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A method for uncertainty assessment and communication in safety-driven design - a case study of unmanned merchant vessel

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Abstract

As the projects on unmanned merchant vessels' technology development and implementation progress, the ships' impact on maritime safety remains largely unclear. Safety is one of the industry's top priorities and a crucial value required for unmanned means of transportation to be accepted by public. Although concept works included safety assessments from their very beginning, results of those were inevitably burdened with uncertainties due to the fact that little is known about prospective systems' design and no empirical data pertaining to their performance is available. As a matter of fact, rarely was the magnitude of uncertainties evaluated and communicated. Such communication may be crucial for future decision-makers to make informed decisions regarding the systems' design and performance. Therefore, we apply a system-theoretic approach to analyze one of the potentially critical aspects of unmanned shipping, namely vessel's transition between remote and autonomous operation with respect to existing hazards and ways of ensuring that safety is not exposed during the process. Furthermore, we apply a method of analyzing and communicating uncertainties pertaining to such safety assessment, by the uncertainties' magnitude categorization. The optimum way of providing designers with information about strength of knowledge supporting the safety analysis is sought.

Keywords: STPA, safety analysis, uncertainties, unmanned shipping

Introduction

With a systemic approach to safety gaining wider attention and acceptance among academia [1], some of its drawbacks have begun to surface. It is postulated that methods based on this approach, such as the System-Theoretic Accident Model and Process (STAMP) can be further improved by for instance addressing issues with assessing feasibility of safety recommendations [2], research-practice gap [3] and potential uncertainties [4]. The information on the latter is claimed to be a significant output of safety analyses and input for decision-making [4]. Moreover, it is an obligation of the analyst to consider (and communicate) the potential for and consequences of an error [5]. The strength of data supporting safety evaluation shall therefore be communicated [6] but little attention has been devoted to this aspect to date among the system-theoretic safety community. In order to bridge this gap, we take the opportunity of a novel technology (unmanned maritime navigation) emerging to elaborate the method of assessing and communicating uncertainties pertaining to system-theoretic safety assessment process.

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From the technical and economical points of view, the implementation of unmanned cargo ships can be feasible [7,8]. Throughout the research projects' deliveries [9–12] and in the increasing number of scientific papers based on the former, the general vision of an unmanned vessel is to a great extent consistent [13–16], but the actual shape of the system remains unknown. They are nevertheless expected to operate on various levels of autonomy and it is the very process of transition between remotely-controlled and autonomous mode that is in scope of our study. This aspect of a vessel's operation is crucial for her safety for (i) either mode has been implemented in shipping to only a very limited extent to date and (ii) malfunction during the process can leave the ship non-operational at high seas.

Therefore, we apply the System-Theoretic Process Analysis (STPA), a method suitable for assessing safety of novel endeavors [4] to identify and analyze the safety control structure of the autonomy mode transition process. Thence, we use this example to introduce a method of categorizing and communicating the uncertainties pertaining to the potential measures of enforcing safety constraints. Such input to the decision-making process can prove beneficial as it describes the strength of arguments being in favor of considering the particular mitigation measure's suitability.

The paper is structured as follows. Section 1 introduces methods applied in the study: the STPA enhanced by uncertainties' evaluation. In Section 2, a brief description of the evaluated process is given together with the safety control structure of the process. Section 3 presents the results of the uncertainty analysis. These are then discussed in Section 4 which is followed by concluding remarks.

1. Methods

Brief description of System-Theoretic Process Analysis (STPA) in Section 1.1. is followed by an introduction of an uncertainty assessment method.

1.1. System-Theoretic Process Analysis - STPA

STPA is a method of assessing a system's safety by analyzing the interactions between its components [17] and the ways in which those can be unsafe [18]. The nature of such interactions shall ensure that the system as a whole remains within safety limits [19,20]. The violation of the defined safety constraints may lead to the emergence of a hazard (a system state or set of conditions that, together with a particular set of worst-case conditions, will lead to an accident).

As a preparation for STPA, a model of the process's safety control structure, depicting mutual relationships between system's components, is developed. Consequently, control loops within it are investigated and a potential for inadequate control is identified. Four potential ways of control action's inadequacy can be distinguished as below:

- a) A control action required for safety is not provided or not followed;
- b) An unsafe control action is provided;
- c) A potentially safe control action is provided at the wrong time or in the wrong sequence;
- d) A control action required for safety is stopped too soon or applied too long [18,20,21].

Thence, each control action is examined with respect to these four potential ways of inadequacy. Components involved and failure scenarios are identified and ways of mitigating the potential for inadequacy recommended [1].

In order to perform the STPA, a list of hazards was created in order to systematize knowledge regarding the safety of an unmanned merchant vessel's process of autonomy mode shift. Following this, a safety control structure was elaborated. This was achieved by reviewing the available literature pertaining to unmanned merchant vessels, including [9,11,15,16,22–26].

As the whole concept of an unmanned vessel capable of crossing oceans is still at a relatively early development phase as this paper is being written, some vital information pertaining to the system's actual shape can be lacking or incorrect. We therefore perform the research on a low level of detail so as to reduce potentially negative consequences of analyzing an incorrect structure. As a matter of fact, it is the Authors' great hope that this paper can contribute to the future solutions' safety as a part of the 'safety-guided design' process.

1.2. Uncertainty assessment and communication

The very purpose of safety analysis is to provide an input to the underlying decision making [27]. It is argued that an analyst is obliged to consider consequences of his/her error, which can only be done by identifying and assessing uncertainties pertaining to the study's results. Wrong or weak assumptions, poor data or unreliable models may lead to unjustified conclusions within the safety assessment and eventually to wrong decisions [5,28–31]. The magnitude of uncertainties itself can be an important factor in the decision-making process [32]. In the presence of important uncertainties, decision-makers may justifiably opt for additional protective measures, which would increase the costs of the enterprise in question [5].

As argued, STAMP and related tools reduce the uncertainties by themselves as they offer a more insightful look into the system behavior [1]. However, they must not be considered as a perfect tool that eliminates the uncertainties completely. One of the main reasons for this is that the STPA is very often used to assess the safety of innovative endeavors, whereas little is known about (future) system's actual layout and behavior, particularly in extreme conditions. Evaluating, communicating and apprehending uncertainties can be of paramount significance.

One of the first attempts to include an uncertainty analysis in STAMP was given in [4] where the strength of knowledge supporting the system-theoretic analysis was postulated as the most important factor to be included. In order to expand this approach, we modified the 'degree of uncertainty' scale as described in [27] (and argued in [5,33,34]) by considering each of 'uncertainty factors' specified there separately, instead of concluding on the resultant uncertainty. Such an approach allows for a more detailed communication of results, with the selection of factors being of significance for particular aspect.

As a result, each mitigation measure as elaborated during the STPA has been assigned the magnitude of uncertainty related to it in each of five categories as presented in Table 1. This was done in a course of desk study based on literature review. For each mitigation measure, the phenomena, model, underlying assumptions, data and experts' opinions were studied and assigned certain 'uncertainty magnitude' value: significant, moderate or minor based on the given guidelines. These were then communicated in the form of tables

and further analyzed with the purpose of refining patterns such as unusually large amounts of significant uncertainties related to certain solutions or parts of the system.

Table 1. Uncertainty scale, inspired by [27] with modification

		Uncertainty magnitude		
		Significant	Moderate	Minor
Category	Phenomena	Low level or no understanding	Medium level of understanding	High level of understanding
	Model	No basis for models or models give poor predictions	Some basis for models, level of simplifications adopted varies across the model; alternative hypotheses exist	Strong basis for the models, which give good predictions
	Assumptions	Poor justifications for the assumptions made, oversimplifying the analysed phenomena	Reasonable justifications for the assumptions made, although simplifying the analysed phenomena	Seen as reasonable
	Data	Not available or reliable	Data of varying quality is available	Much reliable data is available
	Consensus	Lack of consensus	Various views exist among experts	Broad agreement among experts

The method described has been applied to assess the safety of autonomy mode transition process of a hypothetical unmanned vessel.

2. Model

2.1. Unmanned ships

To this point, unmanned vessels are anticipated to follow an ‘adjustable autonomy’ scheme depending on the condition of ship herself and a mission being executed, see Table 2. Two basic modes of their operations are envisaged: remote control and full autonomy, although they could also be manned by regular crews, if necessary [16].

Table 2: Ship autonomy levels, based on [35]

Autonomy level	Description
AL-0	No autonomous function – all decision making is performed manually, i.e. a human controls all actions at the ship level.
AL-1	On-ship decision support – all actions at the ship level are taken by a human operator, but a decision support tool can present options or otherwise influence the actions chosen, for example DP Capability plots and route planning.
AL-2	On and off-ship decision support – all actions at the ship level taken by human operator on board the vessel, but decision support tool can present options or otherwise influence the actions chosen. Data may be provided by systems on or off the ship, for example DP capability plots, OEM recommendations, weather routing.
AL-3	‘Active’ human in the loop – decision and actions at the ship level are performed autonomously with human supervision. High-impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them. Data may be provided by systems on or off the ship.
AL-4	Human on the loop: operator/supervisory – decisions and action are performed autonomously with human supervision. High impact decisions are implemented in a way to give human operators the opportunity to intercede and over-ride them.
AL-5	Fully autonomous – unsupervised or rarely supervised operation where decisions are made and actioned by the system, i.e. impact is at the total ship level.
AL-6	Fully autonomous – unsupervised operation where decisions are made and actioned by the system, i.e. impact is at the total ship level.

Within the former, the vessel’s systems are to be controlled by a human operator from an office-like facility, sometimes referred to as a ‘shore-based control centre’ (mode corresponding to AL-3). Data gathered by on-board sensors shall be transmitted to the

operator and displayed on a console. The person would then make decisions pertaining to ship's navigation and other processes. The main difference between such vision and today's practice is that a human will remain in charge but will not be exposed to weeks-long separation from social life and risks present at high seas. Such an arrangement creates certain issues by itself [13,24,36,37].

For instance, should the communication link fail, the vessel would be left on her own and would need to handle the situation autonomously (AL-5). This might require going dead in water or navigating to a safer area [38], not to mention some more complicated contingencies [39]. Since the autonomous navigation mode needs to be built-in to handle such emergencies, it can also be used to a greater extent – for the whole process of navigation itself. Herein, the level of the ship's autonomy might be increased up to the point where she would require no more attention than a periodical check. Information provided by sensors would be analyzed by highly-sophisticated data fusion algorithms in order to automatically create decisions regarding virtually all aspects of navigation, cargo conditioning, machinery operations, stability and any other of the vessel's activities [14]. The human operator will remain in the loop to a very limited extent as merely a supervisor, in charge of strategic decision-making (i.e. general passage planning) or a trouble-shooter. It is the vessel's on-board control algorithms that will be responsible for making operational decisions and performing routine tasks. Such a situation could last until an operator decides to take over or a vessel encounters extreme or unexpected conditions and prompts the operator to do so.

When that happens, the system is to perform the autonomy mode transition, the safety of which must be assessed.

2.2. Safety control structure

One of the first steps in STPA is the creation of system-level hazards' list. These include:

- H1. Both human operator and Virtual Captain are in control of the vessel;
- H2. Neither of above is in control of the vessel;
- H3. Improper of above is in control of the vessel.

With regard to H1, it shall be noted that human operator might control certain functions of the vessel while delegating control over other tasks to automatic control algorithms. For instance, an operator can make decisions regarding the ship's speed, but it is the vessel's main processing unit (also referred to as a Virtual Captain, VC) responsibility to elaborate actuation decisions on the main engine's revolutions. Thus, certain routine operations are carried out automatically with the human operator being in over-all control.

Within H3, in turn, the control over certain shipborne processes lies within inappropriate controller for the circumstances prevailing. This may occur when, for instance, Virtual Captain remains in charge during navigation in restricted visibility or high traffic density conditions which is against the basic concept of the system [16].

There are two major circumstances in which the transition between remote and autonomous control is to occur. The first can be attributed to a command to do so being given by an operator (case 'A', see Figure 1). The other instance is when certain operational parameters of the system reach the critical value and the need for transition is

recognized (case ‘B’, see Figure 2). The latter includes cases when the potentially unsafe system condition is detected as well as because of a communication link malfunction.

Herein, the system-level commands are transferred between the operator ashore and the VC via a communication link consisting primarily of a satellite system and its peripherals. These include ship-borne antennas on one side and a shore infrastructure on another with the communication satellite in between. The VC’s objective is to process data either fed by ship-borne sensors or originating from an operator and create ship-level commands as an output. The latter are to be executed by various machinery, just to mention ship’s rudder and main engine. The operator’s actions in turn are regulated by operational procedures of the company managing the vessel and their own experience.

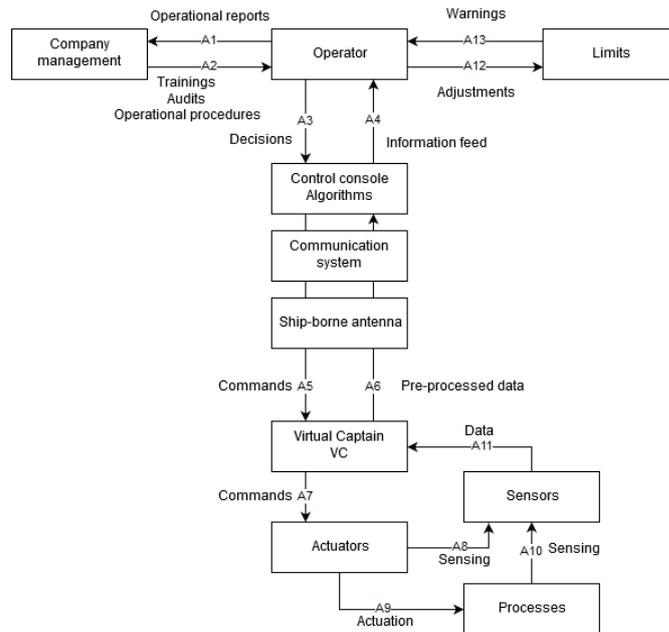


Figure 1. Safety control structures of autonomy mode transition process: case ‘A’: command given by an operator

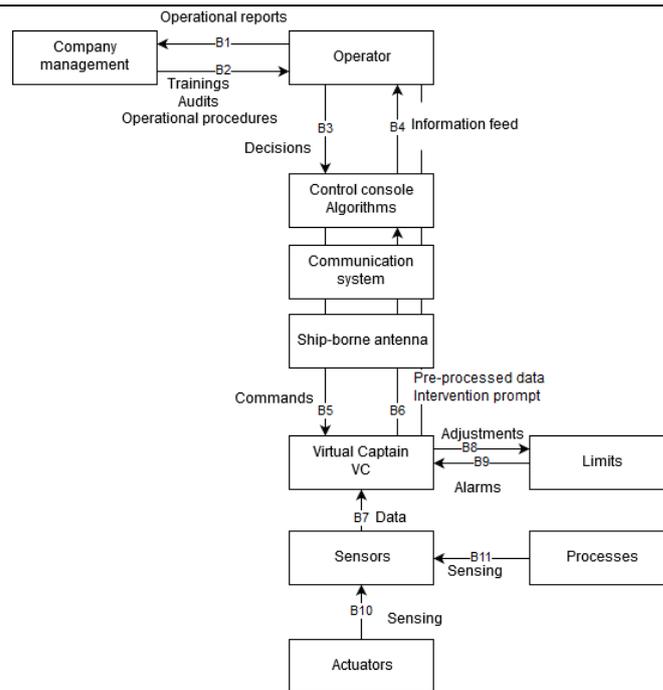


Figure 2. Safety control structures of autonomy mode transition process: case 'B': transition forced due to critical value reached

Having the model created and system-level hazards elaborated, we performed the actual STPA. Each of the control actions as indicated in Figures 1 and 2 was analyzed with respect to potential causal factors and ways of mitigating the inadequacy. Firstly, the potential for inadequate control was identified. Then, possible ways in which hazardous control actions could occur were determined and ways of mitigating such possibilities elaborated.

A total of twenty-nine control actions have been analyzed with as many as 353 safety recommendations elaborated. These belong to three major types covering liveware, software and hardware, although some of the recommendations refer to more than one of these.

3. Results

This Section presents the results of uncertainties' assessment¹.

For each measure intended to mitigate hazards in a process of autonomy mode transition, uncertainties pertaining to its elaboration process have been assessed (see Section 1.2.) and compiled in a form of symbols, indicating the level of uncertainty assigned to the particular mitigation measure (see Supplementary Material available online). Layout of these symbols corresponds to and refers to the relevant rows and columns of Table 1.

The obtained results are summarized in Figures 3-5 where the number of recommendations (hazard mitigation measures) assigned with particular magnitude of uncertainty is given with regard to type of recommendation (as pertaining to liveware,

¹ Due to paper length restrictions, for the full catalogue of control actions please refer to Supplementary Material available under the following hyperlink: <https://goo.gl/ASwU4B>

software or hardware) and covered control action's position within the system (shore facility, communication system or within the vessel itself).

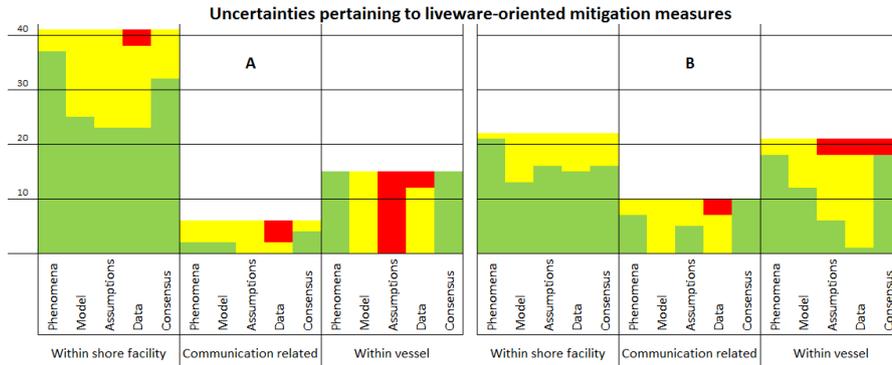


Figure 3. Breakdown of uncertainties pertaining to liveware-oriented mitigation measures by their magnitude

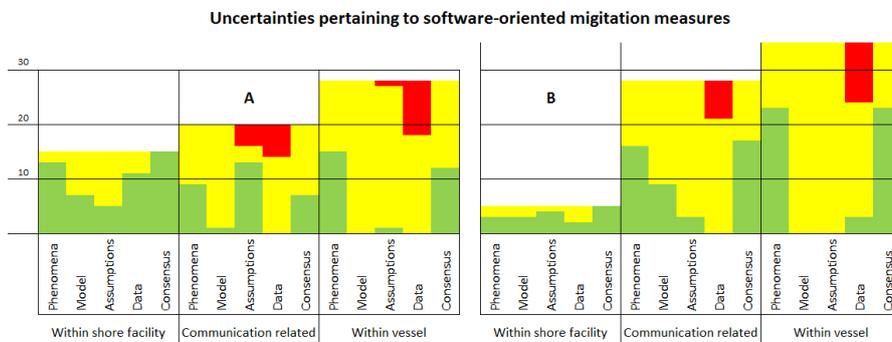


Figure 4. Breakdown of uncertainties pertaining to software-oriented mitigation measures by their magnitude

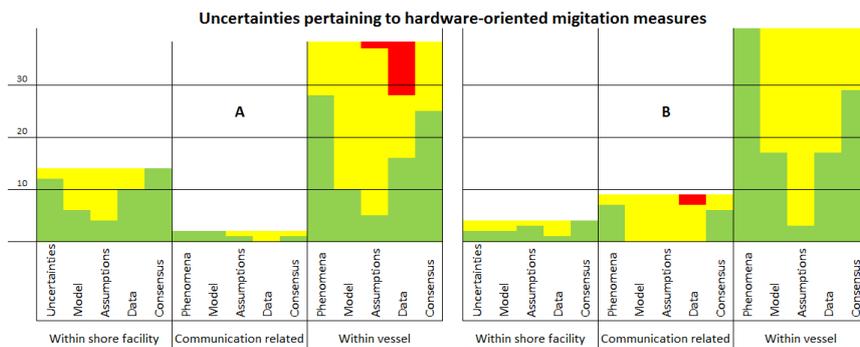


Figure 5. Breakdown of uncertainties pertaining to hardware-oriented mitigation measures by their magnitude

Regardless the fact that vessels in question are to be unmanned by definition, there is a significant number of potential mitigation measures related to liveware as ships' interactions with their operators will play an important role. As can be seen in Figure 3, elaboration of most of the mitigation measures pertaining to liveware can be characterized by a minor level of uncertainty. This is the result of the fact that there are already some procedures existing in remote control of unmanned vehicles, although not necessarily ocean-going merchant vessels. The latter consideration is reflected in the

considerable number of moderate and significant uncertainties assigned to liveware-oriented mitigation measures covering control actions within the (yet-to-be implemented) vessel.

A more detailed discussion of the above results is given in Section 4.

4. Discussion

Within the framework described in Section 1.2., no resultant uncertainty is concluded on based on the magnitudes of uncertainty within five categories as it was postulated in [27]. Instead, uncertainties are communicated in such a way that future system developers and decision-makers can easily recognize aspects of the system requiring additional attention. For instance, a detailed inspection of the uncertainty analysis results (Figures 3-5) leads to the conclusion that assumptions pertaining to operators' remote involvement in on-board activities are fragile, particularly in case 'A' where the operator himself is expected to trigger mode transition. The percentage of 'significant uncertainty' within this group is notable. This may be attributed to the fact that the design of unmanned vessels is expected to differ from this of manned ones in many aspects [12]. Meanwhile, the unmanned vessels' design process as well as the research itself involved individuals having gained their previous experience in 'manned' forms of shipping. Whether their assumptions can be projected onto autonomous shipping is yet to be determined.

On the other hand, certain solutions that have already been implemented in shipping will likely also be present onboard unmanned vessels. This reduces the uncertainties pertaining to hardware issues, but not the software which in turn is to account for fully-autonomous operations that have unlikely been performed to date. This is reflected by the mostly moderate magnitude of uncertainties as depicted in Figure 4.

Nevertheless, a number of 'significant uncertainties' assigned to all groups is rather small in compare to 'moderate' and 'minor' ones, as can be seen in Figure 6. A reason for this could be that there is a relatively high understanding of how the autonomous merchant vessel's system is to be handled in means of design and operation. Experience gained with other unmanned systems is also relevant. The question remains open whether the data or models describing existing systems can be used to assess a similar yet highly-innovative one, as is the case of an unmanned vessel. Such information as well as user experience and tacit knowledge in the form of experts' views should be used with caution as not all aspects of different systems' operation and design can be sufficiently similar to justify its use.

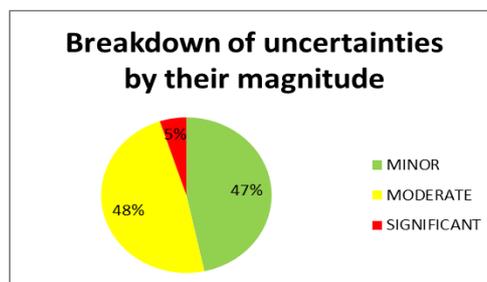


Figure 6. Breakdown of uncertainties by their magnitude

Moreover, uncertainty analysis as applied is not free from shortcomings. Firstly, the method does not ascertain that all potential hazard scenarios have been addressed. Instead, only these mitigation measures that have been elaborated could be further refined into statements pertaining to the uncertainties. The potential for black swans is thus not

eliminated [40]. This is the effect of applying system-theoretic approach, which is said to better model systems' safety performance than previously used methods [1], but still does not guarantee its completeness nor accuracy, due to the incorrect or incomplete safety control structure, for instance [41]. Uncertainty assessment is therefore incomplete, because its input can be incomplete.

Secondly, a relativity of judgments pertaining to magnitude of uncertainty is also not eliminated, thus creating a potential for subjectivity. For instance, it can be difficult for an analyst to distinguish between 'high' and 'medium' level of phenomena's understanding [34]. In such a case, a cautionary or precautionary principles should apply. On the other hand, the very foundation of the presented method lies within describing the extent to which an analyst is convinced that his/her statements are correct, instead of calculating that from hard evidence. Similar effects can be noticed in many of qualitative methods of safety assessment [42].

Thirdly, it is not assessed whether and to what extent a particular mitigation measure can be feasible to implement. Instead, the quality of information describing such mitigation measure is evaluated.

Conclusions

In the course of this study, measures to ensure safety during a transition between autonomy levels of an unmanned merchant vessel have been elaborated and analyzed. Specifically, the quality of data supporting implementation of particular mitigation measures has been assessed. Simple traffic-light symbolism was then used to briefly communicate the results so as to allow future designers of the system to improve their understanding of potentially vulnerable spots where there is insufficient understanding of the phenomena, models are inaccurate or experts disagree with another.

Results indicate that the greatest uncertainties pertain to software solutions, which can be attributed to the fact that it will need to accommodate completely new aspects of a vessel's remote or autonomous control. Nevertheless, the current level of unmanned shipping technology development allows us to assign most of the mitigation measures with either minor or moderate level of uncertainties.

Thereby, the developed method can be used to communicate safety analysts' degree of belief in the results of their work involving the system-theoretic approach to safety. Such assessments of any system or process, not only these pertaining to shipping, either manned or unmanned, can be extended by uncertainties' communication as presented hereby. The potential for further advancements can be sought in more organized method of uncertainty assessment aiming in the reduction of bias (for instance by further refining the criteria) and the reduction of potential for black swans in system-theoretic approach itself. It shall also be verified whether the results of uncertainty assessment had been beneficial for decision-makers.

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