Analysis of Risks Arising from the Use of Autonomous Vessels

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Abstract

This paper focuses on the analysis of risks arising from the use of autonomous ships. The concept of autonomy is defined, different levels of autonomy are mentioned, and the differences between unmanned vessels and autonomous ships are well known. The transition to autonomous ships brings certain risks that need to be managed. Therefore, this paper analyses the risks associated with autonomous ships, which have received significant attention in recent years. An important aspect in considering risks is human error, which according to various studies is the most common cause of maritime accidents. However, autonomy also has the potential to create accidents, which manifest in five unacceptable hazards in the initial configuration of the ship. The main hazard human error, interaction with manned vessels and object detection, interaction with the physical environment, system failure, cyber-attacks, and equipment failure. The focus of the ship's work is to prevent and reduce the probability of critical events and their causes and maximize operational efficiency and performance.

Keywords: autonomy, autonomous system, risk, human error

1. Introduction

Digitization and technological advancement have accelerated the development and emergence of autonomous and remotely operated vessels in the maritime transportation sector. At the Autonomous Ship Technology Symposium 2021 conference, it was mentioned that worldwide, there are more than 1,000 maritime autonomous surface ships (MASS) operated by more than 53 organizations (Dougherty, 2021). This type of vessel consists of highly intelligent and adaptive functions, equipped with various external sensors and actuators for situational awareness, automated control, and adaptable maneuvering to achieve more efficient and sustainable operations.

However, there are many challenges in ensuring the safety and reliability of autonomous operation and navigation systems due to their complex, adaptive, and non-deterministic nature. The issue of a mixed navigational environment, where conventionally operated, remotely operated, and unmanned vessels interact within the same maritime area, can be considered one of the main obstacles to the adoption of autonomous ships. Vulnerabilities can be increased due to potential differences in vessel state awareness between autonomous operational systems and humans in such situations.

According to Komianos (2018), while there are benefits to MASS, they also come with various risks and uncertainties. Implementing autonomous navigation systems can introduce complexities and new hazards, as highlighted by Chae et al. (2020). Initial setup and construction of the Ship Control Center (SCC) and MASS require significant capital investment. The SCC serves as the third dimension of control for the ship and ports, but managing MASS in harbors poses significant challenges (Tam & Jones, 2018).

Van Hooydonk (2014) identified drawbacks of technology, noting that shore controllers in the SCC are responsible for handling multiple ships and assessing various situations at sea. Due to the absence of a crew, maintaining the moving parts of MASS becomes challenging during long voyages, and failures can lead to significant delays. The increase in autonomy levels can also amplify the cybersecurity threat to MASS (Tam & Jones, 2018).

Hackers (or pirates), as highlighted by Tam & Jones (2018), pose a risk of gaining control of the ship, enabling them to manipulate its course, seize valuable cargo, and potentially engage in illicit activities. These security breaches could result in pirates or terrorists using the ship for their own purposes, such as making ransom demands or carrying out acts of terrorism. Furthermore, they could threaten coastal states by blocking port entrances, causing groundings or collisions, transporting contraband items, or targeting military installations or assets (maintaining the names and years in the brackets).

2. Autonomus ships

Autonomous ships and unmanned vessels represent newer advancements in maritime technology. However, automated subsystems have been implemented on ships for several years, making ship operations more efficient and drastically reducing crew size (Vartdal et al., 2018). Therefore, when the term “autonomous ship” is used, it describes the continuation of ongoing automation development. However, important functions such as navigation and complex decision-making are still performed or supervised by the crew present on board (Utne et al., 2018). In the context of autonomous ships, it is important to define the concept of autonomy, different levels of autonomy, and the distinction between unmanned vessels and autonomous ships.

2.1. Definitions of basic terms

Autonomy can be defined differently depending on the specific application. In engineering terms, it can be defined as “the ability of an engineering system to make its own decisions about its actions while performing various tasks, without the need for the involvement of an exogenous system or operator” (Vagia et al., 2016, p. 191).

An autonomous system can also be described as a system that can perform and integrate sensing, perception, analysis, communication, planning, decision-making, and action without the intervention of a human operator (Huang, 2004, p. 15). For a ship, this means that the system can make decisions without input from the crew or other supervisors. In other words, the ship can be fully autonomous and still have a crew present on board, but they don’t need to perform any actions.

It is important to note that an autonomous system is not equivalent to an unmanned system. These two terms can be mistakenly used as synonyms because the concept of an unmanned system is closely associated with the public perception of autonomy. An unmanned system is defined as a physical system with propulsion in which no human operator is present (Huang, 2004, p. 28). Therefore, the system doesn’t necessarily have to be autonomous but can be remotely controlled by an operator at a land-based location.

The Norwegian Forum for Autonomous Ships (NFAS, 2017) provides a similar definition for unmanned vessels. However, it states that passengers or crew may still be present on the ship. If their purpose is to perform actions unrelated to the operation of the vessel, the vessel is still considered unmanned. An example could be the presence of service personnel for passengers.

Autonomous systems are often described by their level of autonomy (LOA) (Huang, 2004). LOA is defined as “a set of metrics that describe detailed aspects of the autonomous system and its operation” (Utne et al., 2017, p. 2). Examples of these metrics can include operator dependence, communication, human-machine interface, etc.

However, different metrics are considered in different taxonomies. Due to the variety of definitions, it is useful to select a taxonomy that suits the specific application. Utne et al. (2017) presented a taxonomy for LOA in autonomous maritime systems. The measurement data used to define different LOAs in this taxonomy are operator dependence, communication structure, human-machine interface, dynamic or networked risk management systems, intelligence, planning functions, and mission complexity. Table 1 illustrates the LOAs according to the mentioned authors.

Table 1. LOA, according to Utne et. al. (2017).

Level	Types of operations
1	Automatic operation (remote control)
2	Consensual control
3	Semi-autonomous operation or exception-based control
4	High autonomy during operation

Source: Utne et. sur. (2017)

As highlighted by NFAS (2017), operator dependence and the level of autonomy are interconnected. Higher autonomy implies a lower level of operator dependence, while lower autonomy entails a higher degree of operator dependence. However, it is important to distinguish between presence and independence. A remotely operated vessel is entirely dependent on the crew, but the crew does not necessarily need to be present on the vessel. A fully autonomous vessel can perform the entire operational cycle without human intervention while still having a few crew members on board. This distinction can be significant in terms of risk acceptance and risk allocation.

2.2. Advantages and disadvantages of autonomous ships

Numerous anticipated advantages of MASS, compared to conventional maritime systems, include increased safety and security (Komianos, 2018), improved human resource management (Burmeister et al., 2014), reduced operational costs (Kretschmann et al., 2017), and decreased air pollution (Burmeister et al., 2014). Furthermore, Porathe et al. (2014) present four reasons why autonomous shipping traffic is considered a viable choice: cost reduction in transportation, the need for better working conditions onboard for the crew and to prevent a future shortage of seafarers, the global requirement to reduce emissions, and the desire to enhance maritime safety.

Despite the aforementioned advantages, MASS still faces several challenges in its development and barriers to wider implementation, including crew unemployment (Komianos, 2018), national and international regulatory obstacles (Komianos, 2018), extensive costs for personnel training (Levander, 2017), significant expenses for developing new infrastructure (Komianos, 2018), maintenance costs (Porathe et al., 2018), and technical challenges in ship and operational system design (Höyhtyä et al., 2017).

The drawbacks of MASS also include vulnerabilities and the risk of computer and system hacking or hijacking, high initial capital investments, unforeseen security risks, the risk of seafarer unemployment in the maritime industry, and the risk of collision with objects at sea. Since risk related to autonomous vessels is the focus of this study, specific potential risks will be described in more detail in the following chapter.

3. Risk analysis related to autonomous ships

Risk can be defined as the “effect of uncertainty on objectives” (ISO 31000, 2018). The effect can be either positive or negative. Furthermore, the standard states that risk is often expressed in terms of the consequences of an event and the associated likelihood of its occurrence. Risk analysis is the process of understanding the nature of risk and determining the level of risk (ISO, 2009).

By conducting a hazard review, sources of potential harm to the system can be identified, providing input data for risk analysis. The traditional view of risk assessment is defined as the product of consequence and likelihood (Rausand, 2013). For autonomous ships, traditional risk analysis will attempt to identify the most probable risks.

Risk related to autonomous ships has received significant attention in recent years. It is an important aspect of autonomous operations and one that must be thoroughly investigated before autonomous ships can be deployed. One hypothesis is that autonomous systems have the potential to be safer compared to human-operated systems (Vartdal et al., 2018). Many attribute this assumption to the elimination of the human element and, therefore, the elimination of human error.

However, the transition towards partially or fully autonomous ships will not eliminate all human errors. Mistakes made by humans can still occur in relation to autonomous ships, leading to hazardous events and accidents. Possible automation errors have been described by Parasuraman and Riley (1997).

The authors emphasize that automation can be seen as substituting human operators with automated systems, making the system less sensitive to operator errors and more sensitive to design errors. Therefore, human errors are still an important aspect to consider when assessing the risk for autonomous ships, even if humans are not directly involved in the operation.

An autonomous system is typically designed for a specific type of operation, with defined boundaries and performance limitations. Within these constraints, efforts are made to design a system that can handle all relevant challenges. However, there is still a probability that an autonomous system will be exposed to conditions that require operating outside the defined performance boundaries. The risks posed by such situations must be considered and included in the Risk Assessment and Control (RAC) for autonomous systems, according to ISO 21448 (2019).

MASS (Maritime Autonomous Surface Ships) can significantly reduce accidents caused by human error; however, they cannot eliminate them. Additionally, since MASS consists of several interconnected systems, some of which are based on newly proposed or advanced technologies, there is still limited evidence to prove that they are risk-free (Komianos, 2018).

Indeed, it has been argued that MASS will introduce new types of risks, which can be inferred based on accidents involving autonomous vehicles in road traffic that have occurred in recent years. Rødseth and Burmeister (2015) identify five unacceptable hazards in the initial configuration of a ship:

1. Interaction with other ships
2. Errors in detection and classification of small and medium-sized objects are critical.
3. Failure to detect objects, especially in low visibility conditions.
4. Failure of the propulsion system
5. Adverse weather conditions can make safe manoeuvring of the ship challenging.

Based on a review of the literature, the main categories of hazards in MASS operations have been identified and presented in Table 2.

Table 2. Risks of MASS Operations

Risk	Risk description
Human error	Although MASS will replace most human tasks, there are still risks associated with, for example, design and remote operations, as well as coding and programming of the integrated system.
Interaction with manned vessels and object detection	MASS can cause collisions due to poor interaction with manned vessels in dense traffic or other objects
Interaction with the physical environment	As the development of MASS is still in its early stages, they are highly sensitive to certain external factors such as winter navigation in icy areas and severe weather conditions.
System failure	Without humans on board, there could be issues when communication links fail or systems behave unpredictably.
Cyber-attacks	Given the high reliance on the internet, operational systems and communications are vulnerable to cyber-attacks.
Equipment failure	There can be some serious consequences that cannot be effectively controlled, especially in emergency situations, such as fires, sensor failures, loss of control, IT equipment malfunctions, and so on.

Source: Chang et al., 2020.

3.1. Human error

While MASS will help reduce human error, Ahvenjärvi (2016) argues that human error or mismatches between humans and tasks cannot be eliminated because the human element is still involved in design and remote control, and human error could shift from the incident phase to the pre-voyage phase due to the extensive coding and programming involved (Burmeister et al., 2014).

Interconnected systems cannot be fully tested or reviewed until actual ship operations. Due to the large number of software packages and complex coding involved, there is a probability that software engineers may make mistakes during design or programming phases, thereby leaving software errors - referred to as bugs - in the system (Bolbot et al., 2018).

Furthermore, operators in the coastal control center face the same or even new risks of human error because they may not be fully aware of the actual on-site conditions. Autonomous ships also require periodic maintenance, either through remote means or physical contact. In both methods, some human errors will be involved, and these should be considered as hazards in MASS operations (Rødseth and Burmeister, 2015).

3.2. Interaction with manned vessels and object detection

Previous research has focused on the interaction between MASS and crewed vessels in relation to object detection (MUNIN, 2016; Ahvenjärvi, 2016; Porathe and Rødseth, 2019; Ramos et al., 2019). While Komianos (2018) stated that MASS can significantly reduce the risk of collisions and be in compliance with COLREGs, they also argue that MASS does not meet Rule 5 of the COLREGs, which requires proper visual and auditory observation on every vessel to assess the situation and the risk of collision.

MUNIN (2016) also identifies several relevant hazards in MASS operations. Furthermore, many studies have focused on collision avoidance and navigation systems. For example, Perera et al. (2018) proposes a collision avoidance algorithm for ships based on fuzzy logic to support decision-making systems in autonomous vessels.

3.3. Interaction with the physical environment

This category of hazards can include adverse weather conditions, poor visibility, icy areas, ice navigation, and strong tidal systems (Banda et al., 2015). Winter navigation in icy regions for MASS would likely involve the assistance of icebreakers, which poses a risk due to the proximity of the vessels (Banda et al., 2015). Severe weather conditions may require manoeuvring at a reduced speed to avoid structural damage to the vessel. All these types of manoeuvres have traditionally been performed through manual control (Wróbel et al., 2017).

3.4. System Failure

Since autonomous vessels heavily rely on information technology (IT), one might wonder if these systems are as capable as human beings. Autonomous systems are based on machine learning, which requires extensive training to cover most potential real-life situations. However, it cannot cover every situation, and exceptional situations are associated with the most severe and dangerous system failures because the behaviour of the system is unpredictable (Ahvenjärvi, 2016).

Furthermore, the design of the system and software should have a certain level of tolerance when unexpected failures occur. Quantifying this tolerance to ensure smooth system operation while maintaining travel safety is not trivial. It is argued that communication link failures will be new hazards introduced by the operation of MASS (Burmeister et al., 2014; Wróbel et al., 2016; Thieme et al., 2018).

3.5. Cyber-attacks

Due to the dependence of autonomous vessels on ICT (Information and Communication Technology), cyber-attacks are considered a major type of hazard in MASS operations (Hogg and Ghosh, 2016; Ghaderi, 2018). Many cyber-attacks have been reported in recent years. For this reason, Hand (2016) states that autonomous vessels will not become a mainstream reality in the next few years due to unresolved cybersecurity issues in the technology.

3.6. Equipment failure

Equipment failure during navigation is another major category of hazards. Since there is no crew on an autonomous vessel, in case of equipment failure, the vessel needs to be immobilized and wait for a repair team to arrive. MUNIN (2016) identified six relevant hazards, including: loss of the vessel or systems in a fire, sensor failure - loss of control, temporary loss of electrical power (e.g., due to a power outage) - loss of control, failure of the IT infrastructure of the vessel (e.g., due to a fire in the server room) - no control, complete loss of propulsion, and complete loss of steering function.

Furthermore, Wróbel et al. (2017) identify all possible scenarios for preventing or managing fires on MASS and state that a fire incident is an extremely challenging issue in MASS operations. Wróbel et al. (2020) also argue that sensor failures will have significant consequences, leading to unsafe and inefficient MASS operations.

4. Risk management for autonomous ships

During the operation of a ship, the focus is on preventing and reducing the likelihood of critical events and their causes, as well as maximizing operational efficiency and performance. Daily operations typically prioritize production efficiency and maintenance activities to prevent disruptions that may occur due to failures of critical technical equipment. In the event of a critical event, an emergency response is activated and implemented to prevent and mitigate the likelihood of serious consequences.

In the industry, most of the current risk analysis methods are used during the system design phase rather than as tools for online risk control during operation, although dynamic approaches to risk analysis have been developed in recent years. Dynamic risk assessment can be defined as a method that updates the estimated risk of process deterioration in accordance with the performance of the management system, safety barriers, inspection and maintenance activities, human factors, and procedures (Khan et al., 2016).

Generally, increased sensor data availability and improved computational capabilities provide enhanced opportunities for dynamic risk assessments (Zio, 2018). Zheng and Zio (2018) present a dynamic risk assessment method that combines a hierarchical Bayesian model with simulations and event trees, enabling risk assessment based on data collection during operation.

This is more in line with the concept of online risk management, which relies on data from various sources such as historical data, sensors and measurements, and experiential data (Vinnem et al., 2015). However, none of these approaches, although they could be useful, are specifically developed for supervisory risk control in general, nor for autonomous ships.

Autonomous systems heavily rely on software, which can be highly complex for advanced systems. Physical separation and segregation of components, such as redundancy in ship machinery systems, can be overridden by software and control systems that operate across physical boundaries and separate systems. Several current risk analysis methods focus on decomposing systems into components, which is challenging with complex systems (Rokseth et al., 2017).

According to Rasmussen (1997), risk management should be considered a control function implemented to maintain the system's processes within the framework of safe operation. Building upon these ideas, Leveson (2011) proposed a theoretical system analysis called Systems Theoretic Process Analysis (STPA), in which safety is controlled by imposing constraints on the system's behavior, and accidents occur due to inadequate control or inadequate implementation of safety constraints. STPA has been used in several applications (Abrecht and Leveson, 2016), including the hazard identification of autonomous ships (Wrobel et al., 2020).

To establish supervisory risk control as part of the intelligence of the control system, it is necessary to address the following aspects (Wrobel et al., 2020):

1. It is necessary to know which hazardous events need to be prevented and their causal factors in the system's operation.
2. It must be possible to observe and verify the presence of causal factors during operation.
3. It is important to know which combinations of causal factors can lead to a dangerous or critical event. Therefore, it is necessary to structure the causal factors and establish the foundations for collecting and evaluating real-time information and observations related to causal factors. Such information

can be of a qualitative, semi-quantitative, or quantitative nature and must be collected during operation or from databases with historical and/or experiential data.

4. It is essential to determine the impact of different combinations of causal factors on the system's risk level. If there is a high risk of violating safety constraints, the system itself (or the operator when in a low level of automation) requires early warnings about a potential hazardous event.

5. Summary

The aim of this study was to thoroughly explore existing literature and previous research and define and explain potential risks associated with autonomous ships. There is an increasing international interest in autonomous and unmanned vessels. Autonomy for a ship means that the system can make decisions without input from the crew or other supervisors. In other words, the ship can be fully autonomous while still having a crew present on board, but they do not have to perform any actions. One of the main arguments for the introduction of autonomous ships is that it will reduce risks associated with ships in general. Furthermore, literature related to autonomous ships often presents the hypothesis of increased safety, as various studies have shown that human error is the most common cause of maritime accidents.

However, autonomy has the potential to create accidents, for example, in the interaction with manned vessels, detection of unknown objects, interaction with the physical environment, system malfunctions, cyber-attacks, and equipment failures. Additionally, autonomous ships employ a new type of technology with limited experience, and it is known that people are more prone to be sceptical towards new technology. Therefore, it is not sufficient to conclude that autonomous ships should be at least as safe as crewed ships. More research is needed to determine how to formulate risk acceptance criteria for autonomous ships. Thus, it can be concluded that there is a risk that ship autonomy will create new types of accidents, partly due to accidents previously prevented by the human crew and partly due to the introduction of new technology and associated new types of accidents.

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