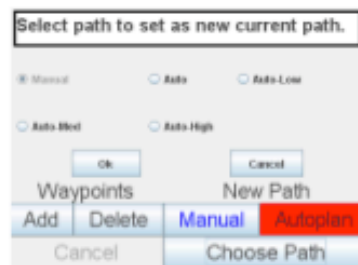


**Figure 10: Choose Path**

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## 5.0    HEALTH AND STATUS TAB

## 5.0   HEALTH AND STATUS TAB

### 5.1 Screen Layout

The health and status tab allows the commander to monitor the complex systems of a submarine by checking for warnings and trend information.  For the submarine, there are a variety of systems that the commander must monitor and the health and status tab provides them with different views for various subsystems.  The initial view is shown in Figure 11.
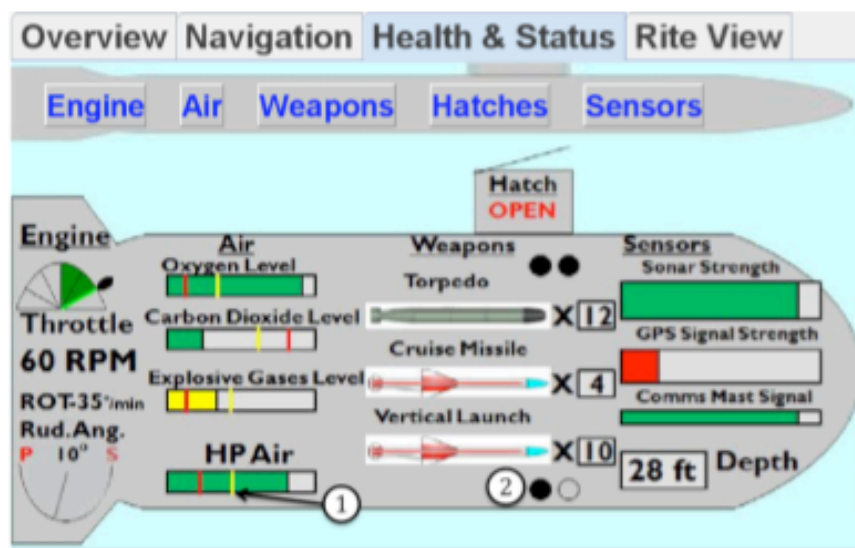


Figure 11: Health and Status Tab

This tab shows a variety of information on engine parameters, air levels, weapons, hatches and sensors. Most of this information is self explanatory, and easy to check for warnings.  Levels in green are acceptable, yellow are caution levels, and red are warning levels.  The small yellow bars in the Air column are adjustable (1), and allow the commander to be notified if the level set by the bar is breached. The small red bars are fixed warnings that will initiate an alarm due to some hard-coded limitation.  The circles represent torpedo tubes (2), and filled in circles mean there is some weapon in the tube.  From this main page, any of the systems can be seen in greater detail using the buttons across the top.

### 5.2   Interaction

The only interactive features of this tab are the small yellow warning bars and the larger buttons on top. By clicking these buttons, the user can get more in depth information on any of the systems.  These systems are described in greater detail below.

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## Engine

Clicking on the **Engine** button reveals the display below. This gives the same information shown in the original view, but in a larger, easier-to-see manner. There are no user inputs for this display, but the contents could change based on the specifics of the submarine.
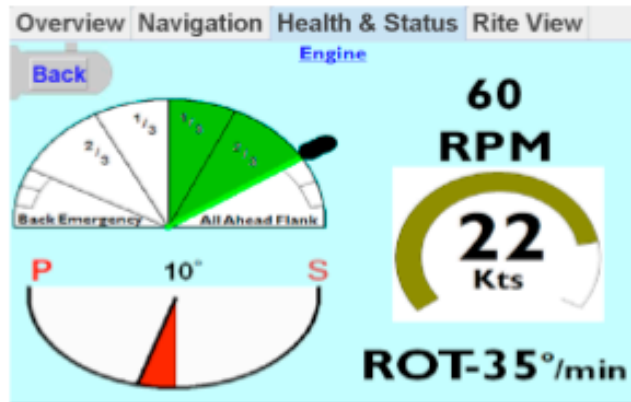


Figure 12: Engine

## Air

Clicking on the **Air** button shows both the high pressure (HP) air measurements and the atmospheric levels over time. The digital readout on the HP Air and Emergency Main Ballast Tank (EMBT) shows the current value, and the yellow bar can be moved to change the point at which the commander is notified. The graph shows the main gases tracked over time with respect to percent allowable. The red bar (1) indicated a set warning level. This level is fixed and cannot be changed, as it represents the absolute minimum value allowed. The yellow bar (2) can be moved by clicking and dragging to move it to a new value. This view is shown in Figure 13.



Figure 13: Air

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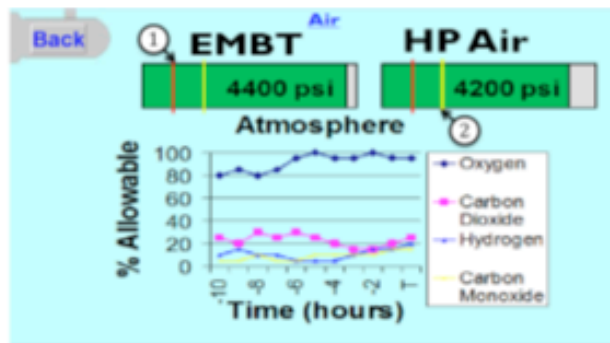
## Weapons

Clicking on the **Weapons** button shows a variety of weapons' information. The type of munitions is shown using standard abbreviations (all abbreviation are defined on page 1-2. This view shows the position of each weapon on the rack, as well as what is in each tube. It also represents the quantity of the vertical launch missiles on board. A sample view is shown in Figure 14.
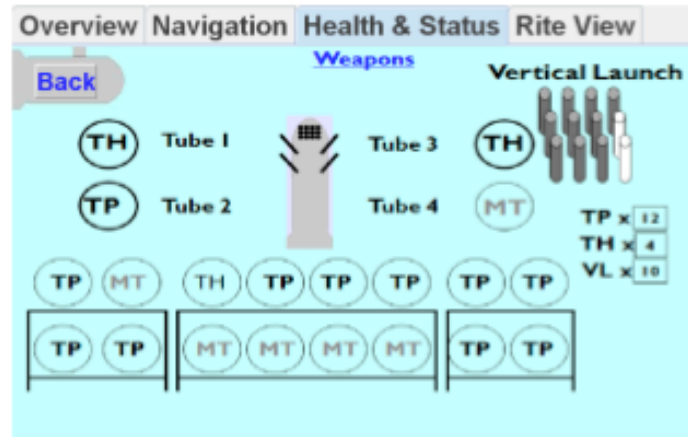


Figure 14: Weapons

## Hatches

Clicking on the **Hatches** button shows information for the different openings into the submarine. From here, the commander can monitor whether each of the entry points is secured. This display could also be augmented with the rig-for-dive checklist to aid in a quick check before submerging (see Figure 15).



Figure 15: Hatches

## Sensors

Clicking on the **Sensors** button shows the strength of the sensors. Since speed makes a big difference for sonar, speed is also shown in the middle. The strength of signals coming from the mast and GPS are shown in green, yellow or red to represent good, average and poor signals, respectively. The same convention is used for the forward (1), trailing (2), and side aperture (3) sonar arrays. The effective range

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for the sonar is shown as a filled in color (red, yellow, or green) based on the maximum range possible. In the view below, the forward and trailing sonar range is 1nm and 0.5nm, respectively, and this is shown as the filled in yellow circles.  If the range were operating at its maximum, the circle would fill in the entire outline, and would be colored green.  From any of these pages, the user can go back to the main health and status tab by clicking on the **Back** button.



Figure 16: Sensors

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## 6.0   RITE VIEW TAB

## 6.0   RITE VIEW TAB

### 6.1   Screen Layout

The Rite View tab is a 3D environment under development by Rite Solutions. The view in the demo is not fully functional, but instead is a series of screen shots strung together to show what the interface would look like. This interface allows for different layers to be turned on and off, and shows the geospatial surroundings to help build the commander's mental model. Figure 17 shows a screen shot of this display.
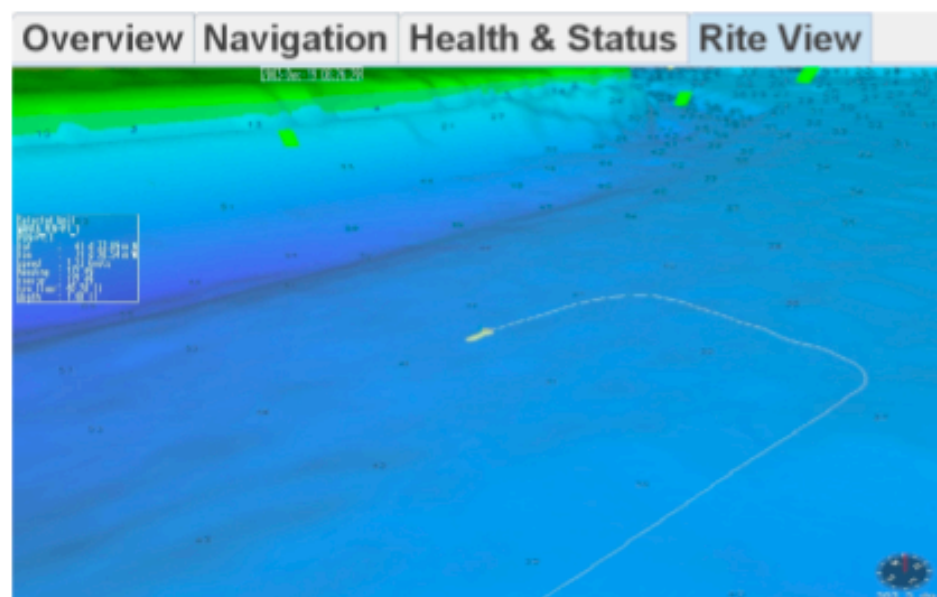


Figure 17: Rite View Tab

### 6.2   Interaction

As stated above, the demo version of the software does not allow for any interaction with the Rite View system. Additional functionalities could be activated in the fully operational version. For example, the current path and contact picture could be changed in time, allowing the commander to fast-forward and see how things might appear in the future. Also, different graphical overlays could be added, such as shipping lanes, paths, or weather. Also, clicking on different ships could give their information, and the view could be manipulated to see the situation from different points of view.

This is the final tab in the demo version of the MSAT. Operationally, different tabs could be added for different operators, as well as additional functionalities related to other missions

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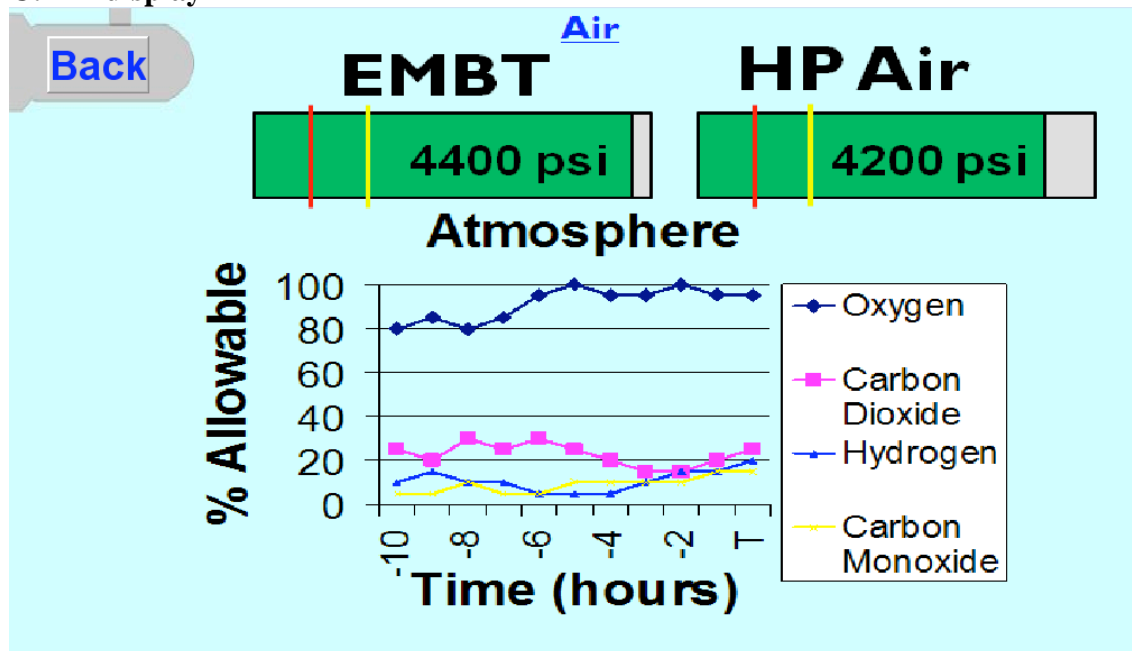
# Appendix G: Health and Status Display
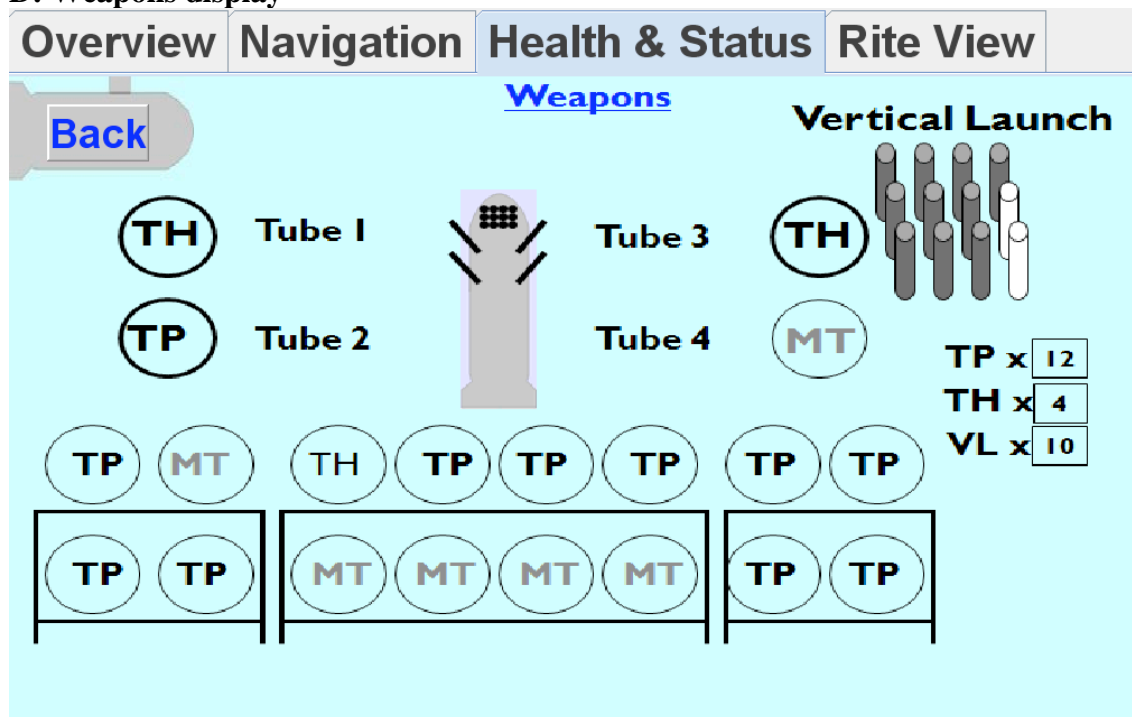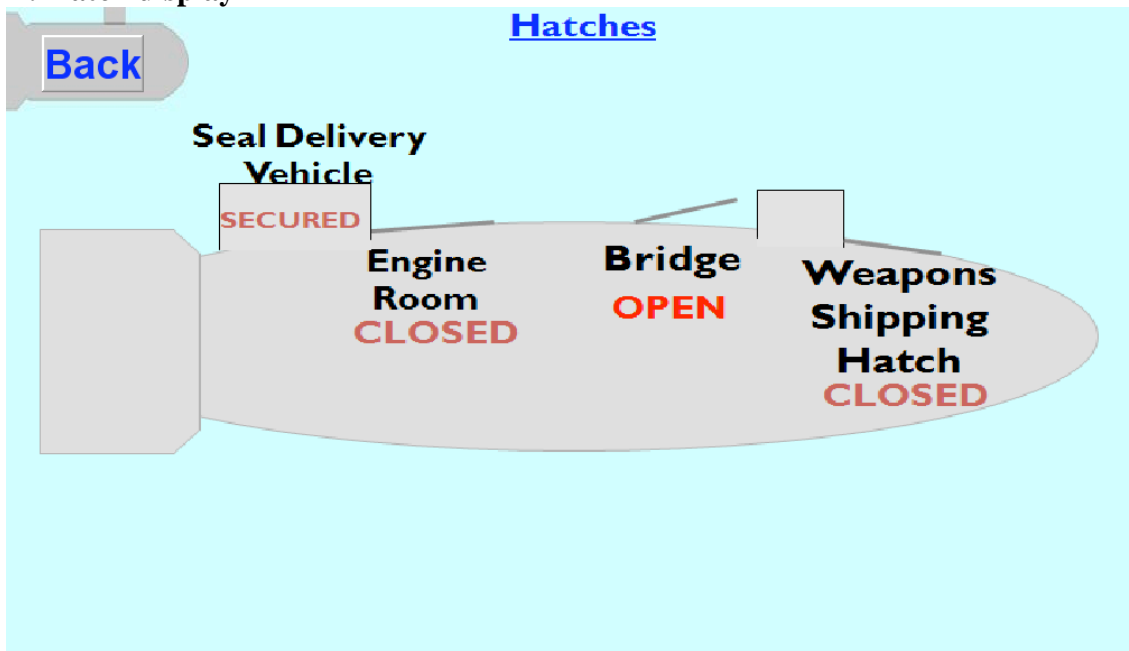
**A: Initial H&S display**
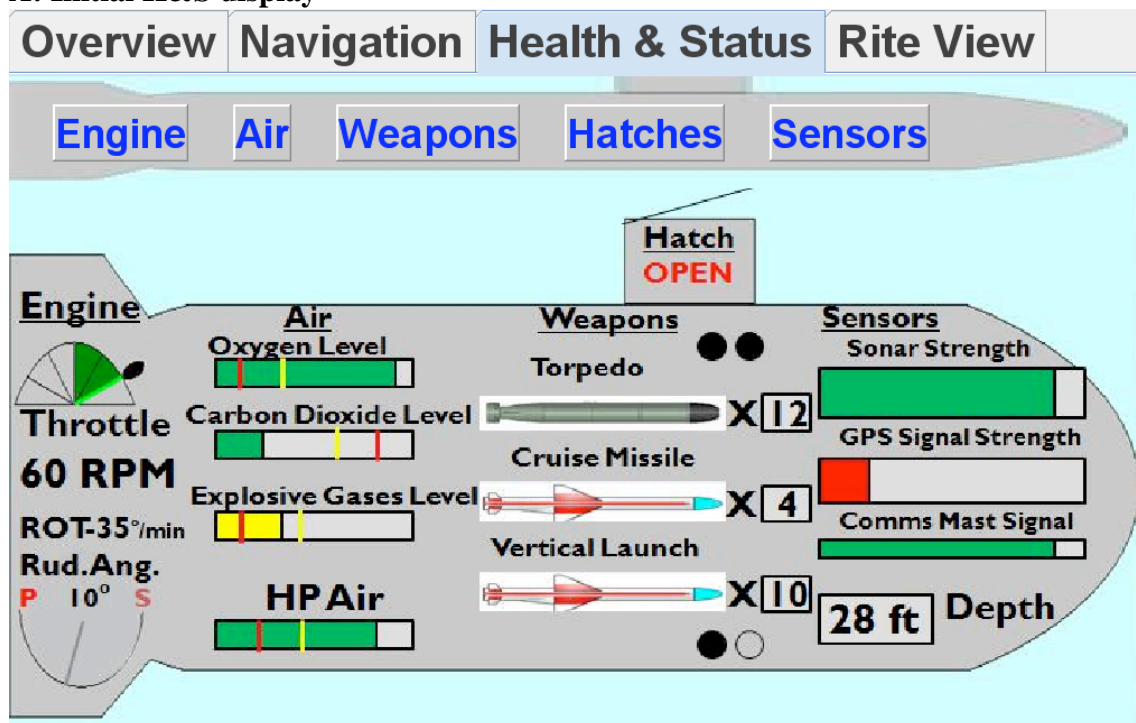


**B: Engine display**
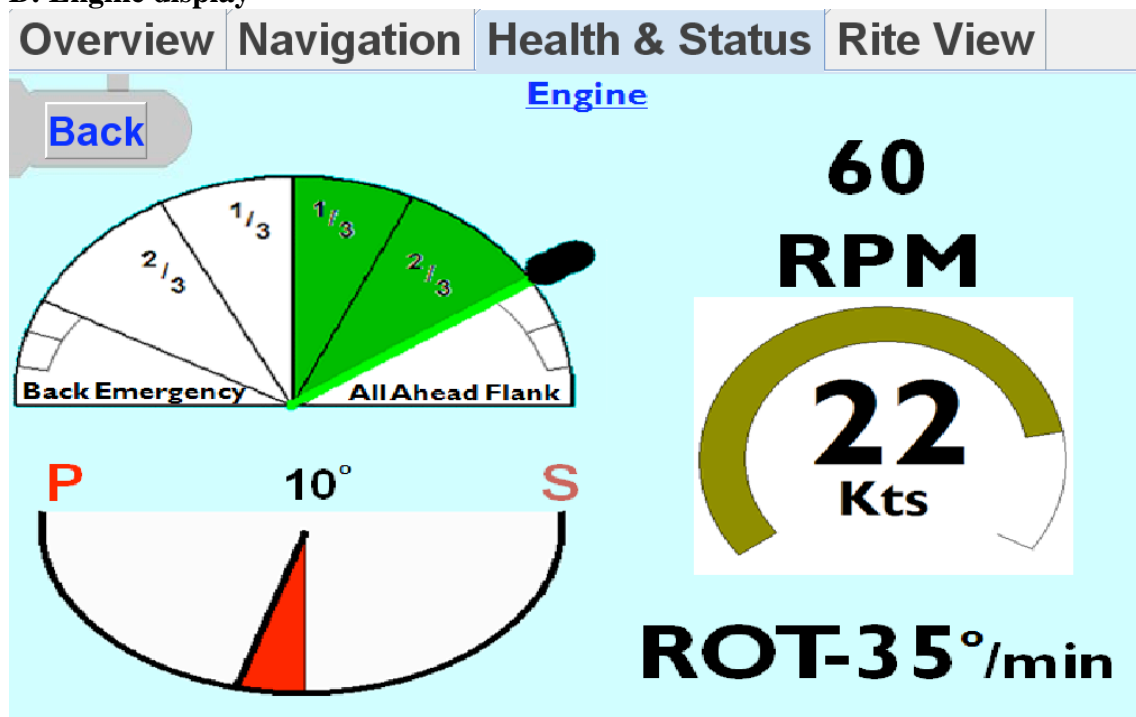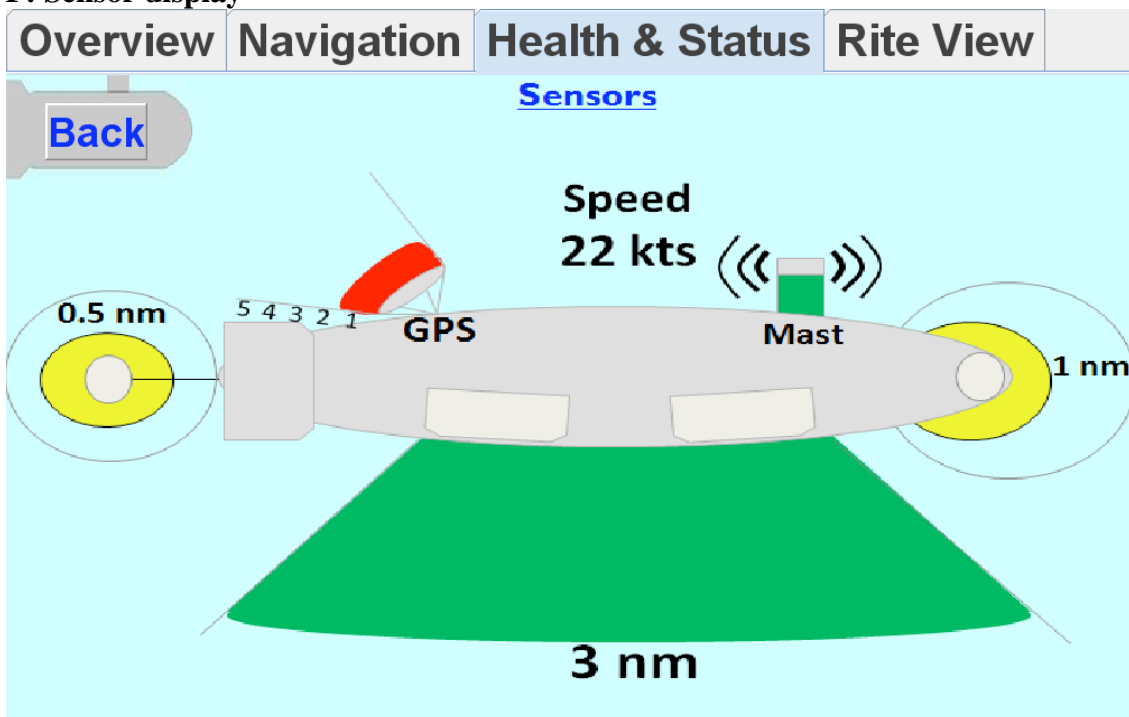
**C: Air display**



**D: Weapons display**

**E: Hatch display**



**F: Sensor display**

# Appendix H: Time and Motion Study Questions

**General Questions**

1. How long does it take to get from the stateroom to the control room?

2. How long does it take to get from the Bridge to the torpedo room?

3. How complete is the CO's mental model of his surroundings at any given time?

**Navigation**

4. How long does it take to get AIS data from a contact?

5. If a problem arises along the current navigation path, how long does it take to notify the CO?

6. Are emerging hazardous areas ever shown on the navigation map?

7. How long would it take to view contacts by CPA time/distance?

8. How long does it take to change one waypoint?

9. How long does it take to check the different parameters (depth, distance, time) of a modified path?

10. How long does it take to plot a completely new path?

11. How much time is spent planning backup paths on shore in case of problems?

12. How many backup paths would typically be planned for an exit harbor scenario?

**Health and Status**

13. How long does it take to check status of engine/rudder (positions, speed)?

14. Can warning levels be customized based on tolerance?

15. How long does it take to determine trends in O2 levels? How many people must be contacted?

16. How are warnings given when HP Air falls below a minimum? (Is it all or none, or is there an early notification?)

17. How long and how many people does it take to determine where munitions are on the rack?

       -Is it possible to determine the position on the rack from the bridge?

18. How long does it take to determine what is in each of the torpedo tubes? How many people must be contacted?

19. How long does it take to check status of systems to ensure readiness for mooring/submerging?

20. How long/what steps are involved in figuring out the reliability of the GPS signal?

21. How long does it take to get an estimate of sonar range?

# Appendix I: Trust Questionnaire

Trust Analysis

1. For this system, please indicate your <u>overall</u> amount of <u>trust</u>.

**1          2          3          4          5**
**No Trust          Somewhat trustworthy          Complete Trust**

---

2. Please indicate the strength of your feeling for the MSAT for each of the factors by circling the corresponding number.

1. How reliable (in terms of avoiding obstacles) is the automation tool?
  **1          2          3          4          5**
**Not reliable                              Reliable**

2. How accurate (in terms of plotting the most efficient path) is the functioning of the automated path planner?
  **1          2          3          4          5**
**Not accurate                              Accurate**

3. Do you understand the behavior and displayed intent of the automated path planner?
  **1          2          3          4          5**
**Not Understand                         Understand**

4. How much do you believe the automated path planner in unknown situations, such as choosing a path without seeing weather information?
  **1          2          3          4          5**
 **No faith                              Faith**

5. How easy is the automated path planner to use?
  **1          2          3          4          5**
**Not Easy                                                    Very Easy**

6. How robust (in terms of recovery from path errors) is the automated path planner?
  **1          2          3          4          5**
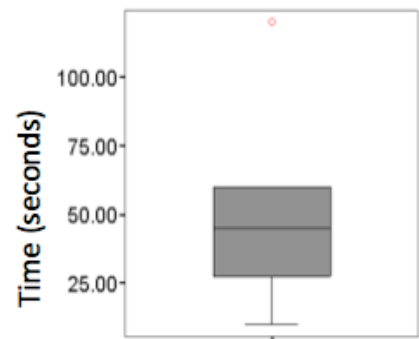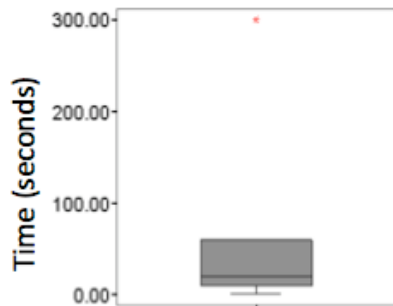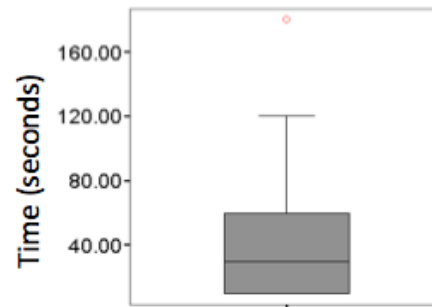**Not robust                              Robust**

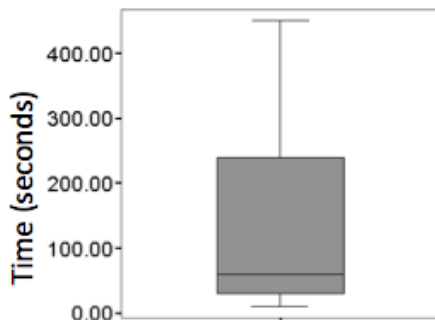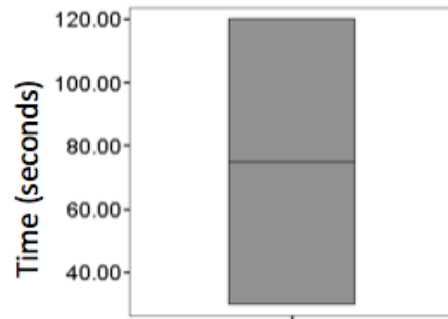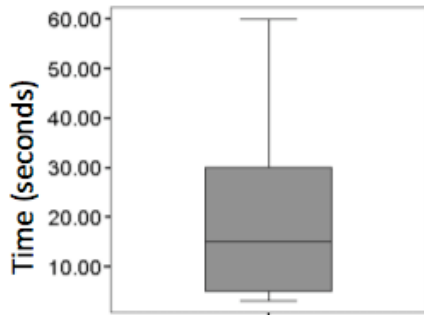7. How much do you like the automated path planner?
  **1          2          3          4          5**
**Dislike                              Like**

<u>Follow up interview questions</u>

1. When using this tool, did you focus on the automatic path planner or the manual mode?

2. Did you ever think about using both?

3. Did the graphs on the right showing path comparisons prove useful for planning?

4. Did you ever check the plot of an auto planned path to check for obstacles, or did you trust that the path would be acceptable?

5. If you did not trust the system, why not?

6. What did you like about the MSAT?

7. What do you dislike about the MSAT?

8. What would you change about the MSAT?

9. Did you enjoy the method of interaction with the tool?

# Appendix J: Task Time Box Plots



Figure J1: Stateroom to control room

Figure J2: Bridge to torpedo room

Figure J3: Gather AIS data

Figure J4: Notify commander of problem on path

Figure J5: Sort contacts by CPA

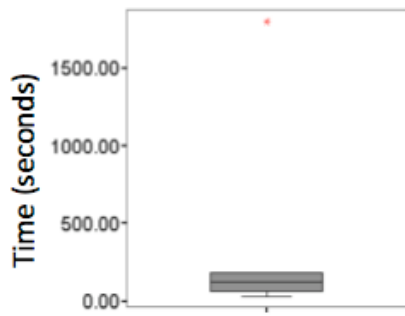Figure J6: Change one waypoint

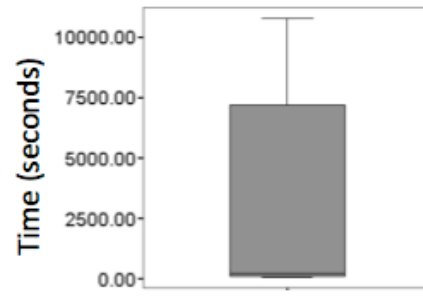Figure J7: Check path parameters
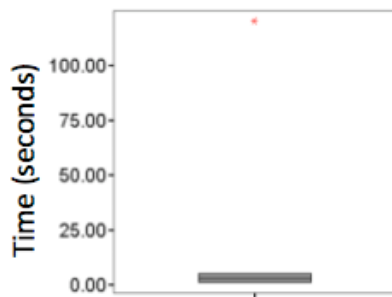
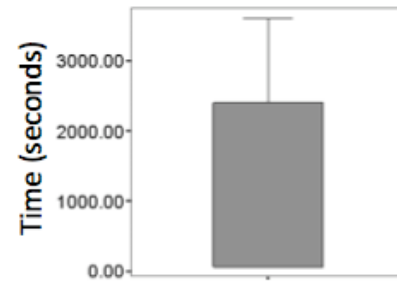
Figure J8: Plot new path


Figure J9: Check engine
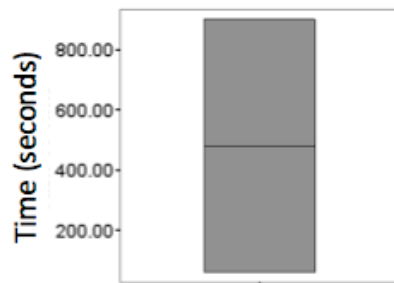

Figure J10: Check atmosphere
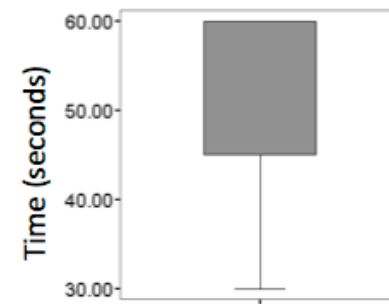

Figure J11: Check weapons position
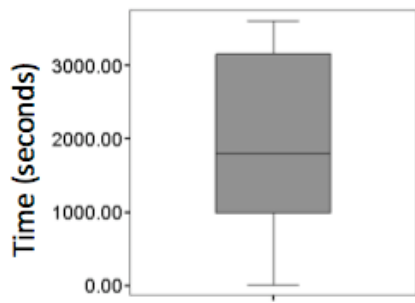

Figure J12:  Check contents of torpedo tubes

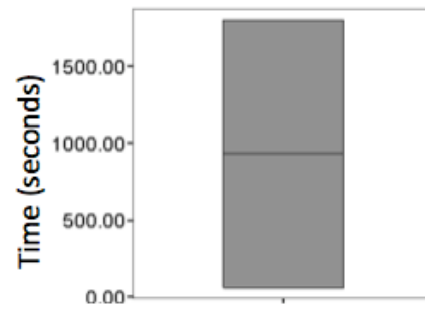Figure J13: Check status for submerging

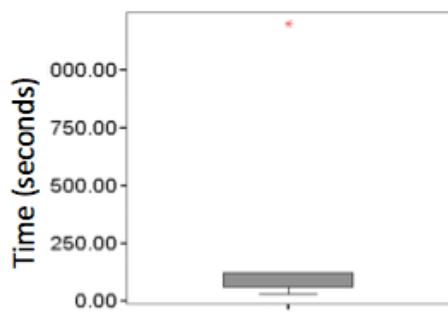

Figure J14: Check status of GPS



Figure J15:  Check sonar range

# Appendix K: Supporting Statistics

## K1: ANOVA table for distance

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Corrected Model | 211.434[b] | 2 | 105.717 | 14.622 | .000 |
| Intercept | 1044.702 | 1 | 1044.702 | 144.493 | .000 |
| Method | 154.616 | 1 | 154.616 | 21.385 | .000 |
| Class | 56.818 | 1 | 56.818 | 7.858 | .009 |
| Error | 209.674 | 29 | 7.230 | | |
| Total | 1465.810 | 32 | | | |
| Corrected Total | 421.108 | 31 | | | |

a. Computed using alpha = .05

b. R Squared = .502 (Adjusted R Squared = .468)

## K2: ANOVA table for time

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Corrected Model | 154799.090[b] | 2 | 77399.545 | 16.933 | .000 |
| Intercept | 862247.120 | 1 | 862247.120 | 188.635 | .000 |
| Method | 150865.245 | 1 | 150865.245 | 33.005 | .000 |
| Class | 3933.845 | 1 | 3933.845 | .861 | .361 |
| Error | 132558.690 | 29 | 4570.989 | | |
| Total | 1149604.900 | 32 | | | |
| Corrected Total | 287357.780 | 31 | | | |

a. Computed using alpha = .05

b. R Squared = .539 (Adjusted R Squared = .507)

## K3: Risk correlations

| Factor Checked against Risk | Spearman ρ | p value |
|---|---|---|
| Age | -0.01 | 0.99 |
| Class (military/civilian) | 0.39 | 0.13 |
| Years maritime experience | -0.23 | 0.39 |
| Years charting | 0.01 | 0.97 |
| Trust | -0.34 | 0.24 |
| Reliability | 0.05 | 0.85 |
| Accurateness | 0.03 | 0.94 |

## K4: Questionnaire responses for each risk level

| Risk Level | Number of subjects in group | Trust Median Score | Reliability Median Score | Accurateness Median Score |
|---|---|---|---|---|
| 1 (Low) | 4 | 4 | 4 | 4 |
| 2 | 3 | 3 | 4 | 4 |
| 3 (Medium) | 2 | 2.5 | 4.5 | 4.5 |
| 4 | 2 | 3.5 | 3.5 | 4.5 |
| 5 (High) | 5 | 3 | 4 | 4 |

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