An initial hierarchical systems structure for systemic hazard analysis of autonomous ships

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Abstract

Safety assurance of autonomous ships is one of the major long-term challenges faced by the maritime world. Applying systemic hazard analysis methods at this early stage will guide the design and operation of safe autonomous ships. This paper proposes an initial hierarchical ship systems structure that could be the basis for a systemic hazard analysis of autonomous ship systems and operations. The approach is based on the systems theory and the principle of hierarchy and has been developed via the combination of models used in past research projects and requirements of the STCW convention. For enabling the operation of autonomous ships, the ship crew functions are either replaced by ship technical systems or assigned to the Shore-Based Control Centre (SCC).

Keywords: Autonomous ship systems; Autonomous Navigation System; Situation awareness, systems theory, system of systems, system function, systemic hazard analysis

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1. Introduction

Autonomous ships aim at improving the safety and efficiency of the maritime operations while also preventing the exposure of the ship crew to on-board hazards (Wróbel et al., 2017). The specification of requirements and procedures for safety assurance in autonomous ships is complex and risks must be accounted for at early design stage. This challenge is also reflected in International Maritime Organization (IMO) who require that future Maritime Autonomous Surface Ships (MASS) should operate at an equivalent level of safety (i.e. be ‘‘at least as safe as’’) conventional vessels (IMO, 2018).

Autonomous ships are expected to be highly complex with software-intensive interacting systems, that require the application of systemic hazard analysis methods that capture hazardous systems interactions (Basnet et.al , 2019). These methods assume that the ship is a system comprising of sub-systems that interact with each other (Leveson, 2011; Valdez Banda et al., 2019).To conduct this hazard analysis, a hierarchical systems description of the autonomous ship is necessary.

In an attempt to open the way toward such developments, this paper reviews results of two of the major research projects in the field of autonomous ship operations namely MUNIN (Maritime Unmanned Navigation through Intelligence in Networks) and AAWA (Advanced Autonomous Waterborne Applications). Consequently, based on lessons learnt, systems theory and STCW functional requirements it suggests an initial hierarchical systems structure for the risk assessment of an autonomous ship at a level of autonomy AL4. In this sense, it contributes toward developing a new framework for hazard analysis beyond classical methods such as the IMO classic Fault Tree Analysis currently used for the development of rules and regulations within the context of Formal Safety Assessment.

2. Necessity of systemic hazard analysis for autonomous ship systems

2.1. Systemic hazard analysis

Systems theory was introduced in 1930’s to cope with the complexity of the systems starting to be built in different domains at that time (Ackoff, 1971; Leveson, 2011). The approach defines complex systems as systems of systems, where every system has a function (or purpose), elements (or components), and interconnections (Arnold & Wade, 2015). According to the hierarchy principle in the systems theory, each system at its level could be a sub-system at a higher level and a set of sub-systems at a lower level (Adams, 2011). The sub-systems interact and work together to perform their main system function and cannot be decomposed into independent physical components (Adams, 2011).

Systems thinking applied to safety revealed that safety is a system property that is affected by the interactions of its components (Hollnagel, 2004; Leveson, 2004). The hazards emerging from these interactions lead to unexpected accidents that were not considered in the traditional risk assessments (Hollnagel, 2004; Leveson, 2004). The systemic hazard analysis methods came as a response to the limitations of the traditional hazard analysis and risk assessment techniques in identifying the hazards associated with the interactions (Aven, 2016; Leveson, 2011).

Numerous traditional linear (cause-effect) hazard analysis methods have been developed and applied to different systems that humans had designed. The most widely applied are Fault Tree Analysis, Event Tree Analysis and HAZOP, which were developed many decades ago. These methods were successful in hazard analysis and risk assessment of relatively simple technical systems (Altabbakh, AlKazimi, Murray, & Grantham, 2014). However, the same techniques applied to the modern complex sociotechnical systems have shown very less effectiveness as they focus only on the components’ failure in a linear causal analysis, which cannot detect the non-linearity in today’s complex systems (Aven, 2016). In addition, these methods rely on historical data of the system, which puts the risk decisions under an increased uncertainty about the knowledge of the emerging technologies that do not have historical data (Aven, 2016; SRA, 2015). Therefore, modern complex systems need a systemic approach for hazard analysis and risk assessment in order to consider both the hazards related to components failures and the new hazards emerging with components interactions.

The most popular system theoretic hazard analysis methods as employed in the literature are STPA (System Theoretic Process Analysis) and FRAM (Functional Resonance Analysis Method). FRAM and STPA applied to complex modern systems have been successful in coping with complexity of the modern systems and capturing the hazards associated with their components interactions (Patriarca et al., 2017; Valdez Banda and Goerlandt, 2018).

2.2. Autonomous ships as complex systems

Autonomous ships are systems with embedded software and high functional dependencies and integration. This makes them complex systems, where a software may control separated subsystems, and depend on other systems operating across the physical boundaries (Utne et al., 2017)

As explained in the previous section, systemic hazard analysis could then be applied to autonomous ships as complex systems and prevent the hazardous scenarios related to both their components and interactions. Applying these modern techniques at the systems development and design stages could improve safety (Fleming et. al, 2013; Ishimatsu et al., 2014; Valdez Banda et al., 2019). The results of the systemic hazard analysis of autonomous ships will then contribute to their safe deployment. The representation of the autonomous ship as a system of systems working together to perform the autonomous ship function would allow the systemic hazard analysis at this early stage of its development.

2.3. Autonomous ship functions and the role of humans in the loop

Fully autonomous ships are supposed to perform all previous functions of the technical systems and hence compensate the human absence. In addition, autonomous ships with their different levels of autonomy should be at least as safe as conventional ships as prescribed by the IMO (IMO, 2018).

The lack of experience in designing and operating autonomous ships justifies the need to employ the experience gained in designing and operating traditional ships. Besides, "*the autonomous ships will most likely remain ships*" and will navigate and behave like conventional ships (Wróbel and Montewka, 2019), which justifies more the need to consider the experience gained in conventional ship operations. Furthermore, the development of the autonomous systems started already by replacing the human capabilities when developers identified the required technologies to replace the human senses during navigation. Some of the suggested technologies were for example cameras and microphone arrays to compensate the human visual and hearing capabilities respectively.

The IMO standards have been continuously amended to hold the experience gained through the design and operation of conventional ships. The International Convention on Standards of Training, Certification and Watch-keeping for Seafarers (STCW) is one of the main IMO legal instruments that has continuously accommodated the updates in the functions of the ship crew based on the experience gained in the ship operation.

3. Review of autonomous ship technical concepts

3.1. MUNIN

The European project "Maritime Unmanned Navigation through Intelligence in Networks" (MUNIN) was the first research project dedicated on developing the technical concept of an autonomous cargo ship. It studied the feasibility and safe implementation of the concept with tests on an existing dry bulk carrier (MUNIN, 2016). The concept suggested that for a simple first application and with the limitation of the connectivity bandwidth, the autonomous ship should be able to sail in open seas most of the time under full autonomy mode (MUNIN, 2015). The definition of the concept has been supported by different IMO conventions including the STCW convention. As shown in Figure 1, five new systems namely : (a) an Advanced Sensor Module (ASM), (b) an Autonomous Navigation System (ANS), (c) an Autonomous Engine Monitoring and Control System (AEMCS), (d) an Autonomous Ship Controller (ASC) and (e) a Shore Control Centre (SCC) were suggested to be essential for the safe operation of autonomous ships in deep sea. In addition, the two old Bridge Automation System and Engine Automation System were existing in the use case ship. The port approaches and special manoeuvres were excluded from the autonomous operation in order to reduce complexity for the early applications.

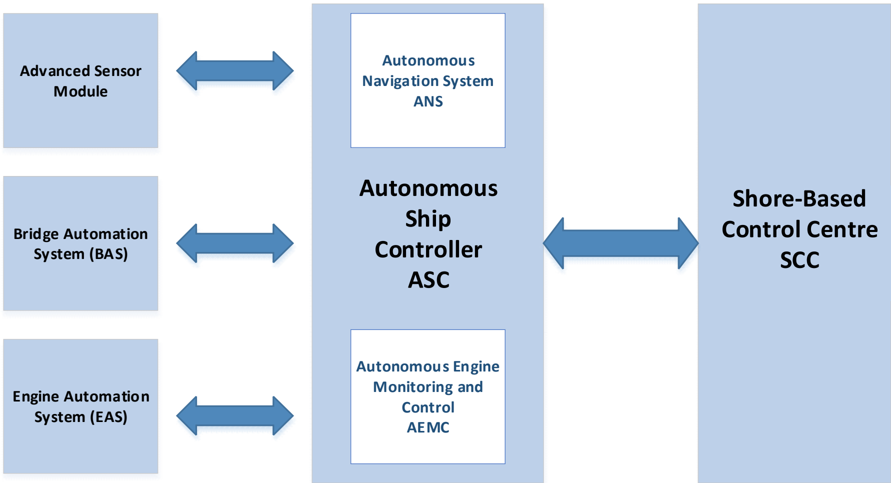

Figure 1: Overview of the autonomous ship modules (MUNIN, 2013)

The advanced sensor module was created in order to complement the absence of humans on-board in performing the lookout function (C. Bruhn, Burmeister, T. Long, & A. Moræus, 2014). The ANS function is “navigating the unmanned autonomous ship safely from boarding point to boarding point (MUNIN, 2015). Under this main function, the ANS should conduct weather routing, determine ship dynamics, control buoyancy and stability, avoid collision and manage alarm and emergencies (MUNIN, 2015). The AEMCS monitors and controls all the engine room systems. The ASC assesses the data from different ship sensors and from the shore and controls the autonomous ship operation. The SCC conducts the voyage planning with the administrative tasks, manages the distress communication and monitors the overall ship operation to manage the complex emergencies. The BAS and the EAS would have to perform the same functionalities in the existent ship; the BAS receives navigation alerts through NAVTEX, keeps log book and follows track with autopilot, while the EAS provides engine data.

The project results recognised that satellite bandwidth and communication quality are great challenges to a full-time remote operation and argued that the ship should be able to operate autonomously most of the time. The same challenge was also recognized by AAWA project late and a dynamic level of autonomy during the voyage was suggested (AAWA, 2016). Thus, the SCC will serve as back up with a remote control in special manoeuvres and critical situations (Rødseth et al., 2013). One more backup system is the “fail to safe” situation, when both the autonomous ship controller and the SCC fail to control the ship or execute the adequate tasks. In this emergency case, the ship should follow a predefined set of actions or route that takes it to a safe situation without considering its initial plan execution.

3.2. AAWA

In AAWA project, the leading Rolls Royce marine group with other partners from the maritime industry and academia sought for applicable technologies with site tests in a defined testbed in Finland. The focus was on autonomous navigation systems. The project defined the autonomous navigation architecture as a set of modules that could together enable the safe navigation of the autonomous ship from port A to port B (AAWA, 2016). Figure 2 illustrates four modules of the ANS (Ship State Definition, Route Planning, Collision Avoidance, Situational Awareness and Dynamic Positioning).

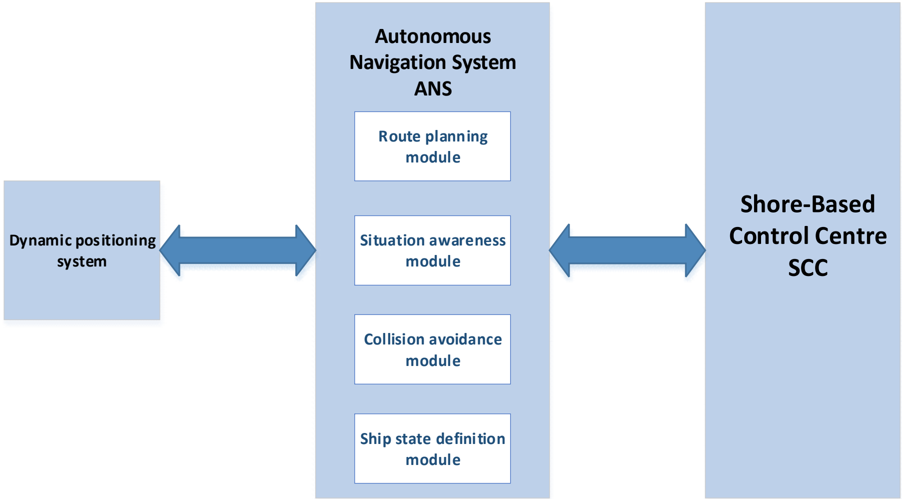

Figure 2: Autonomous Navigation System (ANS) architecture, (AAWA, 2016)

The Ship State Definition module also known as "Virtual Captain" is the highest in the hierarchy of the ANS architecture and it receives and processes information from the other modules in order to make decisions based on a full awareness of the ship situation.

The Route planning module on the other hand is charged of delivering the route plan based on a software that considers information provided in the voyage plan received from the shore. It generates the route on a static mode, while the Collision Avoidance module generates the dynamic path to avoid collision during the plan execution.

The Situation Awareness module fuses the data from its different sensor types and extracts the adequate information to map the ship surroundings. The surroundings map is necessary for the Collision Avoidance module. The project suggested that the currently available sensors technologies can provide the lookout required for a safe navigation if the adequate sensor fusion combinations for each situation are determined (AAWA, 2016). The identified set of sensors having the potential to replace the human lookout were HD cameras, IR cameras, Radar, short range Radar, Lidar (Light Detection and Ranging) and microphones.

The Dynamic Positioning (DP) module controls the propulsion system in order to track a defined route or keep a defined position. Furthermore, the DP module monitors the ship motion and manoeuvrability constraints in order to act accordingly.

4. Combining MUNIN and AAWA concepts with reference from STCW functions

In order to conduct future systemic analysis that are aligned with the development trends, the contribution of MUNIN and AAWA projects should be considered in describing the hierarchical ship systems structure. For this reason in this paper, the combination of the technical concepts in MUNIN and AAWA is considered as the starting point to develop the autonomous ship systems structure. A cross verification with the systems identified based on the seafarers' functions in STCW convention is then conducted to add the missing functions in the structure or merge the systems with same functions. First, the general concept of MUNIN application is employed because it was not restricted to the ANS and it gave the context of operation, which could be considered as a level of autonomy AL4 in Lloyds Register's definition. Then, as AAWA project was focused mainly on the ANS and the research was conducted more recently, and gave more details about the system's technologies to be employed, it was combined with the general concept of MUNIN.

Table 1 illustrates the transition from the different functions of the STCW convention to the correspondent autonomous ship systems that would perform these functions. As each system should have a purpose and a set of sub-systems, each function in the STCW convention at the operational level could be assigned as the purpose of a system in the autonomous ship.

Table 1: STCW functions and the correspondent autonomous ship systems

STCW functions			Autonomous ship systems			
			MUNIN	**AAWA**	**Other ship systems/sub-systems**	
Deck department	**Navigation**	Plan route		Route planning system (Sub)		**ANS**
		Determine position speed and heading			Positioning, Navigation and Timing System	
		Reporting			Communication and reporting system	
		Track route		DP system (Sub)		
		Interpret and apply weather information			Weather monitoring and interpretation system	
		Avoid collisions (consider COLREGs lights and sound signals)		Collision avoidance system (Sub)		
		Maintain proper lookout		Navigational situation awareness system (Sub)		
		Respond to emergencies	SCC			
		Respond to distress signals	SCC			
		Maneuvering		DP system (Sub)		
		Anchoring and mooring			**Anchoring and Mooring system**	
	Cargo handling and stowage	Loading and stowage			**Cargo handling and monitoring system**	
		Unloading				
		Care during the voyage				
	Controlling the operation of the ship and care for persons on board	Compliance with pollution prevention	SCC			
		Ship stability (Trim, buoyancy, watertight integrity)			**Ship stability and integrity system**	
		Fire prevention, control and fighting				
		Life-saving appliances operation	Not applicable to Cargo ships			
		Medical aids application	Not applicable to Cargo ships			
		Compliance with legislation	SCC			
Machinery department	**Marine engineering**	Use hand tools, electrical and electronic measurement and test equipment for fault finding, maintenance and repair operations			**Maintenance planning system**	
		Monitoring of engineering equipment and systems	**AEMC system**			
		Apply safety and emergency procedures for all systems	**AEMC system**			
		Operate main and auxiliary machinery	**AEMC system**		Propulsion, Steering and auxiliary (Sub)	
		Operate pumping systems (bilge, ballast..)	**AEMC system**			
	Electrical, electronic and control engineering	Operate alternators, generators and control systems	**AEMC system**		Power generation and distribution system (Sub)	
	Maintenance and repair	Maintain marine engineering systems including control systems			**Maintenance planning system**	
	Controlling the operation of the ship and care for persons on board	Assigned under deck department				

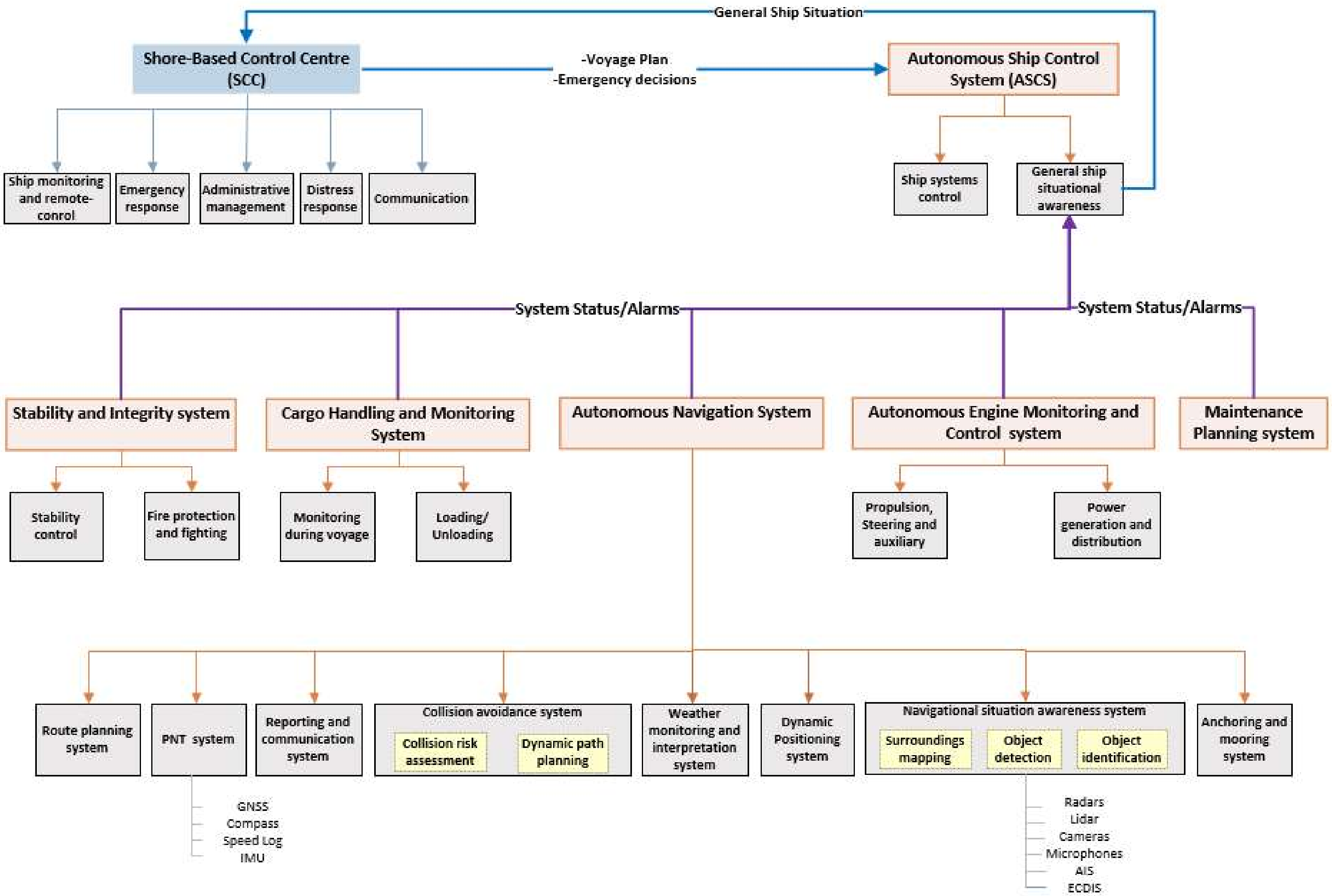

Figure 3: The proposed hierarchical systems structure of the autonomous cargo ship

5. Proposed structure

Figure 3 shows the proposed hierarchical systems structure of the autonomous cargo ship. It is obtained from the analysis described in the previous sections with technical information provided by the mentioned research projects. However, the structure is an initial suggestion of the functional boundaries of the autonomous ship systems and could be subject of further investigation in future work. More details under each function will vary by cargo type, especially for the cargo handling and monitoring system. In addition, autonomous ships other than cargo ships could have additional systems that perform other functions depending on the type of the vessel.

In this structure, each orange box represents one of the autonomous ship systems, the smaller grey boxes are their respective sub-systems. The blue box in the figure represents the SCC with its sub-systems under it with grey boxes. The name of each system refers to the function it performs as specified in the Table 1.

The structure presents the ship systems until two levels of hierarchy: systems and their sub-systems. Only the collision avoidance and the navigational awareness sub-systems have been further detailed into a third level of the hierarchy. Their respective sub-systems were added in the structure in yellow boxes and with the name referring to their functions as suggested in AAWA description of the ANS. Under the PNT and the navigational situation awareness systems, the components as suggested in MUNIN and AAWA were added in text without boxes.

The Autonomous Ship Control System (ASCS) is placed on top of the other systems in the figure only due to its control over the other systems, without any link to the principle of hierarchy in the systems theory. The ASCS is the “virtual captain” that assesses the general ship situation and controls all ship systems.

The ANS sub-systems are described in the next sections.

5.1. Route planning system

This system generates the route plan based on the information in the voyage plan. The voyage plan is delivered by the SCC. The route plan includes the way points, the speed and the heading from point to point.

5.2. Positioning, Navigation and Timing (PNT) system

This system will provide PNT information that will be distributed to other ship systems for different purposes. It will employ the technologies of the Global Navigation Satellite Systems (GNSS) receivers with satellite-based augmentation systems for better accuracy and integrity (Cueto-Felgueroso, 2018; MUNIN, 2015). Other navigation sensors such as the speed log, the Compass and the Inertial Measurement Unit (IMU) could provide the PNT information for redundancy (MUNIN, 2015).

5.3. Reporting and communication system

This system will be responsible for the automatic reporting to the shore and the Automatic Identification System (AIS). It will also conduct simple automatic communications with the ships in a collision avoidance condition. The complex communications and the distress communications will be a responsibility of the SCC.

5.4. Dynamic Positioning (DP) system

Dynamic Positioning system was suggested by Rolls Royce in AAWA project in order to steer the ship with more accuracy with the track mode having control of the ship propulsion and steering systems. The advanced DP system suggested by Rolls Royce will also have better manoeuvrability in addition to the ability of keeping a fixed position even under rough weather (AAWA, 2016). The DP system function in the proposed structure combines the “route tracking” and “manoeuvring” from Table 1.

5.5. Weather monitoring and interpretation system

This system collects the weather information from the associated shipborne sub-systems and the received weather forecast and safety warnings from the shore. It interprets this information to determine their effect on the other ship systems performance, such us visibility for the navigational situational awareness system.

5.6. Collision avoidance system

The collision avoidance system should avoid collisions in different encounter situations with conventional, remote-operated or autonomous ships. It should act according to COLREGs convention; the rule of the road in maritime traffic (AAWA, 2016). It should assess the risk of collision with the identified targets and generate a collision avoidance path with respect to COLREGs (AAWA, 2016; Perera et al., 2015; Varas et al., 2017; Lyu & Yin, 2019). It includes then two sub-systems in Figure 3 with these functions.

5.7. Navigational situation awareness system

The navigational situational awareness system merges the raw data from different sensors' readings including the traditional navigation equipment such as Radar and AIS, and the advanced sensors designed for the autonomous navigation such as infrared cameras or Lidars. As a sub-system of the ANS, it provides the situation awareness of the ship vicinity for the navigational purpose. This system will conduct the surroundings mapping to create a representation of the ship vicinity (AAWA, 2016). In addition, it should detect and identify the objects in the ship vicinity to compensate the absence of humans on board for the lookout function (AAWA, 2016). The surroundings mapping, object detection and object identification could be sub-systems of the navigational situation awareness system. The set of the components technologies under this system was proposed by AAWA project.

5.8. Anchoring and Mooring system

This system would conduct special functions of anchoring and mooring. Depending on the operational conditions, the system could be also operated by the SCC.

6. Discussion

The proposed hierarchical systems structure has included the functions of the autonomous ship under various systems that work together to steer the autonomous ship between ports.

The analysis presented the development trends in this research field as it included the ANS proposed by a more recent project than MUNIN. The route planning system in the ANS is more comprehensive than the weather routing proposed in MUNIN because it will generate a route that considers not only the weather conditions as a constraint but also other voyage plan data. Moreover, with the DP having the tracking and manoeuvring functions, it could maintain the ship position in extreme emergencies and avoid bad consequences (AAWA, 2016). This could be one scenario of the fail to safe mode, when the ship is out of control.

The analysis has also considered the experience gained in conventional ships operation by including the functions prescribed in the STCW convention. The same convention was also one important standard that helped to develop the first technical concept in MUNIN project.

The proposed structure in this paper considers the functional characteristic of each system, which means that every system and sub-system was given a function, rather than focusing on the physical boundaries of the systems. In MUNIN, the autonomous ship description was a mixture of the functions and the physical boundaries of the systems as the researchers were testing the feasibility of the concept on an existing conventional ship. The Bridge Automation for example was considered as a system while it was a mixture of components belonging to different systems. However, focusing on the physical boundaries when describing the autonomous ship systems that are under development could limit the early assessment of the safety of these systems.

The proposed structure suggests that the situational awareness module in AAWA could be called a navigational situation awareness as it ensures the awareness of the ship surroundings for the navigation. The situation awareness in its extended definition is not limited to knowing what is going around (Endsley, 2019). It should also include the awareness of the status of the ship stability, machinery, cargo and other systems that could affect the ship predefined route plan or take it into an emergency (Queensland Government, 2016). This was the function of the ship-state definition module in AAWA and of the ASCS in MUNIN. Therefore, the same function could be assigned to a sub-system (ASCS). It will receive the status and alarms data from each system and process it to provide concise situational awareness data for the ASCS decision-making. Moreover, a concise situational awareness data could be transferred to the SCC especially that the connectivity bandwidth is limited and not ready for huge amount of data (Hoyhtya et al., 2017).

On the other hand, the limited details about the technologies to be installed makes the structure missing the technical components of each system. Rolls Royce already suggested some of these components for the navigational situation awareness and many other components installed on-board currently operated ships are supposed to be part of the autonomous ships. In the future, when further details will be available about the technical components of each of the autonomous ship systems, they could be added to the proposed structure. A refined systemic hazard analysis could be then applied, which is an effective process of designing new complex systems or improving existent systems (Leveson, 2011).

The proposed structure in this study does not include the links between different systems and sub-systems as those are still not specified for all ship systems. It does not also give a strict prescription to the design of the autonomous ships. It rather represents the current development in the autonomous shipping in a structure that would be useful for systemic hazard analysis. The results of a hazard analysis based on this structure would then provide the recommendations for the design process.

7. Conclusion

In software intensive systems such as the autonomous ship systems, software could control components that contribute to the function of the system but are out of the same physical boundaries. The functional characteristic of systems as described in the systems theory was the focus of this paper. The proposed systems structure is based on available autonomous ship systems description from major research projects and known human functions from conventional ship operations.

The hierarchy was developed for conducting future systemic hazard analysis of the autonomous ship under development and contributing to its safety-based design. Deeper analysis of experienced seafarers' tasks in combination with a systemic hazard analysis technique would allow the identification of the interactions between each system components. That would also help to identify the hazards emerging with these interactions. In addition, the same approach if applied to the autonomous ship as a whole system would identify the interactions between the different ship systems and their associated hazards.

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