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Generating certification evidence for the certification of collision avoidance in autonomous surface vessels

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ABSTRACT

The United States Navy plans on fielding autonomous surface vessels in the near future. This paper presents a preliminary approach for certifying an autonomous surface vessel to complete a transoceanic voyage. In particular, this paper will decompose the rules currently outlined by the Convention on the International Regulations for Preventing Collisions at Sea for avoiding a collision when two vessels are in sight of one another in international waters. These requirements are the basis for a specification that we examined to ensure it meets the requirements of the convention. We developed a protocol based on the analyzed specification that will ensure what the vehicle will function appropriately while operating autonomously. We then test this protocol using real-world scenarios currently used to certify human operators. Finally, we showed that if the protocol had been in place during a fatal mishap within the naval surface warfare community the collision would have been avoided. This paper describes how this protocol can be used as evidence for certifying an autonomous controller to complete a task reserved for a fully qualified ship's Commanding Officer in the United States Navy.

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1. Introduction

The United States Navy (USN) has publicly announced that it intends to field autonomous unmanned surface vehicles (USVs) in the near future (PEO LMW 2007). Such USVs can operate far beyond the limitations of human endurance. Despite the expectation that these systems will ultimately operate fully autonomously, an approved process for certifying an autonomous USV to accomplish tasks that are currently reserved for a qualified Commanding Officer (CO) and crew does not exist. This paper extends previous work by the authors regarding certifying autonomy within Naval Aviation (Costello and Xu 2020). We demonstrate a five-part process that can potentially lead to certifying autonomous surface vessels. While the USN has not defined, the level of autonomy (i.e. without a human in (actually at the controls of the vessel) or on (monitoring the vessel while it completes a task have the ability to take over) the loop) that its sought USVs will demonstrate, for the purposes of this paper we assume that an autonomous USV will be required to make decisions based on the information available to it. In this work, we first define the requirements an autonomous vessel must comply with in order to satisfy international agreements regarding collision avoidance. Then we develop a specification based off the requirements. We then analyze the specification to ensure it satisfies the requirements. Next, we develop a protocol

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based on the analyzed specification that can be used by software engineers to program an autonomous USV. Finally, we evaluate the effectiveness of the protocol using methods used to evaluate human navigational competence and against a recent fatal mishap within the naval surface warfare community.

All modern surface ships have some level of automation. This automation is thoroughly tested during the certification process. In this paper, we distinguish between automation and autonomy. For automation, a system functions with no or little human operator involvement; however, the system performance is limited to the specific actions it has been designed to do. Typically, these are well-defined tasks that have predetermined responses (i.e. maintain course and speed). For autonomy, a system has a set of intelligence-based capabilities that allows it to respond to situations that were not pre-programmed or anticipated (i.e. decision-based responses). Autonomous systems have a degree of self-government and self-directed behaviour (Clark et al. 2015). Autonomous systems can also be further differentiated between those that display deterministic behavior (based on known input conditions, the vehicle will exhibit a known behavior) and non-deterministic behavior (the exact behavior of the system cannot be determined based upon the input conditions). Autonomous systems can either have a human 'in the loop,' *i.e.*, actually at the controls of the vehicle, or 'on the loop,' *i.e.*, monitoring the vehicle while it completes a task while maintaining the ability to override and take over. For the purpose of this paper, we assume that an autonomous system lacks a human either in or on the loop.

Depending on the ultimate mission of a particular type of vessel, the USN certifies its vessels for deployment overseas based on a defined certification process. The USN also employs a well-defined qualification process for the ship's CO, who would be referred to as a ship's Captain in the civilian sector. In this work, we focus on deployment certification, which is defined as allowing a USN surface vessel to operate overseas.

Prior to allowing a USN vessel (and her crew) to operate on deployment in international waters, officials require that the vessel be certified as qualified to comply with the requisite rules and requirements. This certification requires data adequate to justify such an approval, which we refer to as certification evidence. This paper describes the development of certification evidence for deployment certification of a well-defined task: collision avoidance during a transoceanic voyage. A transoceanic voyage is defined as transiting between oceans in such a way that shoal water and land masses are not a factor. The process for avoiding collisions is outlined by the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) (United States Coast Guard 2020). All vessels, and ultimately the individual ship's CO, bear the responsibility and are required to comply with COLREGS when operating in international waters (Naval Regulation 1990). Before being qualified to serve as the CO of a USN vessel, the individual officer will have demonstrated a working knowledge of the 41 rules and annexes listed in COLREGS.

Autonomous USVs will not have a CO aboard (or a human in or on the loop to make decisions) and will require a new certification process prior to being allowed to operate in international waters as a flagged vessel of the USN. To provide a path forward for certifying autonomous behavior for the USN surface warfare community, this paper articulates a specific approach for providing certification evidence that can be used for certifying an autonomous controller to exhibit non-deterministic behavior during a transoceanic voyage when it encounters a surface contact (i.e. only two ships involved). We use COLREGS as the basis of defining the edges of a clearance envelope (i.e. the conditions which the vehicle will be certified to exhibit autonomous behavior) where certification officials will allow an autonomous USV to exhibit non-deterministic behavior while avoiding collision.

We decompose the tasks currently completed by a ship's CO and crew during collision avoidance to their basic requirements. To develop these requirements, we observed day-to-day operations aboard a USN vessel during a seven-month deployment to include straight transits and collision avoidance maneuvers. Additionally, we consulted several senior Surface Warfare Officers (SWOs) during multiple interview sessions. Through conversations and observations, we gained insight into what was expected of a fully qualified CO and crew during a transoceanic voyage to avoid collision should they encounter a surface contact.

The certification of a vessel can be seen as an objective engineering-based risk mitigation and acceptance process. The certification and qualification process for a ship's CO is a subjective process, developed through naval tradition over the past two centuries, to enable senior leadership to trust in individuals' judgment at sea. This is particularly important as a ship's CO will represent the USN and the United States in situations where they may not be able to contact anyone above them in the chain of command. Autonomous USVs will not have a human in or on the loop. Because autonomous USVs will not have a human in or on the loop, prior to their authorized deployment, a clearance envelope needs to be defined where autonomous USVs can exhibit non-deterministic behavior. We use COLREGS to define this clearance envelope for collision avoidance. That is, the actions of the USV are not constrained unless and until they encounter a situation that requires action as outlined by COLREGS.

This paper is structured as follows. In the Background Section, in addition to a review of related research in the area, the current certification process for a new ship and its crews is summarized. We also provide a brief summary of the requirements to be designated as the CO of a USN surface vessel. In the Requirements Definition and Specification Section, the actions taken by a qualified CO to avoid collision are deconstructed to their requirements (as defined by COLREGS and naval tradition) and related assumptions. These requirements are then used as the basis for a specification. In the Methods and Procedures Section, we analyze the specification to ensure it meets the requirements through formal verification activities. Finally, we show that specified behavior will satisfy the requirements (given the assumptions). In the Results Section, we present a protocol that can be used by certification officials for the possible certification evidence of autonomous behavior in a naval surface vessel. We also evaluated the protocol against a recent fatal mishap within the USN surface warfare community. In conclusion, we summarize our work and provide directions for future research.

2. Background

A large body of work exists for certifying autonomous air vehicles, and many of the lessons learned translate to certifying autonomous USN vessels, as both air and water vessel operations currently require a human to bear the responsibility of the vehicle. One common theme is to identity errors in the software early in the design cycle, since the latter a defect is found, the more resources (both time and money) are required to correct the issue (Clark et al. 2015; Gross, Fifarek, and Hoffman 2016). Many of the approaches involved modeling and simulation (M&S) to determine if the software is adequate for the system requirements (Israelsen et al. 2017; Abraham 2015; Fisher, Dennis, and Webster 2013; Tobias et al. 2015). Another common approach involves employing formal methods for safety critical software verification and validation (V&V), including run time verification (Baier and Katoen 2008; Kane 2015; Coombes, Chen, and Render 2016; Gross et al. 2016) model checking (Avram et al. 2017; Berezin 2002; Webster et al. 2012; Good et al. 2016) and theorem proving (Berezin 2002; Sutcliffe, Denney, and Fischer 2017; Ouimet 2008; Munoz et al. 2016). Some proposals have detailed methodologies for V&V for the unmanned see and avoid requirement, but only for a two-dimensional problem (Jenie et al. 2016; Guarro et al. 2017). One drawback of these approaches is the limited focus of their work. Because an approved methodology does not exist, their work was limited to one or two pieces of the V&V process, and most did not consult aviation certification officials. One notable exception is the work done by the formal methods group at National Aeronautics and Space Administration (NASA) Langley. Currently, NASA is working on (and has published) several papers on obtaining flight clearances for unmanned aerial systems (UASs) to operate within the national airspace. Their work focuses on formally defining the specification from the requirements of operation within the national airspace, and then V&V via theorem provers (Ghatas et al. 2017; Narkawicz, Munoz, and Dutle 2016). This is designed to give certification officials confirmation that the software will perform per the requirements.

The last 10 years has seen a large uptick in the literature regarding unmanned and autonomous surface vessels. Numerous papers have been published dealing with the unmanned cargo vessels and the legality and practicality of having a ship operating without a crew aboard (Zhou et al. 2020; Karlis 2018; Veal, Tsimplis, and Serdy 2019; Vojkovic and Milenkovic 2020; He et al. 2017; Backalov 2020; Naeem, Henrique, and Hu 2016; Mallam, Nazir, and Sharma 2020; Hogg and Ghosh 2016; Kim et al. 2020; Cheng and Ouyang 2020). However, a majority of this work focused on a limited definition of autonomy. They propose situations where the decision engine would alert humans on board the vessel of when their direction was needed (similar to current crew relief modes) or scenarios where the USV was controlled by an operation center manned by qualified humans who would bear the ultimate responsibility of the vessel's actions. The research community see COLREGS as an ideal framework for building algorithms for autonomous vessel collision avoidance as they provide a rigid structure for how the ship would maneuver if it were to encounter a surface contact (He et al. 2017; Naeem, Henrique, and Hu 2016; Wang et al. 2018; Bassam et al. 2019; Zhao and Roh 2019; Xu et al. 2020; Du et al. 2020; Campbell, Naeem, and Irwin 2012; Beser and Yildirim 2018; Hu et al. 2017; Papageorgiou et al. 2019; Kuwata et al. 2014; Johansen, Perez, and Cristofaro 2016; Sun et al. 2018; Park, Choi, and Choi 2019; Hu et al. 2020; Meyer et al. 2020; Cho, Han, and Kim 2020; Campbell, Abu-Tair, and Naeem 2014).

Previous work on this subject would not satisfy the requirements for certification evidence for autonomous navigation within the USN (i.e. operations without a CO aboard) because it assumes there is ultimately a human to override the autonomous system. Previous work in this area has focused on automating the tasks currently executed by humans. This will allow ships to sail with limited (in the case where a monitor would inform a human onboard when a limit was reached) or no crew (in the case where an operations center is alerted and can remotely out inputs into the craft when the need arises). While these approaches give the appearance of autonomy, there is still a human in or on the loop to intervene when there is an issue. The novel approach we are taking is attempting to find a way to certify a USN vessel for deployment when there will not be a human in or on the loop to take over when an issue arises.

The protocols/control laws used by an autonomous vehicle are essentially the decision engine for determining where the system will go and how it will react to input conditions. Formal methods offer the ability to build the protocols/control laws based on a formally verified specification. The specification is based on the requirements of the software that will control the system. Using a formal methods approach for the development of the protocols offer certification officials insight as to what the system will not do. This insight can be used in the certification of an autonomous controller.

2.1. Current certification process for naval surface vessels

When the USN develops and builds a new class of ship, it develops and executes a certification process for the ship and its crew prior to both being certified for operations on deployment in international waters. This process begins with builder's trials (which focus on the contractor demonstrating the capabilities of the vessel) and acceptance trials (which concentrate on the Navy evaluating the vessel) to ensure the vessel has been built to the requirements developed by the Navy. During this period, the USN ensures that the ship builder was able to meet the specifications of the contract. These are typically objective standards (i.e. the ship must be able to obtain and sustain 32 knots for 5 min in a given sea state). In addition to performance specifications, the hardware and software onboard the vessels are checked to ensure the ship builder performed to the requirements specified by the government.

Once the builders and acceptance trials are complete, the USN will begin certification of the crew to operate the systems onboard the ship via some form of afloat training group in conjunction with multiple evaluation organizations. In this phase, the certification process shifts from the hardware and software of the ship to the human element. Afloat training groups are responsible for evaluating and certifying the ship and its crew for operation on deployment. During the workup phase prior to deployment the CO and crew are evaluated against established standards to ensure they are proficient to operate the various systems of the ship while completing their assigned duties. Ultimately, the crew certification process depends on subjective determinations made by USN leadership regarding the competence of the crew.

2.2. Current certification process of a commanding officer

Under current USN regulations, the responsibility of the CO for his or her command is absolute. They may delegate authority but shall in no way be relieved of the responsibility (Naval Regulation 1990). The overarching purpose of this research is to determine a path forward for certifying a decision engine to act as the CO of a USN vessel. To accomplish this first we must explain the current CO qualification process. This process is formally established by Commander Naval Surface Forces Surface Warfare Career Manual (COMNAVSURFORINST 1412.7) (COMNAVSURFOR 2019). A typical ship's CO is an O-5 (Commander in the USN) who has been commissioned for approximately 15 years. Prior to taking command they will have to have completed the following:

- Designated as a Surface Warfare Officer (SWO)
- Serve as a minimum of 60 months assigned to a surface ship
- Complete SWOS Department Head curriculum
- Attain Engineering Officer of the Watch and Tactical Action Officer qualification
- Complete basic and advance Division Officer Course
- Screen for Department Head
- Complete SWOS command assessment
- Complete a review of his or her leadership skills process
- Demonstrate ship-handling/seamanship skills while assigned to afloat commands
- Be nominated for and complete a command qualification oral board
- Be selected for command at sea by an administrative screening board
- Complete SWOS Pre-Commanding Officers Course
- Complete the Command Leadership Course, including a written exam
- Complete an additional review of their leadership skills
- Complete additional joint military education

While the requirements to take command contain multiple objective steps, there are numerous subjective items that involve leadership examining the decision-making capabilities of that individual under stress. This process has gone through multiple iterations over the last 245 years. The USN surface warfare leadership feels that this process allows the appropriate level of oversight of the potential COs decision-making abilities prior to bestowing the massive responsibility of command of a USN vessel.

The ship's CO cannot always be present on the bridge, and he or she will designate a number of members of their crew as Officer of the Deck (OOD). The OOD is delegated the authority to act on the CO's behalf when the CO is elsewhere on the ship. During the OOD qualification process the OOD candidate will be observed by senior officers to ensure that their decision-making process is sound. Ultimately, the CO will chair an oral board for the OOD candidate that may result in their designation as an OOD. To assist the OOD in their duties during the CO's absence, the CO will establish a number of standing orders, with the first among them being to alert the CO if there is ever a question of what to do on the bridge. In this research, we assume that the actions taken by the USV to avoid collision would be the same that would be taken by a ship's CO, or an OOD acting on behalf of the ships CO in their absence. However, unlike an OOD, an autonomous USV will not have a human to contact if there is a question of how the vessel should act.

While this research is by no means sufficient to provide a complete path toward certifying an autonomous controller to act as the CO of a USN vessel, it does provide a path forward for certifying just one of the tasks currently performed by a ship's CO: collision avoidance during a transoceanic voyage.

3. Requirements definition and specification development

3.1. Development of the basic requirements

The first step in a path for certifying an autonomous USV to complete a task currently reserved for a qualified CO is to define the requirements the USV's decision engine must complete. The requirements for collision avoidance are described by the 41 COLREGS rules (United States Coast Guard 2020). From the first time, a junior officer stands OOD (under instruction) they are expected to follow COLREGS when they encounter another ship. By the time a CO has taken command of a USN vessel they are expected to follow COLREGS unless an emergency situation presents itself. In that situation, they can deviate to avoid collision. A CO will base their decision of what action to take based on the information available to them. This information may come from an automatic system, radar (or other electronic sensors onboard) or human watch standers using various detection methods (i.e. aural, visual and electronic).

During a transoceanic voyage, the ship will have an approved navigation plan which will include a planned intended movement (PIM). A CO is required to stay within a designated tolerance from PIM, and a deviation greater than a specified distance requires notification to fleet command. The navigation plan will generally not follow the most direct course, but will be offset to limit contact with traffic. This is ideal for USVs as it will reduce the number of times that the decision engine must be used to make changes to PIM. The non-deterministic behavior described in this work deals with what the decision engine will do when maneuvering the ship and how it will regain PIM after a surface contact is no longer a factor. These maneuvers will be further influenced by some sort of cost function that will take various resources (i.e. fuel and time) into account when the decision engine determines how to maneuver the ship.

In this work, we assume that all encounters would occur when vessels are in sight of one another (i.e. visibility is not restricted). With this assumption, and in accordance with COLREGS, an encounter with another vessel in international waters can be broken down to six phases. The first phase involves determining if the contact is a collision threat to their vessel. As the first certification for autonomous USVs will require extremely conservative limits, we adopted a rule of thumb used by conservative COs in the USN. It is referred to as the 3-2-1 rule. If the contact vessel's closest point of approach (CPA) is outside of 3 nautical miles (nm) off the bow, 2 nm off the beam or 1 nm off the stern (see Figure 1) it does not pose a threat and no deviation in course and speed is required.

If the contact will violate the 3-2-1 rule the encounter transitions to the second phase: determining if the USV is in an overtaking situation with the contact. Two vessels are in an overtaking situation when one vessel approaches the other more than 22.5 degrees abaft the ships beam (i.e. at night she would be able to see only the stern light but neither of her sidelights) (United States Coast Guard 2020). If the USV is overtaking the contact, the USV will assume the role of the give-way vessel (i.e. the vessel that is required to take early and substantial action to keep out of the way). If the contact is overtaking the USV, the USV will assume the role of the stand-on vessel (i.e. the vessel that must maintain course and speed).

Providing the contact CPA violates the 3-2-1 rule, and the USV is not in an overtaking situation, the encounter shifts to phase three: determining if the contact vessel is stand-on or give-way based on its hierarchy of privilege. If the USV encountered another vessel above it in the hierarchy, the USV would be the give-way vessel. There are seven basic categories in the hierarchy, with the

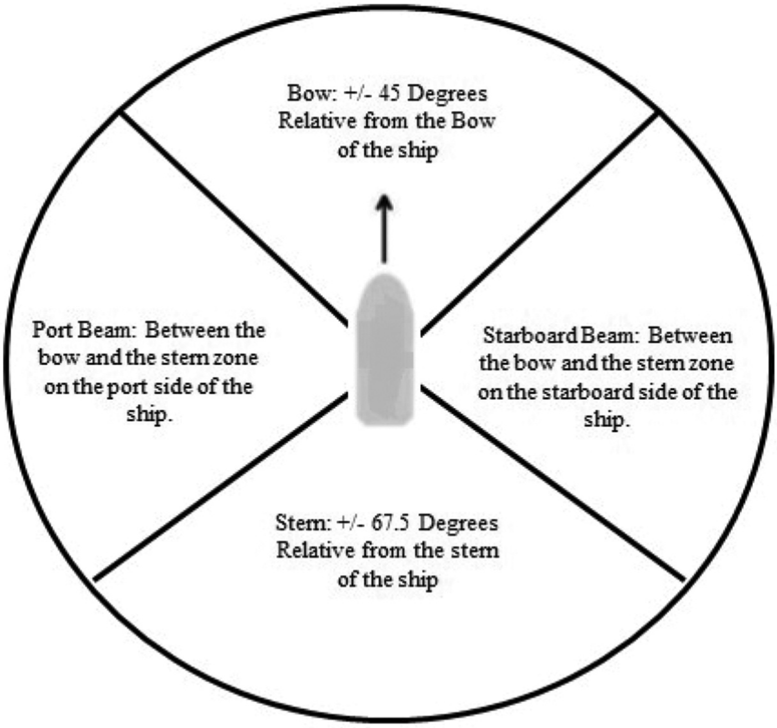


Figure 1. Depiction of bow, stern and beam zones relative to a vessel.

highest level listed first, and each have a day (shapes that can be visually identified by other ships) and night (combination of lights that can be identified by other ships) signaling requirements and definitions of each category are outlined in COLREGS (United States Coast Guard 2020):

- Not Under Command
- Restricted in Her Ability to Maneuver
- Constrained by Her Draft
- Fishing (Commercial Fishing Not Rod and Reel)
- Sailing
- Power-Driven Vessel
- Seaplane

A CO must consider numerous variables to determine where on the hierarchy of privilege their vessel falls under. However, under most situations, a USN vessel will be considered a power-driven vessel while completing a transoceanic voyage. Many of the contacts it will encounter also be power-driven vessels.

Phase four of the encounter is to determine what type of a collision threat is impending (head-on or crossing). This determination is defined by the geometry of the encounter, and is used when the vessels are in sight of one another (we assume a nominal range of 10 nm for this research).

A head-on situation is defined as when two vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision and each shall alter her course to starboard so that each shall pass on the port side of the other. A crossing situation is defined as when two vessels are crossing so as to involve a risk of collision (violates 3-2-1), the vessel which has the other on her own starboard side shall keep out (and be considered the give-way vessel) of the way and shall, if the circumstances of the case permit, avoid crossing ahead of the other vessel (United States Coast Guard 2020). We also assume that whatever situation the vessels (both the contact and the USV) are in once they reach visual range will be maintained until the contact is no longer a factor (i.e. once the USV is identified as the stand-on vessel it will continue to be the stand-on vessel until the contact is no longer a factor based on COLREGS).

Once the type of situation has been defined, the CO of a USN vessel is expected to determine if they are the stand-on or give-way vessel and take the appropriate action (phase 5).

The sixth and final phase of COLREGS encounters deals with the Shall-May-Shall (United States Coast Guard 2020):

- When encountering another vessel, each vessel SHALL comply with the roles detailed in phase 5 (as described above).
- If the give-way vessel is not taking appropriate action before the two vessels reach a danger range the stand-on vessel MAY maneuver to ensure separation.
- If the actions of the other vessel put the two vessels into a critical range (defined by violating the 3-2-1 rule and considered a nominal value defined in this paper and will be further defined when this method is programmed into the individual vessel based on its capabilities), the CO of the USN vessel SHALL maneuver to ensure collision avoidance and maintain the safety of their vessel.

3.2. Specification

For the limited purpose of defining a specification for completing the collision avoidance task between two vessels in sight of one another during a transoceanic voyage by an onboard decision engine, we elected to use a state machine specification (Domı, Pérez, and Rubio 2012) (Figure 2). The state machine specification follows the various states required for the vehicle to pass through from when a contact is first detected, and when the contact is determined not to be a factor to the USV. Table 1 details the various events within the specification that would transfer from one state to another.

The transition states can be summarized as follows:

- **A: Initial Detection of Contact State** - In this state, the system is completing the transoceanic voyage and its sensors detect a contact.

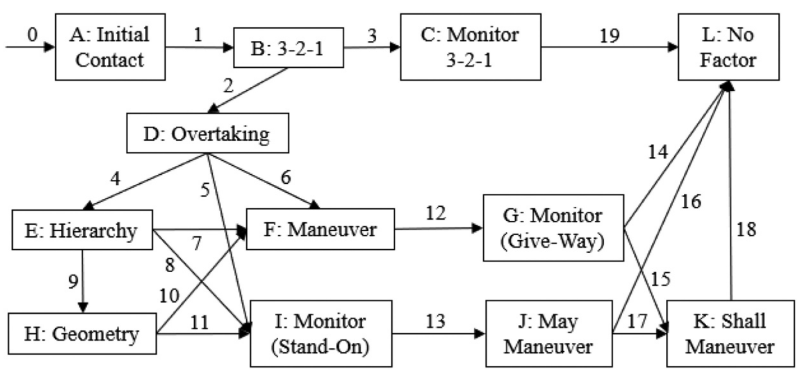


Figure 2. State machine specification which details the decision process for an unmanned surface vessel to avoid collision while completing a transoceanic voyage.

Table 1. Event description for the state machine specification which details the decision process for a unmanned surface vessel to avoid collision while completing the transoceanic voyage.

ID	From	Event	To
0	N/A	Initial Contact	A
1	A	Process Contact for CPA Orientation	B
2	B	CPA Violate 3-2-1	D
3	B	CPA Will not Violate 3-2-1	C
4	D	USV is not Overtaking Contact	E
5	D	Contact is Overtaking USV	I
6	D	USV is Overtaking Contact	F
7	E	USV is Give-Way Vessel (Hierarchy)	F
8	E	USV is Stand-On Vessel (Hierarchy)	I
9	E	Same Hierarchy	H
10	H	USV is Give-Way Vessel (Geometry)	F
11	H	USV is Stand-On Vessel (Geometry)	I
12	F	USV Maneuvers Per COLREGS	G
13	I	USV is Stand-On, Contact Maneuvers	J
14	G	Contact Passes CPA, Range Opening	L
15	G	Contact Maneuver into the Critical Area	K
16	J	Contact Passes CPA, Range Opening	L
17	J	Contact Maneuver into the Critical Area	K
18	K	Contact Passes CPA, Range Opening	L
19	C	Contact Passes CPA, Range Opening	L

- **B: 3-2-1 State** - In this state, the decision engine determines (based on the current course and speed of the unmanned vessel and the predicted course and speed of the contact) if the contact will violate the 3-2-1 CPA rule
- **C: Monitor (3-2-1) State** - In this state, the decision engine monitors the contact to ensure it continues to not violate 3-2-1 until it reaches its CPA and range begins to open.
- **D: Overtaking State** - Decision engine determines if the USV is in an overtaking situation with the contact.
- **E: Hierarchy State** - In this state, the decision engine uses situational awareness (build by its sensors and based on the COLREGS signals) to determine the relationship between the hierarchy of the contact and the USV.
- **F: Maneuver State** - In this state, the USV is the give-way vessel and the decision engine will maneuver (in accordance with COLREGS) to ensure the CPA complies with the 3-2-1 rule.
- **G: Monitor (Give-Way) State** - In this state, the decision engine will continue to monitor the contact to ensure the course deviation it inputs (per COLREGS) will enable safe separation per the 3-2-1 Rule. It would also continue to maneuver to ensure safe separation.
- **H: Geometry State** - Assuming a likely scenario (both ships have the same hierarchy), the decision engine uses this state to determine the geometry of the two vessels, and determine if the decision engine is the stand-on or give-way vessel.
- **I: Monitor (Stand-On) State** - In this state, the decision engine shall maintain its course and speed, allowing the contact to make the appropriate maneuvers (per COLREGS) to ensure safe separation. The decision engine will monitor the contact's actions.
- **J: May Maneuver State** - In this state, the decision engine will maneuver the USV to enable the CPA to comply with the 3-2-1 rule due to the contact (give-way vessel) not executing a maneuver that will give adequate separation. In this paper the may decision range is set for 5 nm (nominal range).
- **K: Shall Maneuver State** - In this state, the decision engine shall maneuver the USV due to the fact that a collision is imminent (i.e. contact has violated the critical range around the USV).
- **L: No Factor State** - In this state, the contact is no longer a factor (i.e. the vessel has passed its CPA point, or CPA will be greater than threshold limit) and the decision engine can exhibit non-deterministic behavior to return the USV to PIM and continue on its transoceanic voyage.

This state machine specification can be considered a top-level overview. Each of the events described in Table 1 have conditions and assumptions built into them. Some of the assumptions are the environmental conditions (i.e. weather or atmospheric conditions) and vehicle limitations (actual limits of the surface vehicle and the sensors installed). These conditions and assumptions must be valid for Figure 2 to be a valid certification artifact. Top level assumptions then become lower-level requirements.

As the specification in Figure 2 represents a subset of the overall functionality of the USV, it has one defined start point (Initial Detection of Contact State). From there the decision engine executes the evaluation of possible steps (per COLREGS) to ensure avoidance of a collision at sea (once the contact is determined not to be a factor).

4. Methods and procedures

This section will apply formal verification activities to the specification outlined in the previous section.

4.1. Operational procedure table

An Operational Procedure Table (OPT) was used to begin the analysis of the specification (Figure 3). As the evidence provided would not qualify as formal verification of the specification,

	Variable										
Collision Avoidance Segment Task	CPA Outside of 3-2-1	Contact is the Stand-On Vessel	USV Maneuvers	Contact Remains Outside of 3-2-1	Contact Maneuvers into Vital Area	CPA Opening Post Emergency Maneuver (Give-Way)	Contact Allowed to Perform a Maneuver	CPA Opens Beyond 3-2-1	CPA Still Within 3-2-1 at 5 nm	Contact Remains Outside of Critical Area	CPA Opening Post Emergency Maneuver (Stand-On)
Initial Detection of Contact	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
No Factor, Monitor (1)	1	N/A	N/A	N.A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
USV is Give Way Vessel	0	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Determine COLREGS Maneuver	0	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
No Factor, Monitor (2)	0	1	1	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Emergency Maneuver Required (1)	0	1	1	N/A	1	N/A	N/A	N/A	N/A	N/A	N/A
No Factor, Monitor (3)	0	1	1	N/A	1	1	N/A	N/A	N/A	N/A	N/A
USV is Stand In Vessel	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Shall Monitor	0	0	N/A	N/A	N/A	N/A	1	N/A	N/A	N/A	N/A
No Factor, Monitor (4)	0	0	N/A	N/A	N/A	N/A	1	1	N/A	N/A	N/A
May Maneuver	0	0	N/A	N/A	N/A	N/A	1	0	1	N/A	N/A
No Factor, Monitor (5)	0	0	N/A	N/A	N/A	N/A	1	N/A	1	1	N/A
Emergency Maneuver Required (2)	0	0	N/A	N/A	N/A	N/A	1	N/A	1	0	N/A
No Factor, Monitor (6)	0	0	N/A	N/A	N/A	N/A	1	N/A	1	0	1

Possible Variable Values

1	Positive
0	Negative
N/A	Not Applicable

Figure 3. Operational procedure table converting the state machine specification into the various tasks required for an USV to accomplish collision avoidance (per COLREGS) during a transoceanic voyage.

we simplified it within the OPT (by combining the hierarchy and geometry checks to determine stand-on/give-way into one step for the analysis of the specification). The variables along the top row represent the requirements for each associated collision avoidance segment task (left column) that is required for a COLREGS-based collision avoidance during a transoceanic voyage. Each variable has its own assumptions (which would be translated to requirements at lower levels). One overlying assumption across all of the variables is that the sensors and onboard systems are able to build an accurate surface picture of what is happening around the USV. The tasks mirror the various states in Figure 2. During each segment, the associated variable is defined (changing from N/A to a 1 or a 0) until the contact is no longer a factor and the USV maintains situational awareness of the contact until it can no longer be tracked by the USV.

The following are the variables and some possible underlying assumptions:

- **CPA Outside of 3-2-1**: The contact course and speed, relative to the USV course and speed, will generate a CPA that complies with the 3-2-1 rule. Assumes the systems onboard the USV can track the contact and predict the CPA.
- **Contact is the Stand-On Vessel**: The contact, based on hierarchy or geometry, is the stand-on vessel and the USV is the give-way vessel. Assumes the systems onboard the USV can accurately predict the geometry of the impending situation or can accurately identify the shapes/lights displayed by the contact. Another option would be to use automatic identification system (AIS) (or another system like AIS). However, the broadcast information available is only as accurate as the human who makes the input. Currently, USN vessels do not solely rely on AIS to identify the stand-on or give-way status.
- **USV Maneuvers**: The USV is the give-way vessel, and maneuvers to ensure compliance with the 3-2-1 rule. Assumes the decision engine is able to compute an appropriate course and speed to maneuver.
- **Contact Remains Outside of 3-2-1**: As the stand-on vessel, the contact maintains course and speed and its CPA complies with the 3-2-1 rule after the USV maneuvers. Assumes the decision engine can track and predict the location of the contact.
- **Contact Maneuvers into Critical Area**: The contact makes an unexpected maneuver that would decrease the CPA and violate 3-2-1. The USV will then maneuver clear via extreme rudder and throttle commands. Assumes the decision engine is able to track and contact as it maneuvers, and can take the appropriate actions.
- **CPA Opening Post Emergency Maneuver (Give-Way)**: Following an emergency maneuver, the CPA to the contact increases to a nominal value where the contact is no longer a collision threat. Assumes the decision engine can track and predict the location of the contact.
- **Contact Allowed to Perform a Maneuver**: USV is the stand-on vessel, and shall maintain course and speed; contact maneuvers per COLREGS to avoid a collision. Assumes the decision engine can track and predict the location of the contact.
- **CPA Opens Beyond 3-2-1**: The contact maneuver increased the CPA to comply with the 3-2-1 rule. Assumes the decision engine can track and predict the location of the contact.
- **CPA Still Within 3-2-1 at 5 nm**: The contact maneuver, or lack thereof, did not enable the CPA to comply with the 3-2-1 rule. Assumes the decision engine can track and predict the location of the contact.
- **Contact Remains Outside of Critical Area**: The contacts course and speed will remain outside of the critical area. Assumes the decision engine can track and predict the location of the contact.
- **CPA Opening Post Emergency Maneuver (Stand-On)**: Following an emergency maneuver, the CPA to the contact increases to a nominal value where the contact is no longer a collision threat. Assumes the decision engine can track and predict the location of the contact.

The following are the collision avoidance segment tasks and their individual definitions:

- **Initial Detection of Contact**: The USV is proceeding along its PIM.
- **No Factor, Monitor (1)**: The contact will comply with the 3-2-1 rule and no deviation from the ships current course or speed is required. The USV will continue to monitor the contact until it can no longer be tracked via its onboard systems.
- **USV is Give-Way Vessel**: The contact is the stand-on vessel and the USV will be required to maneuver (course and or speed) to ensure collision avoidance.
- **Determine COLREGS Maneuver**: The USV determines the best way to comply with COLREGS for collision avoidance.
- **No Factor, Monitor (2)**: The contact has reached its CPA and the range is opening (USV is the give-way vessel). The decision engine must compute a new course and speed to return to PIM and monitor the contact until it can no longer be tracked via onboard systems.
- **Emergency Maneuver Required (1)**: As some point during the situation (USV is the give-way vessel), the contact maneuvers is such a way that it will violate the critical area around the USV.
- **No Factor, Monitor (3)**: Post emergency maneuver (while the USV is the give-way vessel) CPA has increased to a point where it is no longer a factor to the USV. The decision engine must compute a new course and speed to return to PIM and monitor the contact until it can no longer be tracked via onboard systems.
- **USV is Stand-On Vessel**: The contact is the give-way vessel and the USV shall maintain course and speed and allow the contact to made the appropriate action to ensure collision avoidance.
- **Shall Monitor**: The contact will make a maneuver, and the USV will monitor the actions of the contact.
- **No Factor, Monitor (4)**: The contact has reached its CPA and the range is opening (USV is the stand-on vessel) following the contact's maneuver. The USV will monitor the contact until it can no longer be tracked via onboard systems.
- **May Maneuver**: The contact's maneuver (or lack thereof) will not satisfy 3-2-1 when the range to the contact is 5 nm (nominal range for this paper) and the decision engine may maneuver.
- **No Factor, Monitor (5)**: The contact has reached its CPA and the range is opening (USV is the stand-on vessel) following the USV's maneuver after the contact's maneuver. The decision engine must compute a new course and speed to return to PIM and monitor the contact until it can no longer be tracked via onboard systems.
- **Emergency Maneuver Required (2)**: As some point during the situation (USV is the stand-on vessel), the contact maneuvers is such a way that it will violate the critical area around the USV.
- **No Factor, Monitor (6)**: Post emergency maneuver (while the USV is the stand-on vessel) CPA has increased to a point where it is no longer a factor to the USV. The decision engine must compute a new course and speed to return to PIM and monitor the contact until it can no longer be tracked via onboard systems.

4.2. Consistency and completeness

The operational procedure table, Figure 3 (which contains cell values (1, 0 or N/A) of each variable), was used to help define consistency and completeness. The table shows consistency by the fact that no two columns are operational for any combination of values for the variables as no two columns have the same cell values (at most one outcome assigned under each possible scenario). The table shows completeness by the fact that for all values of variables only one column is operational as all possible combinations of the variables are listed within the table, and no two columns are equal (some outcome is assigned to every possible scenario) (Hoover, Gauspari, and Humenn 1996).

4.3. Propositions

To show that the system will complete the task and show what the system will not do, the top level requirements outlined in Figure 3 were separated into propositions which must be evaluated to determine the overall behavior of the USV when executing collision avoidance maneuvers. The propositions were based off the operational procedure table (Figure 3). These propositions alone would not satisfy formally verifying the specification. That would require a detailed formal specification that would contain all possible situations, to include varying environmental conditions, and more explicit definitions then these boolean statements and is beyond the scope of this research.

- *Proposition 1*: Initial CPA of contact will comply with the 3-2-1 rule.
- *Proposition 2*: 3-2-1 valid through CPA without any course/speed change by the USV or contact.
- *Proposition 3*: USV is give-way vessel due to overtaking situation.
- *Proposition 4*: USV is stand-in vessel due to overtaking situation.
- *Proposition 5*: USV is give-way vessel due to hierarchy.
- *Proposition 6*: USV is stand-on vessel due to hierarchy.
- *Proposition 7*: USV is give-way vessel due to geometry.
- *Proposition 8*: USV maneuvers as the give-way vessel to enable a CPA that satisfies 3-2-1.
- *Proposition 9*: Contact maneuvers (with the USV as the stand-on vessel) to enable a CPA that satisfies 3-2-1.
- *Proposition 10*: Post maneuver (either contact or USV) 3-2-1 maintained through CPA.
- *Proposition 11*: Imminent violation of 3-2-1 requiring an emergency maneuver by the USV.

5. Results

In the previous section, we analyzed the specification to ensure that it met the COLREGS requirements for avoiding a collision during a transoceanic voyage. In this section, we develop a protocol based on that analyzed specification. The protocol was then evaluated by manually applying the logic of the protocol against a number of challenging real-world situations that SWOS use during the training of junior officers to stand OOD in an effort to produce evidence that officials can use when certifying a decision engine to make decisions and take actions currently reserved for the CO of a USN vessel. Additionally, we analyzed a recent fatal mishap within the naval surface warfare community against the protocol to demonstrate how the collisions would have been avoided if the protocol was in place.

5.1. Protocol

We used the analyzed specification as a baseline for the requirements the decision engine will need to fulfill in executing the collision avoidance task during a transoceanic voyage. By translating the state machine specification into a flow chart protocol, software designers can develop code based on the analyzed specification. The protocol has been broken into several steps that mirror the COLREGS-based steps a ship's CO would do to avoid a collision. These steps can be traced directly to the supporting propositions presented previously:

- **Assessment A (CPA will Satisfy 3-2-1)**: Proposition 1
- **Assessment B (3-2-1 Valid Through CPA)**: Proposition 2
- **Assessment C (USV is Give-Way Vessel—Overtaking)**: Proposition 3
- **Assessment D (USV is Stand-In Vessel—Overtaking)**: Proposition 4
- **Assessment E (USV is Give-Way Vessel—Hierarchy)**: Proposition 5

- **Assessment F (USV is Stand-On Vessel—Hierarchy)**: Proposition 6
- **Assessment G (USV is Give-Way Vessel—Geometry)**: Proposition 7
- **Assessment H (USV Maneuvers Enables 3-2-1)**: Proposition 8
- **Assessment I (Contact Maneuver Enables 3-2-1)**: Proposition 9
- **Assessment J (3-2-1 Maintained Through CPA)**:Proposition 10
- **Assessment K (USV Must Emergency maneuver to Avoid Collision and CPA Opens)**: Proposition 11

The protocol depicted in Figure 4 satisfies the specification. It can serve as an artifact that certification officials may use when certifying a decision engine to control a naval surface vessel during a transoceanic voyage.

5.2. Evidence leading to the certification of an autonomous USV

The naval surface warfare community has put a renewed emphasis on the ensuring its officers have a firm understanding of COLREGS following recent collisions at sea. The community now requires numerous examinations of its officers through rules of the road exams which translates COLREGS into various situation to evaluate an individuals knowledge and decision-making skills. On average a CO has attended seven courses at the SWOS before taking command. Each course will have a rules of the road exam. In addition, while underway all officers who stand bridge watch are required to take a rule of the road exam once a month. The standard rules of the road exam is 20 questions, with a one hour time limit. The questions are pulled from the United States Coast Guard test bank (Surface Ship 2018).

As part of this research, we contacted leadership at SWOS to partner with them on a path towards certifying autonomy in the naval surface warfare community. They provided us with a test bank of 10 questions that we used to evaluate the protocol. We then manually evaluated the questions via the protocol to ensure the actions taken by the USV would be in accordance with COLREGS.

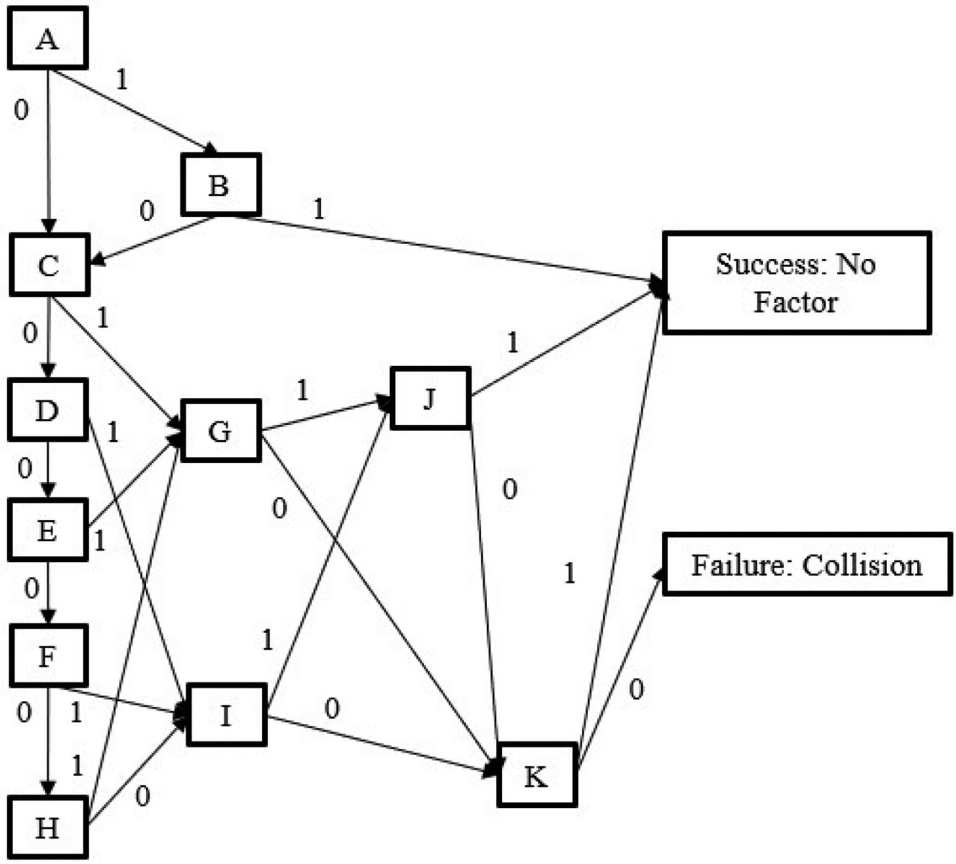
- Example Question: You are aboard vessel ‘A,’ a power driven vessel, on open waters and vessel ‘B,’ a sailing vessel is sighted off your port bow (Figure 5). Which vessel is the stand-on vessel?

- Protocol Response: The USV is the give-way vessel due to Hierarchy (power driven verses sailing) and matches Assessment D.

The protocol was able to exhibit behavior that would satisfy the correct answer from the 10 SWOS-provided rules of the road questions (providing the assumptions were valid). While this analysis alone would not be sufficient enough to qualify the decision engine to operate on deployment without a human in or on the loop, it demonstrated that it could be used to accurately interpret the situation and make similar decisions to a fully qualified CO. This can serve as evidence for eventual deployment certification of an autonomous USV.

5.3. Case study, recent fatal mishap within the naval surface warfare community and how the protocol would have preformed

In 2017, the USN had two fatal collisions with civilian vessels. On 17 July 2017, the USS Fitzgerald collided with the Philippine-flagged container ship ACX Crystal 80 nm outside of Tokyo, killing 7 Sailors (National Transportation Safety Board 2020). On 21 August 2017, the USS McCain collide with the Liberian-flagged tanker Alnic MC east of the Strait of Malacca, killing 10 Sailors (National Transportation Safety Board 2019). While the USS McCain collision was compounded by an emergency, the USS Fitzgerald collision was clearly a result of the crew not following COLREGS.



A: Contact will Satisfy 3-2-1
B: No 3-2-1 Change Through CPA
C: USV is Give-Way Vessel – Overtaking
D: USV is Stand-On Vessel – Overtaking
E: USV is Give-Way Vessel - Hierarchy
F: USV is the Stand-On Vessel - Hierarchy
G: USV Maneuver Enables 3-2-1
H: USV is Give-Way Vessel - Geometry
I: Contact Maneuver Enables 3-2-1
J: 3-2-1 Maintained Through CPA
K: USV Must Execute Emergency Maneuver to Avoid Collision – and CPA Opens

Figure 4. Protocol which meets the requirements of the specification detailing the decision process for an unmanned system to complete the various tasks required for an USV to accomplish collision avoidance (per COLREGS) during a transoceanic voyage (1 = Yes, 0 = No).

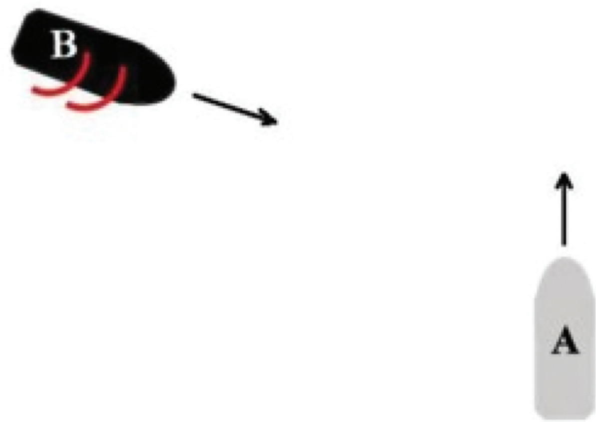


Figure 5. Diagram of the situation outlined in the example questions from SWOS regarding stand-on vs. give-way status.

On 3 August of 2020 the United States National Transportation Safety Board (NTSB) released a Marine Accident Report (National Transportation Safety Board 2020) regarding the USS Fitzgerald collision, which claimed the lives of three sailors and caused over $300 million in damages to the destroyer. The ACX Crystal sustained damage to its bow. The Fitzgerald was traveling south from Japan to the Philippines at 22.1 knots. The ACX Crystal was traveling east, northeast at 18.5 knots transiting form Nagoya to Tokyo Japan. The two ships were operating as power driving vessels and were approaching each other with a relative speed in excess of 30 knots at 0130 in the morning of 17 June 2017. By geometry, the two ships were in a crossing situation and the USS Fitzgerald was clearly the give-way vessel. However, the USS Fitzgerald did not give way. Neither ship attempted to make radio contact with each other. When the vessels were 1,000 m apart the ACX Crystal attempted to alter course to avoid collision. Approximately 20-s prior to impact the Officer of the Deck aboard the USS Fitzgerald attempted to make abrupt engine and heading changes to avoid collision. Their efforts were unable to prevent the mishap. The NTSB highlighted several safety concerns with the collision. However, it cited both vessels failure to follow required actions in accordance with COLREGS.

When applying our protocol against the USS Fitzgerald collision, it is important to analyze the encounter per the specification, which ultimately would show the validity of our protocol. Figure 6 recreates the specification outlined in Figure 2, highlighting the steps the decision engine would have taken had it been controlling in the USS Fitzgerald the night of the mishap.

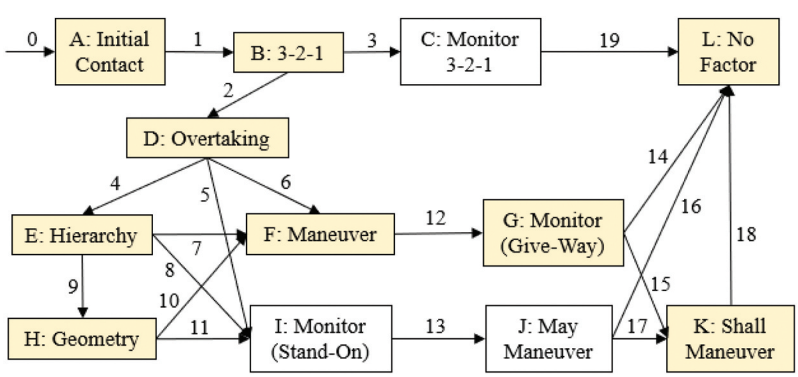


Figure 6. Follows the states the USS Fitzgerald would have followed to avoid the collision with the ACS crystal.

At 12 nm, the bridge crew aboard the USS Fitzgerald detected the ACS Crystal. This would have translated into State A in Figure 6. The bridge crew aboard the USS Fitzgerald neglected to take appropriate actions, this ultimately led to the collision. The decision engine would have determined that the ACS Crystal would have violated the 3-2-1 rule (State B). It would then have analyzed the encounter to determine if it was in an overtaking situation (State D). Next, it would analyze the encounter to see if there was a difference in the Hierarchy (State E). Finally, it would have determined that the USS Fitzgerald was the Give-Way vessel due to the geometry of the encounter (State H). The decision engine would then have maneuvered (State F) and monitored the ACS Crystal (State G) to ensure its critical area would not have been violated. At 5 nm, the bridge crew aboard the USS Fitzgerald should have taken immediate action to avoid a collision, the decision engine would have as it was in State K, shall maneuver. Ultimately, the two vessels would have safely departed the area and completed their voyage (State L).

6. Conclusion

To facilitate a USN vessel to operate autonomously (without a human in or on the loop) a clear definition of the requirements needs to be agreed upon prior to software development. This paper presented artifacts for a certification in support of an autonomous controller that is designed to complete a COLREGS-based collision avoidance task during a transoceanic voyage.

This paper was a first step toward developing a methodology for clearing autonomous behavior to complete the collision avoidance task. We defined the requirements normally reserved for a CO to enable collision avoidance when encountering a surface contact during a transoceanic voyage in accordance with COLREGS. These requirements were developed through coordination with senior leadership within the naval surface warfare community. Next, we developed a specification. We then systematically examined the specification in an effort to ensure it satisfies the requirements. Finally, we translated the analyzed specification into a protocol and evaluated it against 10 scenarios that are currently used during the qualification of OODs. The protocol can then be used by software designers when developing the decision engine of the USV. All of the artifacts developed in this paper can be used as certification evidence for autonomous behavior.

The logical next step is a limited M&S of the protocols/control laws to insure that the vehicle will function as intended. This will attempt to show the system will only display non-deterministic behavior while it is within the clearance envelope and would serve as a risk mitigation step prior to actual USV testing. Following M&S, a design of experiments for test and evaluation needs to be developed (test plan). Most conventional developmental test techniques are designed for a human to test an unproven system. In this case, test points will need to be developed that demonstrate in an operational relevant environment the test vehicle can produce results similar to the demonstrated behaviors in M&S. This is the test plan of the specification. Following vehicle test, a summary of the test results would be the final piece of data that certification officials would need to certify a machine to make decisions currently reserved for qualified CO.

This paper has presented top level evidence from requirements definition to protocol definition. Future work that focuses on each of the sub-tasks would be invaluable to certification officials. They could use this to define/refine an envelope by which to certify what a decision engine would not do. Future work that utilizes formal methods to verify the specification could also serve as certification evidence. Future work that were to concentrate on developing tools to complete the remaining steps of the proposed methodology are critical prior to an actual autonomous controller's development. Additionally, if future protocols could be developed the include emergency situations they may help future autonomous USVs avoid mishaps like the one between the USS McCain and the Alnic MC. Without a clear path, and mature clearance tools, certification of controllers to accomplish tasked currently reserves for a CO will continue to be limited in their scope and limited in their real-world application.

Disclosure statement

No potential conflict of interest was reported by the authors.

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