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A framework for description of autonomous ship systems and operations

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Abstract. The Concept of Operations, or ConOps, has become a central document for the specification, design and approval of autonomous ship systems and operations in the absence of prescriptive rules and regulations. The flexible structure of the ConOps and the fact that it is written in prose text makes it very accessible for all involved stakeholders, but also prone to discrepancies between the descriptions and the actual design. This paper proposes a description framework, for autonomous ship systems and operations, that covers the information items requested through the ConOps. The proposed framework has the potential to facilitate development of a formalized ConOps, which in turn could lead to a standardization of the current approval procedures for autonomous ship systems and operations.

1. Introduction

The development of autonomous ship systems is to a large degree driven by the need to improve the sustainability and cost-effectiveness of zero-carbon shipping. The shift from conventional to autonomous shipping will have a significant impact on how ships interact with their surroundings. We expect that the autonomous ships will be designed to fit much more effectively into supply chains and logistics systems [1]. We also expect more automation and increased digital communication in ports and fairways. New interactions with onshore personnel that take over functions from the traditional ship crew will also be introduced, and the interaction between ships with and without crew onboard will need careful considerations. This and other elements in the automated ship's surroundings will require new communication principles and mechanisms. We expect an extensive shift from voice communication to digital information exchanges between automated entities.

The transition from conventional to autonomous shipping is challenging. The enabling technologies for autonomous ship systems are largely untested and technology development runs in parallel with implementation projects [2]. Issues with integration of technical systems has always been a challenge in the maritime industry, and these issues are not expected to diminish for autonomous ships. A tighter integration with shore-based systems adds on to the complexity of both the systems and operations. We expect that few, if any, large autonomous ships will operate completely without human control in the foreseeable future, but they will have personnel placed onshore both for supervision and control. Lack of crew onboard the ship will also require us to re-think how daily maintenance activities shall be carried out [3]. There are several regulatory gaps both on a national and international level. There are no prescriptive rules and regulations neither



for ships nor for equipment, and the definitions and responsibilities of the master, crew and responsible person used in conventional shipping are not defined for autonomous shipping [4].

The purpose of this paper is to provide a systematic framework for description of autonomous ship systems and operations. The target group of the framework are the stakeholders involved in the design and specification, the approval, and the implementation of autonomous ship systems. The proposed framework is a result of ongoing work with development of a design standard and a holistic design methodology for autonomous ship systems and operations in the *AUTOSHIP project* [5]. The objective of the framework is to support a structured way of organizing information throughout the design process and the corresponding approval activities, as well as to lay the foundation for detailed design activities, system implementation, testing and final approvals.

The framework is needed for several reasons. Development of new technology that supports crew reductions onboard ships need clear and consistent descriptions of the relationships between the physical components and the roles of the human actors in the autonomous ship system. The system context is a critical part of the system design as it will define the system boundary and the most important communication paths. The definition of the components that are inside or outside of an autonomous ship system will have a major impact on the context.

The difference between the autonomous ship system and its context needs to be well understood, and higher degrees of automation and integration of the system into specific supply chains and logistics systems will require more context awareness during the design process compared to conventional ship design processes.

In the following sections, we will discuss the expected approval process for autonomous ships and analyse the information items that the authorities request through the Concept of Operations. We will explain how the description framework is built up and discuss the advantages of adopting the framework for design and approval activities.

2. The expected approval process

The approval process for conventional ships, seen from an industry perspective, is relatively straight forward today. Much of the components and equipment is already type approved and the final approval of the ship by the flag state or its recognized organisations is normally based on prescriptive rules that are well suited to the industrial production processes. In addition, the class societies will be involved, governed by the chosen class notations. All stakeholders involved in the design, the build and the operation of the ship must ensure that the systems comply with known requirements through the well-defined acceptance criteria and test regimes.

This is not the case for autonomous ship systems and operations as of today. The required technology is unproven, and the development of this technology runs in parallel with ongoing implementation projects. One could also say that the application domain for autonomous ships can be very different than the domain for conventional ships: The desire to integrate an autonomous ship into specific supply chains and logistics systems to optimize the cost-effectiveness could potentially reduce the system flexibility and put constraints on the allowable operating area. The lack of experience with the necessary technology, the operations and to some extent the application domain is reflected by the lack of well-defined acceptance criteria and consequently prescriptive rules.

There are however several initiatives that together work on closing the gaps. IMO has issued an interim guideline for MASS trials to guide the authorities and stakeholders in the process of planning and executing trials [6]. ISO has provided input to IMO on definitions of automation and autonomy with the purpose of aligning the understanding of the terminology for autonomous ships among involved stakeholders [7]. Several classification societies have issued guidelines for the design and operation of autonomous ship systems to facilitate development and implementation initiatives [8], [9], [10], [11]. We expect that the classification societies will gain experience through their involvement in the processes, and then contribute to the transition towards a more streamlined regulation framework. Until that happens, the IMO *Guidelines for the Approval of*

Alternatives and Equivalents [12] is thus the current norm for the design, the implementation and the approval of autonomous ship systems. The Norwegian Maritime Authority (NMA) has as a response issued a more specific circular [13] that is aligned with the IMO guidelines.

We do not expect that rules and regulations will be developed and made available for the industry within short time, as the scoping and drafting exercises within IMO are time-consuming processes. This will lead to many challenges and complications in the approval process of autonomous ship systems that will be time consuming and costly for the involved stakeholders if not managed in a structured and systematic way. Type approvals for new technology and equipment are not possible within the current regime. We expect more testing of both individual systems and integration testing prior to final approvals at commissioning and sea-trials. It is also likely that the ship needs to be approved together with the system, at least for those components that are tightly linked with the control and monitoring strategy. This leads to a case-by-case approval regime, where the autonomous ships cannot be easily relocated to another operating area without reapprovals. It also indicates that it probably not will be allowed to generalize the approval process of a ship, but perhaps parts of it.

Whereas the approval process primarily is concerned with the safety and the security of autonomous ship systems and operations, we expect that cost-effectiveness and sustainability aspects will be more closely linked compared to today's conventional ship regime. As cost-effective and sustainable operations are the primary motivation of the development initiatives, these aspects will play an increasingly significant role when designing out and mitigating safety and security hazards. We do not want autonomous ship systems that reduces the cost-effectiveness or worsens the environmental impact of shipping operations, unless there are special circumstances where a "higher than normal" safety and security level is desirable.

A key challenge is to precisely communicate all aspects of the autonomous ship system and operations that are relevant for the approval activities, and understandable for a wide range of involved stakeholders. For this purpose, the Concept of Operations has become a central document for the specification of autonomous ship operations in the absence of both international and national rules for the design, building and operation of autonomous ships.

3. The Concept of Operations (ConOps)

A number of maritime industry guidelines explicitly refers to the ConOps as a document that is to be used to communicate the design of autonomous ship systems and operations [9], [10], [11]. This also applies to the NMA circular that explicitly lists the ConOps as one of the documents that is to be submitted as part of the autonomous ship system design study to initiate the preliminary design approval process [13].

There are various definitions of the ConOps in international standards and it is not within the scope of this paper to discuss these. The framework for description of autonomous ship systems and operations that will be proposed in this paper should capture the information items that is requested through the ConOps. The previous mentioned maritime guidelines has for that reason been analyzed, and a summary of the main information items that these guidelines request as part of the ConOps is listed in Table 1. The summary includes some non-exhaustive examples of specific details, and also reflects information requests from a maritime guideline that implicitly requests similar type of information [8].

Categories one to five list information items intended to describe the ship and the components that it shall interact with, and this can be viewed as a description of the autonomous ship system and the system context. Categories six and seven are a mix of functional and operational requirements, as well as descriptions of the operating conditions. Category nine is concerned with the safety management and operational management of the autonomous ship system.

The amount of information requested through the ConOps is extensive and should together be considered as a collection of requirements that will need to be verified against the relevant authorities' or class societies' specific needs. The ConOps should be looked upon as a living

document that is maintained throughout the life cycle of the autonomous ship system. It is to be expected that the detail level will increase as the available information base is improved and the uncertainties reduced.

Table 1. Summary of information elements requested in the Concept of Operations.

1	Physical characteristics of ship - major system elements and how they are connected and interact, performance characteristics.
	1.1 Size, speed, cargo type and capacity, cargo handling.
	1.2 Steering, propulsion, energy storage and capacity, endurance.
	1.3 Navigation system, sensors, position fixing systems and accuracy, detection capabilities.
	1.4 Hull integrity, stability, hull strength.
	1.5 Fire protection, cargo monitoring.
	1.6 Communication systems.
2	External supporting systems during normal operations. Performance characteristics.
	2.1 External sensor or positioning systems.
	2.2 External automation in port for cargo, cold ironing, berthing.
	2.3 Planned response services, tugs, escort.
3	Crew, passenger and others on board
	3.1 How persons can enter ship.
	3.2 How safety of persons is catered for.
	3.3 Life support systems, if any.
4	Remote Control Centre.
	4.1 Features of RCC if in use, manning levels, location, redundancy.
	4.2 Communication systems for safe control.
	4.3 Forms of human-machine interfaces where applicable.
	4.4 Mechanisms for coordination of ship automation, ship crew and RCC personnel.
5	Communication with other ships, VTS, MRS.
	5.1 Responsibilities for communication (RCC, automation, other).
	5.2 Procedures and preparedness.
6	Functions and operations.
	6.1 Intended area of operation, significant phases in operation and voyage, operational environment and characteristics, limitations and restrictions.
	6.2 Functions to be performed during operations and voyage.
	6.3 Operational risk factors, including e.g. traffic density, environmental conditions, geography.
	6.4 Division of responsibility between human and automation in the different functions/phases of operation ("degree of automation/control/autonomy").
	6.5 Additional support where applicable, e.g. incidence response, planned response.
	6.6 Fallback solutions, minimum risk conditions.
7	Recovery, incident and emergency preparedness.
	7.1 Incident or emergency preparedness systems and plans.
	7.2 Towage, on board recovery teams.
8	Safety management system.
	8.1 Logistics management.
	8.2 Operations planning.
	8.3 Operational procedures and responsibilities.
	8.4 System health monitoring and system maintenance plans and facilities.

The advantage of the ConOps is that the format is very accessible for all stakeholders. It is normally written in prose text and the structure is flexible. However, as the objective of the document also is to facilitate precise communication of a specific design between the involved stakeholders, the format has some shortcomings.

The use of prose text can be subject to individual interpretations. Information in the document will be transferred from prose text into other engineering systems and tools, and back again. Discrepancies between the ConOps description and the actual design could easily occur, causing a mismatch between the design intention, the approval basis and subsequently the acceptance criteria. The question whether this can be avoided has led to the question whether it is possible to formalize the ConOps, and subsequently the identification of the need to have a framework for description of autonomous ship systems and operations.

4. The AUTOSHIP description framework

The objective of the AUTOSHIP description framework is to support a structured way of organizing information throughout the design process and the corresponding approval activities for autonomous ship systems and operations, as well as to lay the foundation for detailed design activities, system implementation, testing and final approvals. To achieve this, we have identified that the framework should facilitate:

- a precise description and clear understanding of what an autonomous ship is,
- a precise description and clear understanding of the roles and relationships in the autonomous ship system,
- systematic analysis of the autonomous ship systems ability to carry out the intended voyages and operations, including safety, security and cost-effectiveness, and
- it should capture all information items that will be requested in the ConOps, as a minimum, to satisfy the authorities.

The relationship between the four description documents that together constitutes the description framework for autonomous ship systems and operations proposed in this paper, the scope of the AUTOSHIP design methodology and the scope of the ConOps is illustrated in Figure 1.

AUTOSHIP design method				
Autonomous ship system description	System context description	Operational envelope description	Scenario description	
			<i>General operations</i>	<i>Supply chain and logistics</i>
ConOps				

Figure 1. Relationship between the four design description documents and the ConOps.

The objective of the *autonomous ship system description*, the *system context description* and the *operational envelope description* is to provide a general overview of what the proposed design can do. These three documents have a one-to-one relationship with the ConOps.

The objective of the *scenario description* is to provide an exact description of what the proposed design shall do, and this must match the abilities and constraints defined in the descriptions of the autonomous ship system, the system context, and the operational envelope. Note that the scenario description is divided into two parts: *General operations* and *supply chain and logistics*. The primary concern for the approval of a system design is related to the general operations part of the scenario description, which is important for the safety and security analysis.

The supply chain and logistics part will contain specific details of the intended operation, including more details on cargo flows and the overall logistics model. If the ship is moved to another operation, it will in many cases be possible to change only the supply chain and logistics

part, if this is within the boundaries of the general operation. This would allow reapproval for a new operation by only checking that these two documents are consistent. It should not be necessary to go through a full approval process again. The AUTOSHIP design methodology will also evaluate the sustainability and cost-effectiveness of the autonomous ship system, and for this purpose an extensive supply chain and logistics description is needed.

The relationship between the description framework, the system objectives and the resulting design is illustrated in Figure 2. The system objectives are the highest-level objectives for the design of the autonomous ship system and its operations, and these form the input needed to start the design and specification process. They are typically linked to the business and societal effects of the resulting outcome of implementing the design [14]. One example of a system objective is to reduce the cost per transported unit of goods, and another is to increase the frequency of goods deliveries to customers from a biweekly to a weekly basis. The collection of the four description documents is the design that will be subject to approval activities, and it will, if deemed economically viable, safe and sustainable, be subject to further detailed design activities, implementation, testing and final approvals. The following subsections will outline the structure of each of the four description documents.

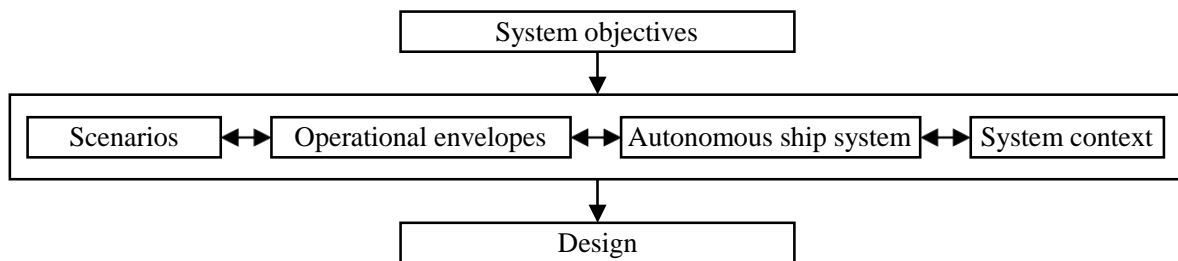


Figure 2. High-level structure of the framework.

4.1. Scenario description

The objective of the scenario description is to provide a description of what the proposed system design shall do. The first part of this document includes a high-level description of the operations that must be carried out given the specific system objectives. It also includes the properties of the specific voyage. The second part of the document contains a detailed description of the supply chain and logistics system that the autonomous ship system is part of. In the following, only the first part will be discussed as this is most relevant for the approval process.

The scenario description provides an overview of the general operations in a framework that divides the use cases into generic voyage phases [3]. This is illustrated in Figure 3, where each of the generic voyage phases contain one or more operations.

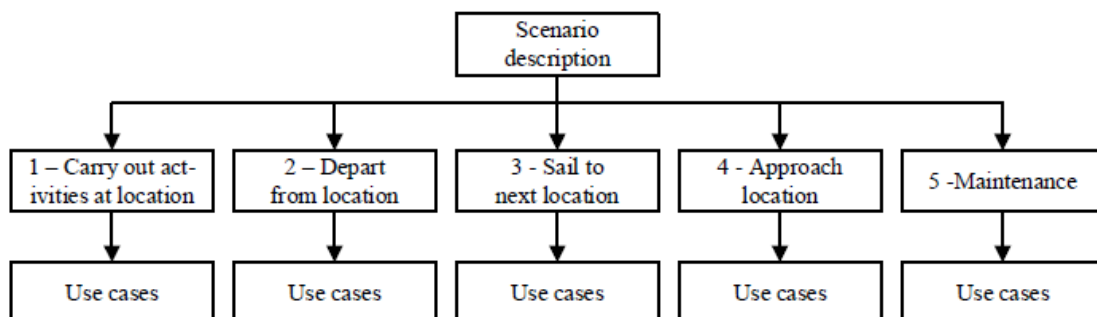


Figure 3. Structure of the general operations in the scenario description.

The process of identifying the general operations is supported by a systematic supply chain

analysis and a proposal for process subdivision. The systematic supply chain analysis supports identification of use cases based on semi-structured interviews of stakeholders as well as analysis of available quantitative data for the specific supply chain and logistics system in question [3]. The process subdivision provides guidance on relevant operations, functions, and tasks in an autonomous ship system divided into ship operations, ship management operations, inland waterways operations, port operations, coastal operations and on-site operations [5].

Identification and categorization of general operations and use-cases into generic voyage phases is not sufficient to describe the scenarios that the autonomous ship system shall be designed for. The properties of each operation must also be linked to the actual voyage and the specific sailing route which is described in the supply chain and logistics document. The general operations will have to describe each class of voyage phases, e.g. characterized by maximum wave height, visibility, duration etc.

In the supply chain and logistics document, the voyage is described using directed graphs with nodes and edges [15]. Each node corresponds to a geographical position and each edge is a voyage leg between two positions. This is illustrated in Figure 4. In the general operations these can be described as general use cases with parameters as suggested above.

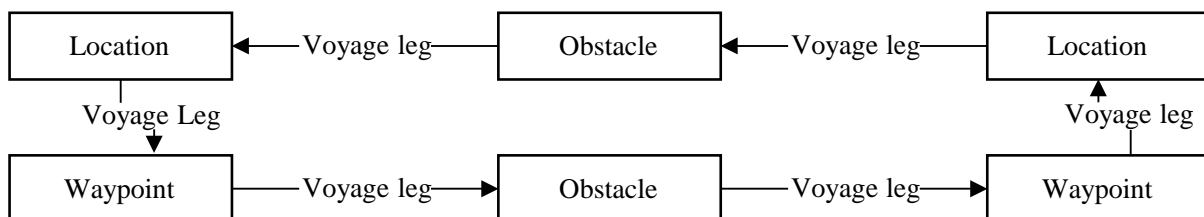


Figure 4. Structure of the voyage in the scenario description.

The voyage contains three main types of nodes. A location describes a factory, quay, or any equivalence where the ship carries out activities such as loading and offloading of goods. An obstacle is a location on the route where the ships needs to pass e.g. a water lock or bridge but does not offload or load any goods. A waypoint separates two voyage legs that have different characteristics. The objective of this description is to provide an accurate overview of the operational area and the characteristics of all locations and voyage legs that the ship will be subject to during operations.

The systematic supply chain analysis is also used to establish the voyage description, and much of the information that is obtained in this analysis will also be leveraged to create the operational envelope description.

4.2. Operational envelope description

The Operational Envelope (OE) is defined as "the specific conditions and scenarios under which a given autonomous ship system is designed to function" in [5]. An important step in the design process of autonomous ship systems is to do an operability study where the capabilities of the autonomous ship system is assessed. The capability assessment considers the tasks the autonomous ship shall perform, and under which conditions the tasks must be performed. The result is a set of operational limits for the autonomous ship system. The objective of the operational envelope is to provide an accurate overview of all operating conditions that the autonomous ship system will encounter, and translate this to boundaries for the identified operations and voyages, and a strategy for distribution of and transfer of control between automation and humans. The structure of the operational envelope description is illustrated in Figure 5.

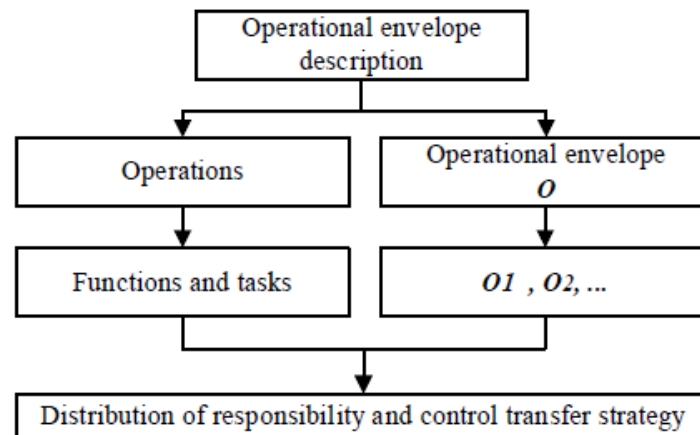


Figure 5. Structure of the operational envelope description.

The operational envelope description is based on the high-level overview of the operations and conditions identified in the general operations. Each scenario and operation consist of a set of functions that can be further subdivided into specific tasks until an adequate level of details is reached. All functions and tasks are subject to one or more operating conditions.

The conditions of the OE include weather complexity, traffic complexity and geographical complexity in the temporal and spatial dimension of the operating area. The autonomous ship system needs to be aware of changes in these conditions, and to be able to act in an appropriate manner to ensure that it stays within the limits of the operational envelope boundary, or alternatively fall back into a safe state or minimum risk condition outside the OE. Development of the operational envelope description will require iterations over the autonomous ship system description as it includes a description of the distribution of responsibility and transfer of control between the components and roles defined in the autonomous ship system.

4.3. Autonomous ship system description

The objective of the autonomous ship system description is to provide a description of all physical components and roles that together ensure effective monitoring and control of the autonomous ship processes for the ship's intended operation or voyage. The autonomous ship system must be viewed as a cyber-physical system of systems that consists of many physical components both onshore and onboard the ship. These physical components interact with each other and they are connected and communicate.

The structure of the autonomous ship system description is illustrated in Figure 6. The physical components and roles are either allocated to the ship or to shore. The ship will have a combination of various equipment, automation systems and crew onboard, and various equipment, automation systems and personnel will support the ship operation from one or several shore-based locations.

The automation systems, ship crew and shore personnel will together have the overall responsibility of operating both the ship and shore equipment, and this distribution of responsibility is reflected in the operational envelope description. The main components of the communication architecture, and the implementation of procedures, information models and protocols will affect how control can be transferred between humans and automation and explicitly contribute to the operability.

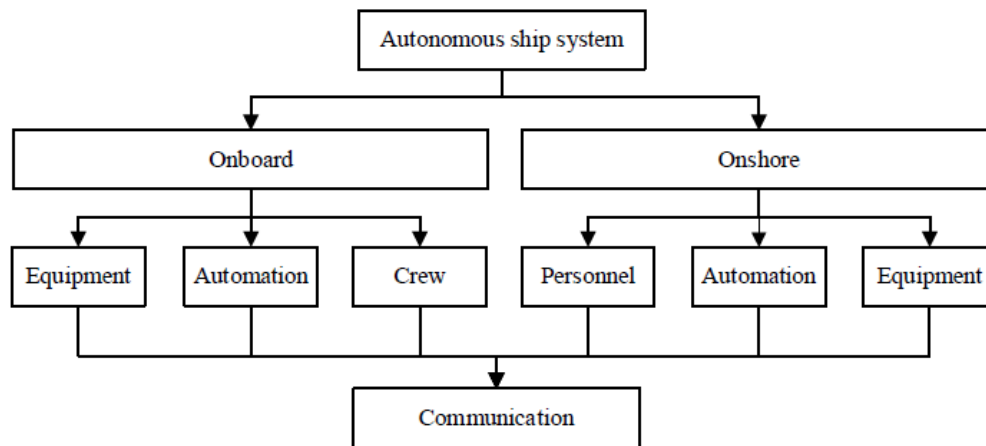


Figure 6. Structure of the autonomous ship system description.

The definition of the autonomous ship system proposed in the AUTOSHIP project is illustrated in Figure 7 and a detailed description of the components and roles is given in [5]. The physical components and roles within this definition has been selected based on the criteria of including the components that are tightly integrated with the control and monitoring strategy of the autonomous ship.

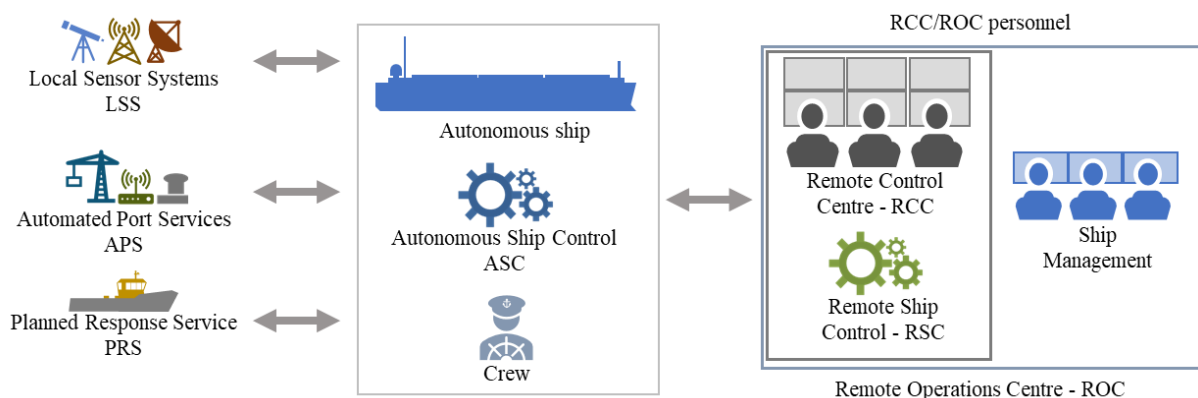


Figure 7. Examples of components and roles in an autonomous ship system [5].

It should be noted that it is possible that both the number and types of components, as well as the number of ships in the autonomous ship system could vary depending on the specific system objectives.

4.4. System context description

The objective of the system context description is to provide an accurate description of the boundaries between the autonomous ship system and its environment that includes the components, the roles and the most important communication paths. The structure of the system context description is illustrated in Figure 8.

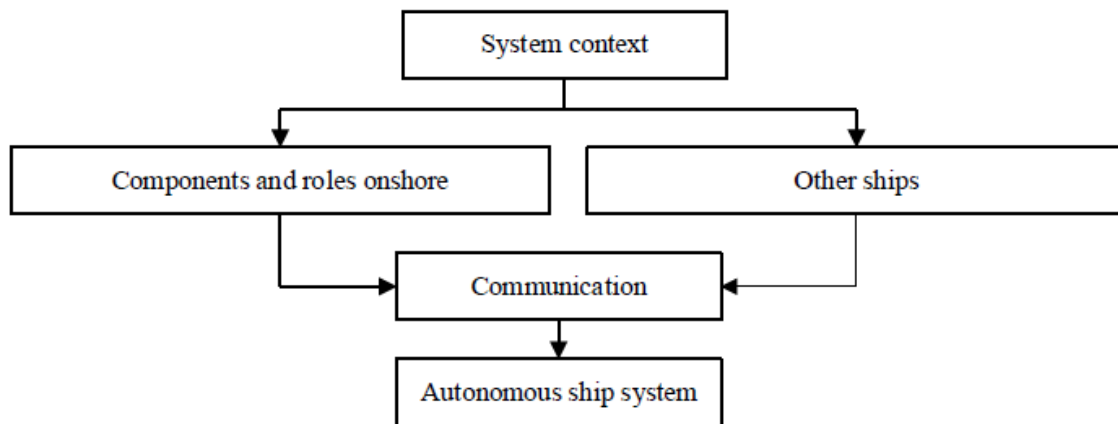


Figure 8. Structure of the system context description.

The description is divided into two parts. The first part contains a description of the shore-based components and roles that the autonomous ship system interacts with. The second part of the document contains a description of other ships that operate within the defined operating area of the autonomous ship system. The essence of the system context description is to capture the communication requirements between the autonomous ship system and the context components.

The definition of what is inside or outside the boundaries of the autonomous ship system is subjective and likely to be influenced by the individual designer or design team. The selection of the components that belong in the autonomous ship system creates the necessary boundary to define the system context of the autonomous ship system. The definition of the system context proposed in the AUTOSHIP project is illustrated in Figure 9.

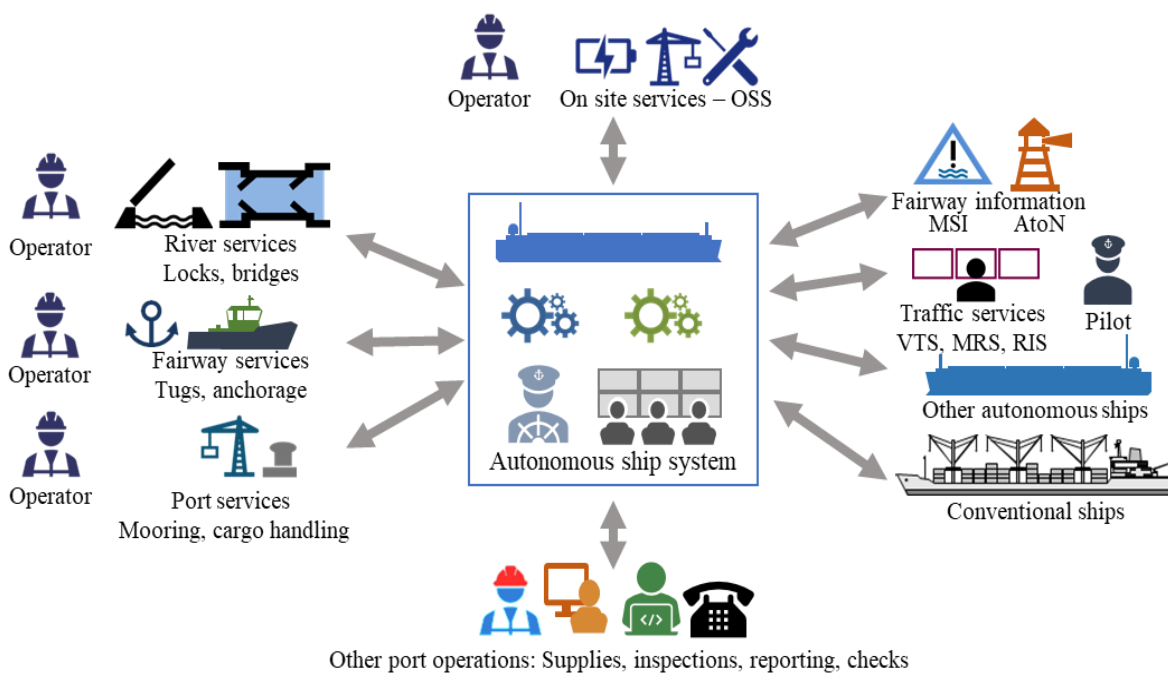


Figure 9. Examples of components and roles in the context of the autonomous ship system [5].

A detailed description of these components and roles is given in [5], and it should be noted that the system context only includes components that exchange information with the autonomous ship.

Unknown objects in the water are not included as they are mapped through the traffic complexity conditions in the operational envelope description.

5. Discussion

We believe that it is possible to formalize the ConOps, and the AUTOSHIP framework for description of autonomous ship systems and operations proposed in this paper is the first step in this process. The framework facilitates the use of a formal modeling approach, and even though it might be impossible to avoid prose text descriptions completely, the shift towards a formal description will most likely reduce discrepancies between the actual design and the design descriptions. A formal description of the autonomous ship system and operations would also facilitate effective reuse of information between different designs and allow us to create strong links between the design description and the approval basis, the acceptance criteria and test results.

The structure of the proposed framework also has some features that lead us to believe that it is possible to standardize parts of the approval processes. The high-level structure of the autonomous ship system description, the system context description and the operational envelope description will probably not change much from design to design. We anticipate that it is possible to create a maximum template that only needs to be configured according to the contents of the scenario description. This would allow for a more efficient process. This also has the implication that should one decide to change the operating area of an already built autonomous ship in the future, then reapproval would require that an updated scenario description is assessed and analyzed with the already existing autonomous ship description, the system context description and the operational envelope description.

The description of the operations in terms of the general operations description would also allow a much simpler reapproval process, should the ship be moved to another operating area.

The use of a common description framework will allow us to compare designs in cost and benefit analysis using the same basic structure. This also applies to safety, security, and cybersecurity analysis that requires a well-defined description of roles and relationships between the autonomous ship system components and its environment.

In a wider scope, a common framework for description of autonomous ship systems will ease work on standardisation activities, which are considered as essential for successful implementation of autonomous shipping. This particularly applies to the communication links between the autonomous ship system and its context. Furthermore, a common description framework complemented by a corresponding common terminology that is being developed for autonomous and automated ships, will enable more consistent communication in the technical and scientific community researching this area.

6. Conclusions

This paper has introduced a framework for description of autonomous ship systems and operations that consists of four description documents: The scenario description, the operational environment description, the autonomous ship system description and the system context description. The contents of the description framework cover the information items that the authorities request through the ConOps. The framework has the potential to facilitate development of a formalized ConOps. This could in turn lead to a standardization of the current approval procedures for autonomous ship systems and operations. Further research is required to validate the framework through implementation and testing on specific use-cases.

Acknowledgements

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