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Identifying research directions of a remotely-controlled merchant ship by revisiting her system-theoretic safety control structure

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ABSTRACT

Despite the concept of Maritime Autonomous Surface Ships (MASS) being in the limelight of research and development effort within the shipping industry, there are still some existing research gaps. These pertain not only to technical solutions to be implemented but also to the issue of the impact of new technology on maritime safety. In an attempt to identify these gaps, we perform a literature review of the operational features of remotely-controlled merchant vessels. The framework is based on a safety control structure developed in accordance with the principles of System-Theoretic Process Analysis (STPA). The results indicate that most scholars focus on the high-end components of the system, while some organizational and human-oriented issues remain under-explored. These results can be found relevant by scholars and industry partners active in the domain of autonomous shipping.

1. Introduction

With a growing interest in unmanned shipping concept, some research and development (R&D) projects have been funded. One of them, *Advanced Autonomous Waterborne Applications Initiative* (AAWA), resulted in a publication of a system-theoretic safety control structure of a remotely-controlled merchant ship (Wróbel et al., 2018a), among other deliverables. The concept of autonomous merchant shipping should be understood as carriage of passengers or goods by the sea with limited human intervention. It is still being developed and attracts the attention of numerous scholars who strive to investigate certain problems within their area of expertise (Uzzi et al., 2018). However, their combined effort appears to be unequally distributed among operational aspects of prospective *Maritime Autonomous Surface Ships* (MASS).

Many articles focused on selected issues of *Autonomous Surface Vessels* (ASVs) operation can be found in the literature, see (Liu et al., 2016). Nevertheless, due to the progressive and rapid development of autonomous solutions in the domain of merchant shipping, many problems remain unresolved. To already identified gaps and limitations belong, among others, communication in ship-shore relation, as well as between cooperating vessels, (Raboin et al., 2015). Likewise, the utilization of various types of sensors faces several different limitations (Liu et al., 2016). The fields of vessel control, situation awareness (Man et al., 2018), data processing, and shore services (Burmeister et al., 2014a) are also unsatisfactorily covered. The legal aspect of introducing MASSs is also considered by researchers (Ringbom, 2019; Veal et al., 2019), as well as a development of classification rules (Ringbom, 2019), management process for a design phase (Valdez Banda et al., 2019), and interaction with manned vessels (Porathe, 2017). Even the basic definitions related to autonomous merchant shipping vary among different publications (IMO MSC, 2019; Porathe et al., 2018; Ringbom, 2019). Notwithstanding, there appears to exist much more unresolved issues pertaining to the design and operation of MASSs (Wróbel et al., 2018b).

Therefore, the aim of this paper is to identify existing and future research directions in the field of autonomous merchant vessels. In an attempt to investigate what has been done already and what needs further attention, we revisit the safety structure originally developed in the previous research under AAWA project and perform a literature review for specific control actions (CAs). To this end, we focused on remotely-controlled merchant ships (IMO *Degree of Autonomy* 3, DoA 3) rather than fully-autonomous ones (IMO DoA 4). For the DoA definitions see Table 1. Even though there is more scientific interest in the latter, potentially due to their greater innovativeness, remote control of sea-going vessels is better-understood as it consists *merely* in transferring the control processes to another location (Rødseth, 2018). Mean-

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Table 1
Degrees of autonomy framework as defined for the purposes of regulatory scoping exercise (IMO MSC, 2018).

Degree of Autonomy	Description	Definition
1	Ship with automated processes and decision support	Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated.
2	Remotely controlled ship with seafarers on board	The ship is controlled and operated from another location, but seafarers are on board.
3	Remotely controlled ship without seafarers on board	Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.
4	Fully autonomous ship	The operating system of the ship is able to make decisions and determine actions by itself.

while, full autonomy implies changing the whole paradigm of ship operations, enormously increasing the role of control algorithms. It is also argued that the implementation of remotely-controlled vessels will be more feasible than fully-autonomous, from both legal (Ringbom, 2019) and technical (Wärtsilä, 2017; Zhou et al., 2019) points of view. Therefore, in the remainder of the herein paper, expressions such as *unmanned* or *autonomous* vessel are generally related to a *remotely-controlled* one, unless otherwise specified.

In order to perform a preliminary safety analysis of a remotely-controlled merchant vessel, in this paper, the results of *System-Theoretic Process Analysis* (STPA) have been employed. Within STPA, the focus is on ensuring proper interactions between components of the system rather than on the reliability of a particular component. In the herein paper, we examine the safety structure with a focus on a particular interaction and not on the overall layout of the system. To achieve this, 47 scientific and technical papers have been reviewed.

Through this analysis, we strive to identify potentially under-investigated aspects of a remotely-controlled merchant vessel operations. As a general rule, the fact that a topic is covered by a research paper indicates that it is an important field of research (Doumont, 2014), a field that scholars wish to advance (Le Grange, 2003) through their study itself. Moreover, it usually implies that the topic was under-explored prior to the publication of the paper and that its authors attempted to bridge some research gap. Consequently, scientific papers can be good indicators of what research areas were of greatest relevance at a time they were submitted or published (Gil et al., 2020). Thus, the more papers cover a given domain, the more research gaps have been identified within it, potentially awaiting resolution (Peat et al., 2002; Toffel, 2016; Uzzi et al., 2018). The identification of such gaps in the domain of autonomous shipping may help direct the research effort to the most under-investigated issues.

The remainder of this paper is structured as follows. Firstly, the methods and materials used in the research are described (Section 2), including the case study provided to exemplify the executed procedure. These are followed by results and their analysis in Section 3, which are then discussed in Section 4. Finally, conclusions are drawn.

2. Methods and materials

In the herein study, two interlinked approaches have been used to identify research directions and gaps related to autonomous merchant shipping. The qualitative method of *System-Theoretic Process Analysis* (STPA), was used to determine the control actions in the previously designed control structure (Wróbel et al., 2018a). Afterward, based on the literature review, the quantitative approach was utilized to examine references to each action. The system-theoretic method and its main principles are introduced in Section 2.1. The description of the model used in the study, as well as details of reviewed documents, are presented in Section 2.2. Materials used in the present research are described in Section 2.3. The example of attributing and investigating references to the control actions is presented as a case study in the last part of this Section 2.4.

2.1. System-Theoretic Process Analysis

STPA is a relatively new safety analysis technique (Leveson and Thomas, 2018). It is used to determine hazards and scrutinize the safety of complex systems. The development of this method was triggered by findings in STAMP (*System-Theoretic Accident Model and Process*). The main goal of the STPA, which is an integral and deep-rooted part of STAMP is the determination of how hazards can occur and how to prevent losses within the system. The occurrence of UCA (*Unsafe Control Action*), an erroneous execution of a specific CA or a lack of its carrying out may lead to violation of whole system safety. This approach allows for *investigating the accident before it occurs* and using STPA as early as on the design and creation stage of the analyzed safety system.

Apart from STPA, various methods were being used to analyze the safety of autonomous ships, mainly quantitative ones (Rødseth and Burmeister, 2015; Kretschmann et al., 2015). However, these were based on untested datasets pertaining to MASS safety performance (Wróbel et al., 2017). The application of qualitative STPA allowed for a non-judgmental analysis based on literature review and expert elicitation (Wróbel et al., 2018a).

A typical procedure executed in the STPA presented in Fig. 1 is as follows:

1. Determination of analysis purpose by identification of possible losses, hazards, and safety constraints.
2. Design of control structure that is the composition of controllers, control actions, feedback loops, components inputs and outputs, and

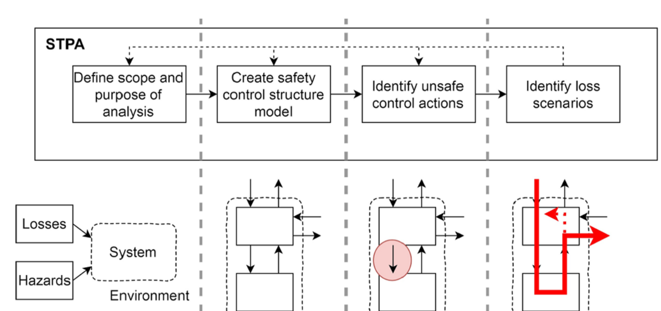

Fig. 1. A typical STPA procedure, inspired by Leveson and Thomas (2018).

processes embedded in the model of the system.

3. Determination of potential UCAs, i.e. actions, which will lead to hazard when occur.
4. Identification of critical scenarios that lead to losses. Therefore, reasons for UCAs occurrence and incorrect execution (or their lack) of proposed control actions should be considered.

2.2. Safety control structure

The original safety control structure of a remotely-controlled merchant vessel delivered in the previous research (Wróbel et al., 2018a) has been revisited, see Fig. 2. Control actions identified in the initial study and included within the structure model are listed in Table 2.

2.3. Materials

The original structure developed in Wróbel et al. (2018a) and presented in Fig. 2 was an effect of a literature study that supported an expert elicitation. The final layout of the structure depended on the latter far more than the former. Therefore, a more structured literature review enhanced by newly-published papers can be beneficial to understand a state-of-the-art of remotely-controlled merchant vessels.

Thence, in an attempt to find any references to the control actions found in the original structure, we have reviewed papers, reports, and theses relevant to the field, which we identified among our own resources from previous research projects. Therein, some 150 documents have been filtered out. Additionally, in order to identify and consider also recently-published documents, a web search query has been applied in August 2019 and afterward updated in January 2020 with search phrases such as *remotely-controlled ships*, *unmanned vessels*. Only documents published in 2012 or later have been included as that year marks a publication of initial results of the cutting-edge MUNIN project (Rødseth and Burmeister, 2012). Its results have been later refined by many other authors and still constitute a ground-breaking achievement in the field of autonomous shipping. The closing date was the end of 2019.

The results have been screened out to identify documents relevant to the field of remotely-controlled merchant vessels. Only papers related to the concept of merchant shipping (by which transportation of goods or passengers by sea is understood) were taken into consideration. The papers describing remote control applications in other domains were discarded even though their findings could be beneficial for the development of safe remote operations of merchant vessels (Wahlström et al., 2015).

Table 3 lists the reviewed publications while Table 4 provides their summary. Additionally, the breakdown of all reviewed documents by publication year and their type is depicted in Fig. 3. We assumed that each reference to a specific control action is equally significant in the analysis. The occurrence of the reference indicates that authors of the scrutinized paper were aware of the represented aspect. For certain reasons, they considered it important enough to be addressed or at least mentioned in the document.

When a given document covered factors pertaining to both fully-autonomous and remotely-controlled merchant vessels, we only extracted these relevant to the latter. Nevertheless, it was sometimes difficult to clearly identify what DoA is referred to. If that was the case,

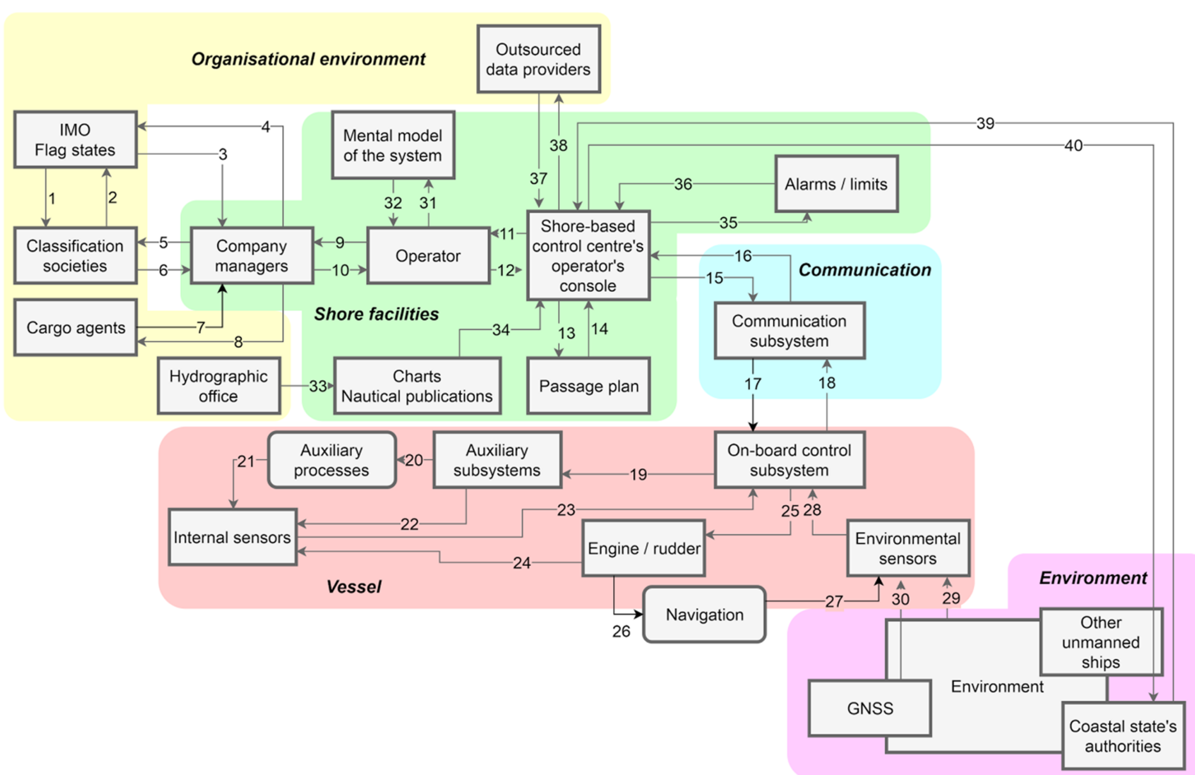

Fig. 2. Original safety control structure (Wróbel et al., 2018a).

Table 2
Summary of control actions presented in the safety structure.

Control action	Control action name	Source	Target
1	International legislation	IMO/Flag state administrations	Classification societies
2	Suggestions for improvement	Classification societies	IMO/Flag state administrations
3	International legislation	IMO/Flag state administrations	Company managers
4	Suggestions for improvement	Company managers	IMO/Flag state administrations
5a	Suggestions for improvement	Company managers	Classification societies
5b	Operational or statistical data	Company managers	Classification societies
6a	Rules for classification	Classification societies	Company managers
6b	External audits	Classification societies	Company managers
7a	Cargo and stowage information	Cargo agents	Company managers
7b	Commercial pressure	Cargo agents	Company managers
7c	Payments	Cargo agents	Company managers
8	Vessel information	Company managers	Cargo agents
9	Operational reports	Operator	Company managers
10a	Operational procedures	Company managers	Operator
10b	Audits	Company managers	Operator
10c	Training	Company managers	Operator
11	Collection of operational data	Operator's console	Operator
12	Decision elaboration	Operator	Operator's console
13	Creation/update	Operator's console	Passage plan
14	Check of the passage plan	Passage plan	Operator's console
15	Decisions' relay	Operator's console	Communication subsystem
16	Feedback relay	Communication subsystem	Operator's console
17	Decisions' relay	Communication subsystem	On-board control subsystem
18	Feedback relay	On-board control subsystem	Communication subsystem
19	Equipment set-points	On-board control subsystem	Auxiliary subsystems
20	Actuation	Auxiliary subsystems	Auxiliary processes
21	Sensing	Auxiliary processes	Internal sensors
22	Sensing	Auxiliary subsystems	Internal sensors
23	Data on operational status transfer	Internal sensors	On-board control subsystem
24	Sensing	Engine / rudder	Internal sensors
25	Equipment set-points update	On-board control subsystem	Engine / rudder
26	Actuation	Engine / rudder	Navigation
27	Sensing	Navigation	Environmental sensors
28	Transfer of data on ship motions and environment	Environmental sensors	On-board control subsystem
29	Sensing	Environment	Environmental sensors
30	Sensing	GNSS	Environmental sensors
31	Update	Operator	Mental model
32	Review of the mental model of system and situation	Mental model	Operator
33	Updates	Hydrographic office	Charts & nautical publications
34	Review of the model of the environment	Charts & nautical publications	Operator's console
35	Update	Operator's console	Alarms / limits
36	Warnings	Alarms/limits	Operator's console
37	Outsourced data	Outsourced data providers	Operator's console
38	Requests for data	Operator's console	Outsourced data providers
39	Requests or commands	Coastal state's authorities	Operator's console
40	Reports	Operator's console	Coastal state's authorities

the entire paper was excluded from the analysis in order to reduce potential errors. The reason for that can be the ambiguity in definitions pertaining to unmanned navigation and different approaches being applied to the problem of autonomy (DNV-GL, 2018; Rødseth, 2018; Rødseth and Nordahl, 2017), particularly in the initial period of technology development.

We have excluded papers co-authored by ourselves from the analysis to avoid potential framing. We have also dismissed vague statements about which we were unconvinced to which control action, if any, they should be assigned. However, we did include in-text references to previously published papers. In this case, we believed that a reference to other papers strengthens the significance of the original one.

2.4. Research procedure - case study

Identification of references related to operational aspects of unmanned ships and their assignment to a particular control action is exemplified in the following case study. Namely, a paper by Ramos et al. entitled *Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events* (Ramos et al., 2019) is reviewed. Although the paper is centered around the operations of *Shore Control Centre* (SCC), it also includes some interesting insight into the overall arrangement of the system. Herein, the statements identified as relevant to a specific control action together with its number and description is given in Table 5. As can be noted, the paper in question mentioned a relatively high number of operational aspects of unmanned ships.

Table 3
Summary of publications reviewed during the study.

#	Title	Reference to document	Year published	Type
1	Developments toward the unmanned ship	(Rødseth and Burmeister, 2012)	2012	Conference paper
2	Maritime Unmanned Navigation through Intelligence in Networks - Architecture specification	(Rødseth et al., 2013)	2013	Technical report
3	Situation awareness in remote control centres for unmanned ships	(Porathe et al., 2014)	2014	Conference paper
4	Conducting look-out on an unmanned vessel: Introduction to the advanced sensor module for MUNIN's autonomous dry bulk carrier	(Bruhn et al., 2014)	2014	Conference paper
5	A System Architecture for an Unmanned Ship	(Rødseth and Tjora, 2014)	2014	Conference paper
6	The production of unmanned vessels and its legal implications in the maritime industry	(Ortiz de Rozas, 2014)	2014	Thesis
7	Autonomous Unmanned Merchant Vessel and its Contribution towards the e-Navigation Implementation: The MUNIN Perspective	(Burmeister et al., 2014a)	2014	Journal paper
8	Seeking Harmony in Shore-based Unmanned Ship Handling-From the Perspective of Human Factors, What Is the Difference We Need to Focus on from Being Onboard to Onshore?	(Man et al., 2014)	2014	Conference paper
9	Can unmanned ships improve navigational safety	(Burmeister et al., 2014b)	2014	Conference paper
10	Secure Communication for E-Navigation and Remote Control of Unmanned Ships	(Rødseth and Lee, 2015)	2015	Conference paper
11	New ship designs for autonomous vessels	(Rødseth and Burmeister, 2015b)	2015	Technical report
12	Risk Assessment for an Unmanned Merchant Ship	(Rødseth and Burmeister, 2015)	2015	Journal paper
13	Human Factors Challenges in Unmanned Ship Operations – Insights from Other Domains	(Wahlström et al., 2015)	2015	Conference paper
14	Command and control of unmanned vessels: keeping shore based operators in-the-loop	(MacKinnon et al., 2015)	2015	Conference paper
15	From desk to field - Human factor issues in remote monitoring and controlling of autonomous unmanned vessels	(Man et al., 2015)	2015	Conference paper
16	Autonomous merchant vessels: examination of factors that impact the effective implementation of unmanned ships	(Hogg and Ghosh, 2016)	2016	Journal paper
17	Autonomous safety on vessels - an international overview and trends within the transport sector	(Rylander and Man, 2016)	2016	Technical report
18	The Human Element and Autonomous Ships	(Ahvenjärvi, 2016)	2016	Journal paper
19	A navigating navigator onboard or a monitoring operator ashore? Towards safe, effective, and sustainable maritime transportation: findings from five recent EU projects	(Porathe, 2016)	2016	Conference paper
20	Control concepts for navigation of autonomous ships in ports	(Van Den Boogaard et al., 2016)	2016	Conference paper
21	Existing conventions and unmanned ships - need for changes?	(Noma, 2016)	2016	Thesis
22	Interaction Between Unmanned Vessels and COLREGS	(Öhland and Stenman, 2017)	2017	Thesis
23	Connectivity for Autonomous Ships: Architecture, Use Cases, and Research Challenges	(Höyhtyä et al., 2017)	2017	Conference paper
24	Integrated 5G Satellite-Terrestrial Systems: Use Cases for Road Safety and Autonomous Ships	(Höyhtyä et al., 2017b)	2017	Conference paper
25	Challenges of unmanned vessels: technical risks and legal problems	(Aro and Heiskari, 2017)	2017	Thesis
26	A pre-analysis on autonomous ships	(Blanke et al., 2017)	2017	Technical report
27	Human factor issues during remote ship monitoring tasks: An ecological lesson for system design in a distributed context	(Man et al., 2018)	2018	Journal paper
28	Assessing ship risk model applicability to Marine Autonomous Surface Ships	(Thieme et al., 2018)	2018	Journal paper
29	Towards autonomous shipping: operational challenges of unmanned short sea cargo vessels	(Kooij et al., 2018)	2018	Conference paper
30	Maritime law issues related to the operation of unmanned autonomous cargo ships	(Karlis, 2018)	2018	Journal paper
31	Smart ships – autonomous or remote controlled?	(Kobyliński, 2018)	2018	Journal paper
32	Towards the unmanned ship code	(Bergström et al., 2018)	2018	Conference paper
33	Accounting for human failure in autonomous ships operations	(M. Ramos et al., 2018)	2018	Conference paper
34	E-navigation, digitalization and unmanned ships: challenges for future maritime education and training	(Baldauf et al., 2018)	2018	Conference paper
35	Human Interactions Framework for Remote Ship Operations	(Kari et al., 2018)	2018	Conference paper
36	On factors affecting autonomous ships operators performance in a Shore Control Center	(M. A. Ramos et al., 2018)	2018	Conference paper
37	Autonomous and remotely operated ships - class guideline	(DNV-GL, 2018)	2018	Technical report
38	Quantitative Processing of Situation Awareness for Autonomous Ships Navigation	(Zhou et al., 2019)	2019	Journal paper
39	Research on shore-based intelligent vessel support system based on multi-source navigation sensors simulation	(Yang et al., 2019)	2019	Journal paper
40	Regulating Autonomous Ships—Concepts, Challenges and Precedents	(Ringbom, 2019)	2019	Journal paper
41	When will autonomous ships arrive? A technological forecasting perspective	(Kooij et al., 2019)	2019	Conference paper
42	Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events	(Ramos et al., 2019)	2019	Journal paper
43	Addressing the Accidental Risks of Maritime Transportation: Could Autonomous Shipping Technology Improve the Statistics?	(Hoem et al., 2019)	2019	Journal paper
44	Operations of Maritime Autonomous Surface Ships	(Pietrzykowski and Hajduk, 2019)	2019	Journal paper
45	Safety Challenges for Maritime Autonomous Surface Ships: A Systematic Review	(Dreyer and Oltedal, 2019)	2019	Conference paper
46	Merging Conventionally Navigating Ships and MASS - Merging VTS , FOC and SCC?	(Baldauf et al., 2019)	2019	Journal paper
47	Human-centred maritime autonomy - An ethnography of the future	(Lutzhoft et al., 2019)	2019	Conference paper

Table 4
Summary of reviewed publications.

Year	Document type	Number of documents	Affiliation	Number of persons affiliated	Country	Number of authors
2012	Conference paper	1	MARINTEK	1	Norway	1
			Fraunhofer	1	Germany	1
2013	Technical report	1	MARINTEK	3	Norway	3
2014	Conference paper	5	Chalmers UT	7	Sweden	7
			Fraunhofer	4	Norway	7
			MARINTEK	3	Germany	4
			aptomar	2		
	Thesis	1	University of Oslo	1	Norway	1
	Journal paper	1	Fraunhofer	2	Germany	2
			MARINTEK	1	Norway	1
			Chalmers UT	1	Sweden	1
2015	Conference paper	4	Chalmers UT	6	Sweden	6
			NTNU	2	Finland	4
			VTT	2	Norway	3
			University of Tampere	1	S Korea	1
			Rolls-Royce	1		
			MARINTEK	1		
			Electronics and Telecommunication Research Institute	1		
	Technical report	1	MARINTEK	1	Norway	1
			Fraunhofer	1	Germany	1
	Journal paper	1	MARINTEK	1	Norway	1
			Fraunhofer	1	Germany	1
2016	Journal paper	2	University of Tasmania	2	Australia	2
			Satakunta University of Applied Sciences	1	Finland	1
	Conference paper	2	Delft University of Technology	5	The Netherlands	5
			NTNU	1	Norway	1
	Technical report	1	Viktoria Swedish ICT	1	Sweden	2
			Chalmers UT	1		
	Thesis	1	World Maritime University WMU	1	Sweden	1
2017	Conference paper	2	VTT	8	Finland	10
			Rolls-Royce	2		
	Thesis	2	Turku University of Applied Sciences	3	Finland	3
	Technical report	1	Technical University of Denmark	3	Denmark	3
2018	Conference paper	6	NTNU	7	Norway	9
			Aalto University	5	Finland	6
			Delft UT	4	The Netherlands	4
			WMU	4	Sweden	4
			University of California Los Angeles UCLA	2	USA	2
			Rolls-Royce	1		
			University College of Southeast Norway	1		
			University of Oslo	1		
	Journal paper	4	Chalmers UT	5	Sweden	5
			NTNU	3	Norway	3
			University of Tasmania	1	Poland	2
			Gdańsk University of Technology	1	Australia	1
			Foundation for Safety of Navigation	1		
	Technical report	1	DNV-GL	1	Norway	1
2019	Journal paper	7	Dalian Maritime University	7	PR China	7
			NTNU	4	Norway	7
			World Maritime University	4	Sweden	4
			SINTEF	2	Poland	2
			Maritime University of Szczecin	2	Germany	2
			Hochschule Wismar	2	Singapore	1
			University of Oslo	1	USA	1
			National University of Singapore	1		
			UCLA	1		
	Conference paper	3	Western Norway University of Applied Sciences	6	Norway	6
			Delft TU	3	The Netherlands	3
			United States Air Force Office of Scientific Research	1	USA	2
			Massachusetts Institute of Technology	1	United Kingdom	1
			Lloyds Register	1		

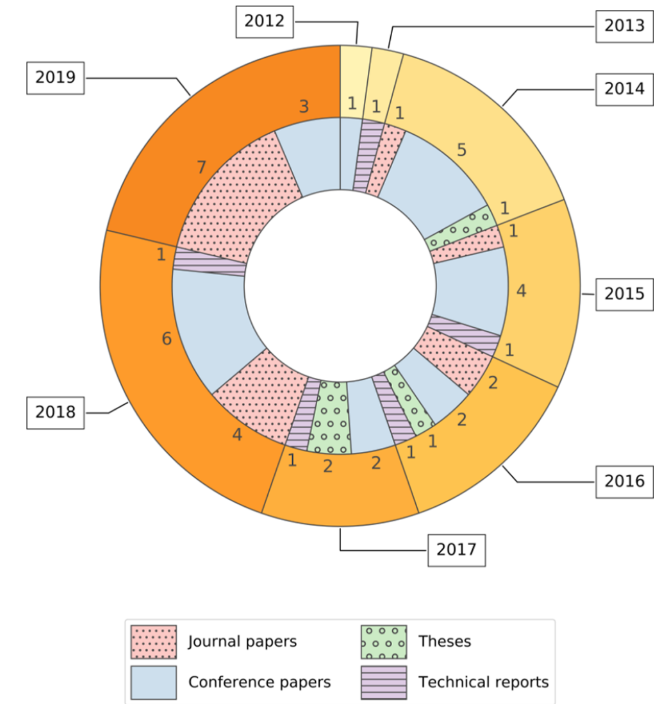

Fig. 3. The breakdown of all reviewed documents by publication year and the type.

3. Results and analysis

The following section presents the results of the conducted analysis. Several data breakdowns have been prepared with regard to particular control actions and the overall trend of reference distribution. This allows for a verification in which topics of autonomous shipping researchers are paying particular attention.

In Fig. 4 the annual distribution of references is presented. As can be seen, their number increases gradually from the beginning of the analyzed period. More references to control actions in subsequent years are related to the growing interest of academia, and the increase of the total number of scientific publications in the field of autonomous and unmanned shipping (Gu et al., 2019).

In Figs. 5 and 6, the numbers of references to particular control actions in the years 2012–2019 are given in two forms. In Fig. 5 the number of references is assigned to each CA which allows for easy identification of CAs being of the greatest and the smallest interest among researchers. Fig. 6 depicts the percentage of references to particular control action with respect to the total number of papers each year. As can be observed on both charts, the CAs #15 - #18 have been referred by the authors of scrutinized documents every year. All reviewed papers mentioned four control actions essential for the operations of remotely-controlled vessels. These (#15 through #18) consisted of ensuring communication between the ship and the shore control center. On the other side, the lack of attention has been taken to CAs #5a & #5b, which have been omitted during the entire analyzed period.

The most dynamic change of specialists' attention can be observed in CAs #11, #12, #21-24, and #29. For some reason, a decline in interest in CAs #21-24 (sensors, hardware) can be observed after 2017, which corresponded to an increase in references to CAs #11-12. The latter is related to liveware. Such a phenomenon might indicate that scholars acknowledged human operators' role in ensuring the safety of the system, thus marking human factors as an important aspect of unmanned systems.

Fig. 7 depicts a number of references to control actions within the original safety control structure. The wider the arrow denoting a particular control action, the more references. It can be noticed that the groups with the highest interest among the specialists are the communication, shore facilities, and the vessel. A relatively small amount of attention has been paid to the organizational environment.

4. Discussion

The following section discusses conducted research, including the limitations identified during the carrying study. To the main drawbacks elaborated within this section belong: preparation of the data sample, the ambiguity of definitions used, equality of CAs importance, as well as a possible defective original control structure.

4.1. Identification of research directions

The conducted analysis of document collection allows for an indication of the direction of development taken by researchers and the industry in the field of merchant MASS. The quantitative approach used for investigating control action references over the years led to the overview of topics in which specialists related to the unmanned shipping pay particular attention.

Most of the papers focused on the sharp-end of the system, which is consistent with recent findings presented in Hulme et al. (2019). It is acknowledged that most of the scholars tend to focus on technical and physical aspects of sociotechnical systems, perhaps because they are easier to analyze in a quantitative way, see Fig. 7.

Another reason for the above could be that scholars usually tend to investigate areas already familiar to them, for instance, through educational background or previous research experience. The reviewed documents as listed in Table 3 have been published by a total of 93 individuals. Twenty-seven of them could be positively identified in a *Google Scholar* database. Among them, 21 authors provided information on their primary areas of research. Ten of them work in engineering, four in research on human factors and the same number in the safety domain. One person investigates legal aspects and two - other fields.

Interestingly, little attention is paid to the fact that commands sent to the main engine(s) or rudder(s) not necessarily affect the actuation of the components, which would lead to the change of ship motion (CAs #25,26). It could arise, for instance, from malfunctions of the equipment. In that case, a command is successfully sent to the machinery, but the mechanism itself cannot affect the phenomena it is supposed to control. As a result, remote operators' commands are not executed properly or are not executed at all, which could have catastrophic consequences.

All reviewed papers mentioned four control actions essential for the operations of remotely-controlled vessels (#15 through #18). However, there are few explicit statements pertaining to the communication link arrangement within the reviewed documents. It is rarely said that data is transmitted between the vessel and the SCC by any medium or via any device whatsoever. Instead, vague statements such as *remote communication* or *remote monitoring* are used without any reference to the actual technical or organizational solutions. Nevertheless, we have decided to include these references within our analysis as they reflect a *general* understanding of the arrangement. Similarly, only a few authors consider the interaction of the remote operator with a control software (CAs #11 & 12) - this is mainly done when considering situation awareness issues (MacKinnon et al., 2015; Man et al., 2018).

Table 5
References to control actions - case study.

#	The statement within the paper	CA no.	Control action name	Rationale for assigning a reference to a control action
1	*operators' tasks […] will be guided through procedures*	10a	Operational procedures and their updates	A clear reference to procedures to be followed by operators
2	*success of the tasks relies on […] training*	10c	Training	A clear reference to the fact that operators shall be trained
3	*Obtain information through system*	11	Collection of operational data	Reference to the fact that an operator shall collect some data by the use of a human–machine interface (HMI)
4	*Remotely control ship to safe path*	12	Decisions elaboration	An umbrella term used in the said article to describe decision making and execution by an operator to operate the system
5	*path planning*	13	Creation/update	A reference to what is also known as *passage planning* in maritime navigation practice
6	*Intentions of own ship*	14	Check of the passage plan	An activity of monitoring the ship's progress in accordance with the passage plan
7	*The SCC is linked to the ships using the available communication technologies*	15	Decisions' relay	A reference to the existence of a (two-way) communication link between SCC and a vessel with the utilization of certain technical solutions
8	*The SCC is linked to the ships using the available communication technologies*	16	Feedback relay	
9	*The SCC is linked to the ships using the available communication technologies*	17	Decisions' relay	
10	*The SCC is linked to the ships using the available communication technologies*	18	Feedback relay	
11	*information available on the screen during regular operation ([…], fuel, equipment status […])*	21	Sensing	A reference to the real-time engineering data that must be collected by the sensors in order to be displayed to the operator
12	*information available on the screen during regular operation ([…], fuel, equipment status […])*	22	Sensing	
13	*Monitor ships status*	23	Data on equipment and processes' status transfer	Information pertaining to the operational status as collected by sensors must be transmitted to the central control system in order to be relayed to the SCC
14	*information available on the screen during regular operation ([…], fuel, equipment status […])*	24	Sensing	A reference to the real-time engineering data that must be collected by the sensors in order to be displayed to the operator
15	*Remotely control ship to safe path*	25	Equipment set-points update	The umbrella term of 'remotely controlling ship to safe path' includes issuing a command for certain equipment to change its set-points: rudder angle, main engine revolutions etc.
16	*Evaluate speed, distance, direction of own ship*	27	Sensing	A reference to the need of assessing the navigational parameters of the vessel through probing her movements etc.
17	*information available on the screen during regular operation (own ship status – speed, direction, […] weather; waves; surroundings)*	28	Transfer of data on ship motions and environment	Implies that an information collected by various environmental sensors must be transmitted to the operator via the vessel internal network, communication subsystem etc.
18	*In addition to […] weather; waves; surroundings), the operators should have information about […]*	29	Sensing	Underlines a necessity of measuring the components of the environment (and providing the operator with this information).
19	*would trigger a warning at the SCC*	36	Warnings	A reference to the system of triggers and warnings that would attract SCC operators to certain phenomena.
20	*Communicate with VTS*	39	Requests or commands	A direct reference to the need of establishing a two-way communication with shore authorities, such as a Vessel Traffic System
21	*Communicate with VTS*	40	Reports	

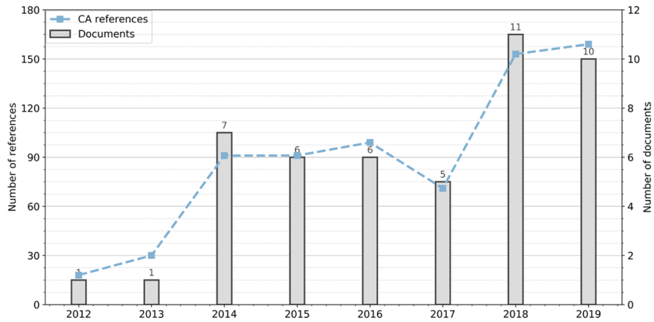

Fig. 4. Number of references and documents by year.

4.2. Limitations of the study

4.2.1. Dataset preparation and analysis

Like every study, the hereby research faces some limitations. Although the autonomous ships could have a potential to change the entire shipping industry, a surprisingly low number of publications relevant to the field of remotely controlled merchant ships has been found as a result of the web search. This indicates a potential incompleteness of the search itself. Phrases such as *remotely controlled ships* return as much as 16,900 results as of May 2019 when typed in *Google Scholar* search engine. However, the vast majority of these results pertain to different domains such as hull-cleaning devices, remotely controlled electric airplanes, ship-borne gravity stabilized antennas, etc.

Therefore, it was necessary to narrow the data sample merely to the papers related to the scope of the study. However, due to the lack of official definition of a *merchant ship* and vague meanings of terms associated with unmanned shipping, such as *autonomous* or *remotely-controlled*, the process of data filtering had to be carried out personally by the authors. It is therefore possible that some highly relevant papers may have been omitted in the process of data sample preparation. The scrutinized sample should not be considered as complete and comprehensive. The fact that a literature review has been performed manually inevitably caused subjectivity in sample preparation, due to the conforming of criteria. It could also lead to the potential omission of certain findings, references to CAs in this case.

Moreover, the publications used in the review were not limited to a particular type, like journal papers. From one side, it allows for finding interesting documents, which are valuable for the analyzed topic but due to their type (technical reports, academic thesis), they are not indexed in the core collections of peer-reviewed scientific databases like *Web of Science* (WoS). For different types of documents, their structure and publishing requirements differ.

For the purpose of results analysis, we assumed that each reference to a particular control action is equally relevant. This may not always be the case as each scientific paper shall have its main line of argument and a story to be told built around this rationale. Nevertheless, some subplots are always present. Initially, we attempted to distinguish references to control actions between those that belong to the main stories and those that do not. This turned out to give poor results, as only three references could be unambiguously identified as belonging to the main stories as provided within the titles of the documents. The number was rather low when compared to a total of 712 references found. We therefore abandoned the idea of making a distinction to more and less relevant references. The above can indicate that only some high-end considerations of autonomous shipping can be performed presently, covering various aspects at once. This, in turn, is most likely caused by the fact that the technology of autonomous shipping remains at a relatively early stage of development. As of late 2019, some prototypes have only been implemented and demonstrations performed (Brekke et al., 2019; Kutsuna et al., 2019).

4.2.2. The (in)correctness of the original model

For the purpose of the herein study, we have assumed that the original safety control structure (Wróbel et al., 2018b) based on the system-theoretic approach has been developed to a good effect, correctly and comprehensively. Nevertheless, since it has been elaborated through a literature study and expert elicitation, it may contain some subjectivity itself. No attempt was made to improve or change it. Due to the above, there might be some unexplored aspects of MASS operations relevant or critical to their safety that have not been identified during the elaboration of an original safety control structure. By this, they were also not included in the analysis as they would not fit into any of the analyzed interactions. For the same reason, the contributions of reviewed papers may not fully reflect the current state-of-the-art in the research on MASS safety as the herein analysis may be distorted by the original framework. Only the references to interactions included in the safety control structure would be included in the analysis. Should the original safety control structure be constructed somewhat differently (in any sense), the results of its closer investigation through a literature review would also be dissimilar.

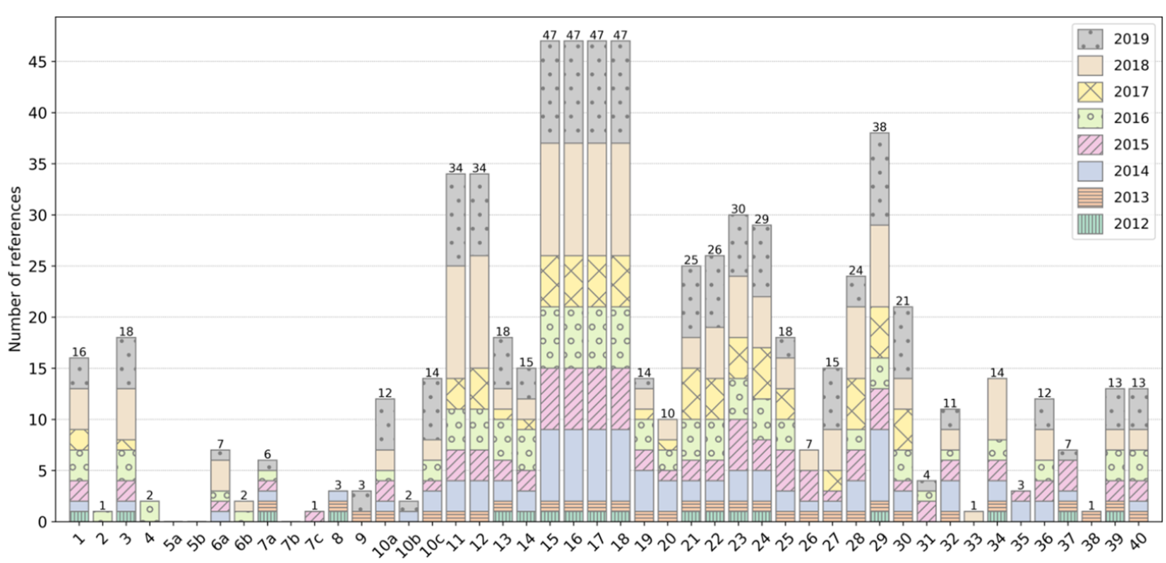

Fig. 5. References to particular control action in each analyzed year.

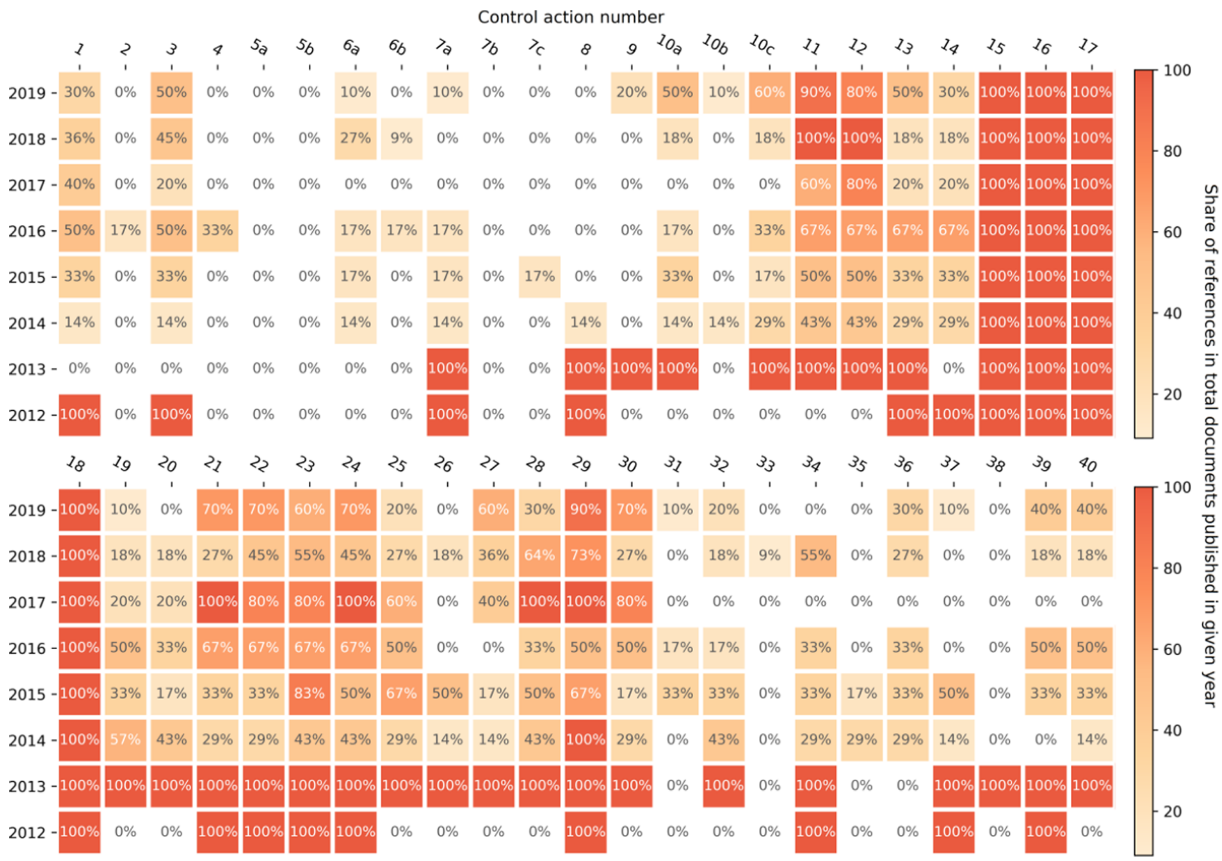

Fig. 6. Breakdown of CA references in consecutive years in relation to total papers published in a given year.

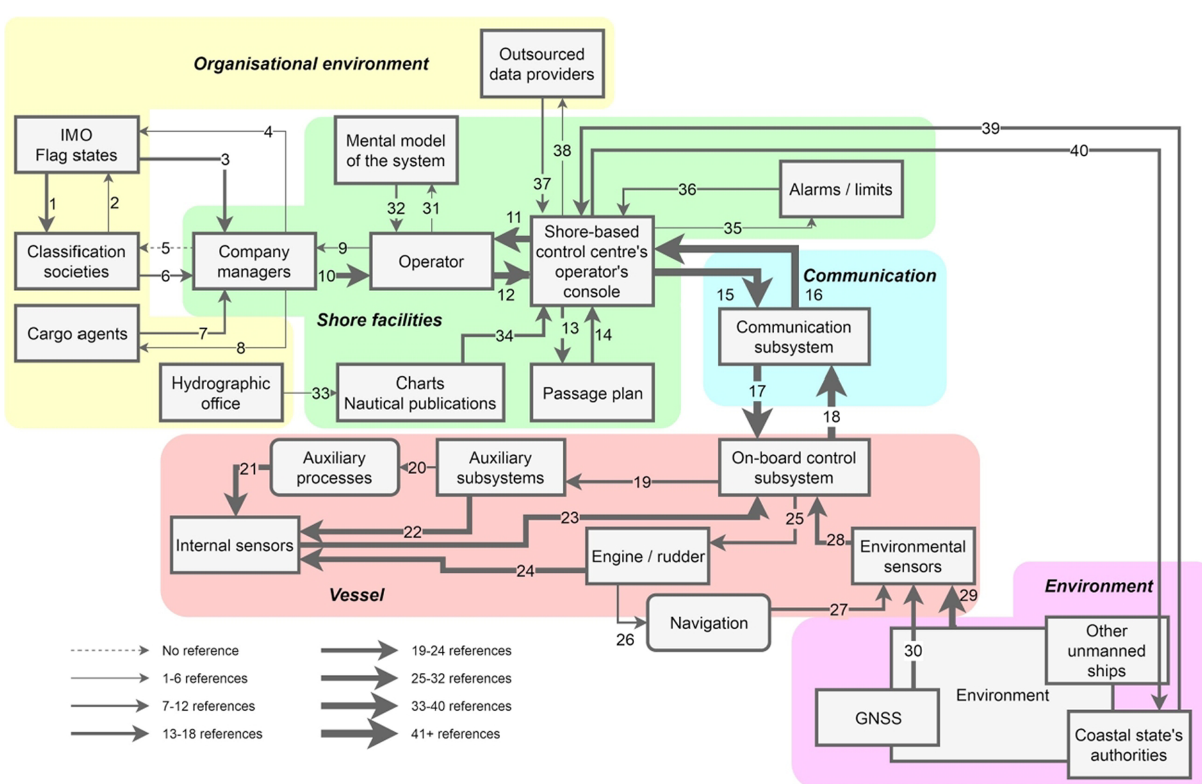

Fig. 7. Total number of references related to specific control action.

5. Conclusions

In therein paper, we aimed at identifying the research directions within the domain of remotely-controlled merchant vessels, based on a previously-developed framework that utilized a system-theoretic approach. Within this framework, we have determined that the vast majority of papers published to date focuses on technical aspects of the said ship operations and design. This can indicate that the topic is underexplored, and additional research is still needed. On the other hand, since autonomous ships are still at a conceptual phase with only a few prototypes afloat, it might be the case that only technical factors are sufficiently explored. Therefore, researchers focus their efforts on them, in order to avoid concluding on unfinished businesses. Other factors (organizational, legal, social, etc.) might be characterized by greater uncertainties at this point that any inquiries into it would be nothing else but wandering into the fog. On the other hand, more intensified research work on these topics might help develop a safe and efficient autonomous shipping system. With technical advancements being developed, what is sometimes believed to be *secondary concerns*: organizational and social issues, lag behind. However, these are at least as relevant for the safety and performance of prospective autonomous systems and must therefore be investigated more thoroughly.

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