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VerifAI: Framework for Functional Verification of AI-based Systems in the Maritime Domain

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ABSTRACT: With the continuous emergence and steady development of new technologies the way for Maritime Autonomous Surface Ship (MASS) is being paved. However, this manifold of available and imminent technologies challenges regulatory bodies and auditing authorities. Technologies which make use of Artificial Intelligence (AI), in particular Machine Learning (ML), play a special role. On one hand, they are not covered by current regulations or audit processes and, on the other hand, they may represent black boxes whose behaviours are not readily explainable and thus impede audit processes even further. In an upcoming study titled *VerifAI* the authors focus on this gap within European and German regulatory bodies and auditing authorities. The technological scope lies on MASS-related products which rely on partially or fully AI-based systems. In the present article the original authors summarize the outlined study. The authors review the current regulatory status concerning audit processes and the market situation concerning available and imminent (partially) AI-based systems of MASS-related products. To close the gap a conceptual, integrated framework consisting of a Safety Guideline for the manufacturers and a Verification Guideline for the auditing authorities is presented. The framework aims to give regulatory bodies and auditing authorities an overview of necessary steps for robust verification of safe products without hindering innovation or requiring in-depth knowledge about the (black box-like) systems. The results are condensed into recommendations for actions, listing the most important results, and proposing entry points as well as future research in the field of verifying (partially) AI-based MASS-related products.

1 INTRODUCTION

The maritime sector is characterized by an increasing amount of digitisation and automation. Automation of onboard systems plays an increasingly relevant role in the provision of safe operation which is marked by the growing development of autonomous navigation solutions [1]. These solutions can be beneficial to analyse situations proactively and react quickly, leading to an increase in the overall safety of navigation operations. Furthermore, digitisation and automation play an essential role in the development of MASS. The underlying systems are realised through different techniques which can follow simple rule-based approaches up to more complex ML-based techniques.

In this context, AI-based systems (hereinafter called *systems*) are noteworthy due to their promising capabilities. However, to support the conceptualization, development and implementation of these systems and further enable their verification, processes in the maritime regulatory bodies and auditing authorities have to be adapted. The challenge in understanding these systems is their technical structure due to which some systems and their behaviours can be considered a black box, hence not transparent or explainable [2], [3].

The present article summarizes the study *VerifAI* which has been carried out by the German Federal Maritime and Hydrographic Agency and the Fraunhofer Center for Maritime Logistics, i.e. the authors of the present article. In this study the authors present the current regulatory status in Europe and, more specifically, Germany. Available and imminent AI-based MASS-related products (hereinafter called *products*) are investigated as part of a market study. It is outlined how current audit processes do not cover these systems, and how the introduction of feasible, scalable and robust audit processes faces a number of challenges:

- Generalization of the operational domain of the systems
- Data quality management in the development and data procurement during audit processes
- Increasing variety of complex and novel system architectures

To mitigate this gap, the authors developed a conceptual and integrated process framework which consists of a Safety Guideline for the manufacturer and a Verification Guideline for the auditing authority. The framework follows a model-agnostic approach to cover the wide variety of available and imminent AI-based systems. The focus of the framework lies in answering the question of "whether" and not "how" a system is functioning.

The present article is structured as follows: In Chapter 2 related work is presented and compared to the present article. Subsequently, in Chapter 3 the current regulatory status and market situation are summarized and eventually the gap between these two is demonstrated. A proposal on how to close this gap is presented in Chapter 4. The proposed framework can be seen as the novel and main contribution of this article. Subsequently, in Chapter 5 recommendations for actions for regulatory bodies and auditing authorities are derived. The article closes with the conclusion (cf. Chapter 6) and future work (cf. Chapter 7).

2 RELATED WORK

Progress in the field of MASS audit, more precisely testing and verification, can be divided into two parts: firstly, identifying relevant regulatory processes to audit marine equipment and, secondly, looking at state-of-the-art techniques on making the behaviour of such systems auditable.

Research in the regulatory field was constrained to the European Union (EU) as the scope of the investigation is a framework with the aim to be compatible with the existing audit framework in Europe. The current state of regulations on marine equipment is mainly defined in the Maritime Equipment Directive (MED) [4] outlining relevant standards applicable to pre-defined types of equipment. The considered AI-based systems are not referred. Therefore, it is not possible to evaluate the applicability of current regulations for the audit of MASS. Future standardisations could be derived from imminent regulations such as the Artificial Intelligence Act (AI Act) of the EU [5]. However, neither a timeline nor a precise scope can be clarified, by now.

Technical research in the field of audit of MASS is also limited due to the novelty of the underlying products or systems. Early developments of a framework can be seen in the work of Rokseth et al. who describe a methodological approach to assess the overall safety of an autonomous system in the maritime domain [6]. This approach can be primarily applied for the risk assessment of a system but gives no indication of regulatory conformity or methods to be considered.

The approach of Ringbom [7] associates regulatory methods to the level of autonomy as outlined by the International Maritime Organization (IMO) in [8] and illustrates the main challenges of the missing formalization. This perception coincides with the challenges identified by the authors of the present article. The focus of the present article is on level 1 and 4 systems according to IMO. Remotely operated systems are explicitly not evaluated. Finally, Ringbom seeks to clarify some of the key features and terminology related to automation in shipping as well as to illustrate how the different concepts are interconnected. A proposed framework for distinguishing the key elements involved in the regulation of autonomous ships is outlined. The regulatory challenge is assessed through an examination of specific legal hurdles and past practice of the IMO in regulating automation in shipping, with a particular focus on bridge operations. It states that a solid regulatory framework for autonomous shipping operations should be able to deal with variations and should not be limited to a specified level of manning or autonomy.

3 STATUS QUO

The current situation of both, the regulatory status and the market situation, indicate that AI-based systems are not considered, yet. More precisely current regulatory processes do not cover black box-like systems whose behaviour is not explicitly explainable.

A prominent example for a black box model is a neural network. A neural network consists of layers of nodes where each node represents some form of function and is highly interconnected with other nodes. Such a model's behaviour is not readily transparent nor explainable and its audit is not covered by current regulatory processes.

This gap between the regulatory status and the market situation is outlined in the following subchapters.

3.1 *Regulatory status*

According to the International Convention for the Safety of Life at Sea (SOLAS) [9], the market introduction of a novel equipment for a ship requires testing and verification of its manufacturing process, functionality and operation on board the ship. In particular, when equipment is approved with the aim of autonomising processes on seagoing ships, comprehensive testing is necessary to ensure the operational safety.

The verification of the safety of marine equipment in the EU is carried out in accordance with the MED by means of a conformity assessment procedure by notified bodies. Notified bodies are institutions accredited by national authorities which are mandated to carry out verification procedures. The process of ensuring the conformity of a product to be placed on the European market takes place in terms of its design, construction and performance. The EU outlines the conformity assessment process with its possible testing modules and options under the Marine Equipment Regulation [4]

The European AI Act, which is currently being drafted, will have a significant influence on the development of AI-based systems. However, according to Article 2, only Article 84 (evaluation and review) will apply to safety-critical AI-based systems that fall within the scope of the MED. In accordance with Article 78 of the AI Act, in order to meet the requirements the MED shall be amended [5].

3.2 *Market situation*

As already shown in the review of the regulatory status, currently, there is no suitable procedure for the audit of AI-based systems. Therefore, the safety of these systems is in the hands of their manufactures. Obviously, manufacturers do not disclose sensible information about their systems as this could lead to competitive disadvantage.

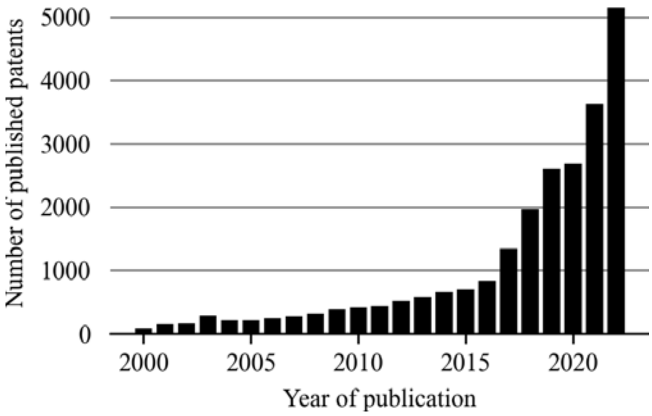

Figure 1. Published patents accessible with the combined search term “ship” and “autonomous” via Google Patents [10].

This lack for comprehensibility of the systems proper functioning is continuously becoming more serious as the diversity, technical maturity and also the number of AI-based systems advances. The increasing number of autonomous systems brought to market can be shown by the growth of international patent applications in the MASS sector. Figure 1 depicts this growth in patent applications published annually from 2000 to 2022 for the combined search term “ship” and “autonomous”. The clearly visible trend may be an indication that the number of AI-enabled products entering the market each year will continue to increase. With reference to the lack of regulatory procedures or auditing processes identified in Chapter 3.1, there is a need to establish appropriate testing and certification processes.

To gain an understanding of the product or system types which are not covered by existing audit processes, a market study was carried out within the *VerifAI* study with a focus on available systems or those close to market readiness. In total 18 systems were identified and subsequently categorized according to their field of application and sensors used as data sources. The resulting tabular overview can be found in the upcoming full-text study. The results from the market study show that frequently used sensors like Radar [11] and Automatic Identification System (AIS) [12] do follow existing information exchange standards. By contrast, every identified system relied on camera systems from the visible red, green, blue (RGB) range, despite any standards. In particular, the use of camera systems, be it RGB, infrared or other ranges, and subsequent AI-based processing poses hurdles due to a lack of standards in the maritime context. Consequently, audit processes for such AI-based systems cannot be standardised and the audit takes additional effort compared to systems with standardised information exchanges.

4 CONCEPTUAL FRAMEWORK

In this chapter, our framework is presented which supports at closing the gap between the illustrated regulatory status and market situation. The proposed approach consists of two guidelines:

- *Safety Guideline* for the manufacturer.
- *Verification Guideline* for the auditing authority.

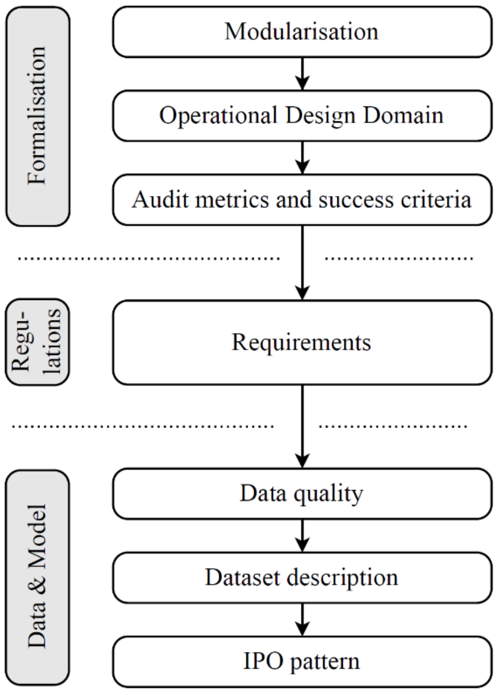

Figure 2. Concept of the Safety Guideline based on three process stages: *Formalisation*, *Regulations* and *Data & Model*.

The integration of both guidelines makes sure that through its life cycle the AI-based system meets audit-facilitating requirements. Thus, the two goals of the Safety Guideline (cf. Figure 2) are: 1) ensure the auditability of the (black box-like) AI-based system and 2) the development of a sufficiently safe system with chance of successful verification. It is recommended that the manufacturer takes the Safety Guideline into account early in the life cycle, i.e. in the concept phase.

The Verification Guideline (cf. Figure 3) is directed at the auditing authority. It follows two goals: 1) audit of proper functions in terms of information technology and safety 2) a robust certification process.

The manufacturer prepares the audit by providing the following content to the auditing authority:

- AI-based system which is modularised into (AI-based) components
- functional description of each component
- input and output description of each component

The above-mentioned content is provided by the manufacturer as part of the audit. Both technical descriptions are based on the concepts of Input-Process-Output (IPO) patterns and having a well-defined Operational Design Domain (ODD) (cf. Chapters 4.1 and 4.2)

4.1 *Concept of a Verification Guideline*

The first process stage *Preliminary Audit* consists of four processes. Initially, it must be verified that the present system, conform the criteria of being an AI-based system. This implies that, on one hand, there is a clear definition of AI in the audit context, and on the other hand, that at least one component of the system conforms this definition. Next, the auditing authority has to make sure, that the present system is sufficiently modularised into components for the audit. Based on IPO patterns, this is the case when the description of the present system components behaviours cover and associate all inputs with their corresponding outputs. As a result, it is clear to the auditing authority which system components must be audited and how each of them functions according to the IPO pattern. For this purpose, concepts as suggested by Burmeister et al. can be adduced [13]. Subsequently, the ODD of each system component is checked for completeness. It is considered complete when the ODD of each component clearly defines its boundaries, the range of input and output values and which input values have been applied during the development. Even though aiming at automotive industry, a conceivable framework for the formalization of ODD is presented by Gyllenhammar et al. [14]. This framework is extended by Rødseth et al. specifically towards autonomous ship systems [15]. As a result, for each component, it must be clear which output is expected for which input. In the last process step of the *Preliminary Audit* stage, the provided audit metrics and success criteria are checked. The provided audit metrics must enable the auditing authority to measure the functioning of each component based on how the output values meet the expectations given for test input values. Corresponding success criteria enable the evaluation of success by indicating how close the output values meet the actual expectations. A component is functioning properly when it complies with the success criteria. As mentioned before the proposed framework follows a model-agnostic approach. Applied to the Preliminary Audit this means, that the auditing authority must be enabled to answer "whether" a present system is functioning properly and not "how" it internally does.

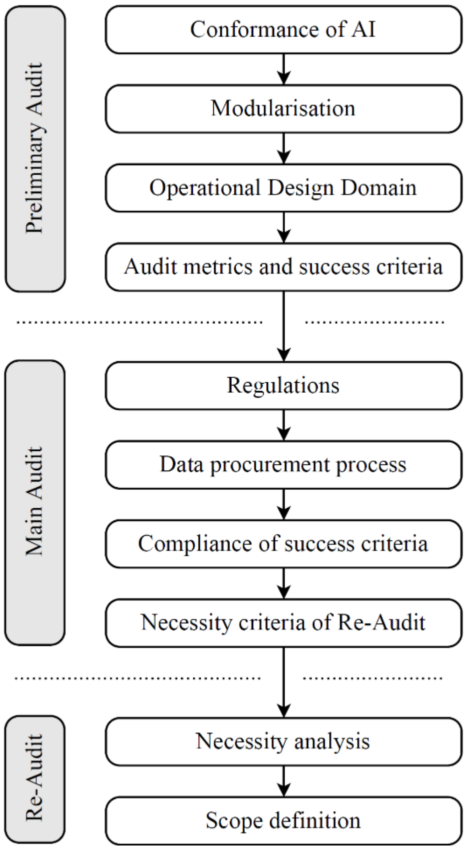

Figure 3. Concept of the Verification Guideline based on three process stages: *Preliminary Audit*, *Main Audit* and *Re-Audit*.

When the audit framework has been checked successively in *Preliminary Audit*, the *Main Audit* follows (cf. Figure 3). In the first process step, the auditing authority has to make sure that the AI-based system complies with applicable regulations for example acts, such as the forthcoming AI Act [5], or norms, such as the National Marine Electronics Association (NMEA) 0183 standard [16]. In the subsequent process step, the auditing authority procures test data for the audit. Due to the technical description of the input values description which is delivered by the manufacturer (cf. Chapter 4) the auditing authority should be able to procure appropriate data. Data procurement can be based on the acquisition or recording of real data, augmenting existing data or generating synthetic data. It is important to note that it must be ensured not to use test data which has been already used by the manufacturer during the development, i.e. training, of the model. Otherwise, results will be distorted for the benefit of the AI-based system. A conceivable solution to this problem may be situational synthetic data generation [17], [18], [19]. These approaches are also being progressively developed for image data as it is known to the broad public in case of *DALL-E 2* [20] and *Stable Diffusion* [21]. When an appropriate dataset is available, the actual audit process follows. Now, data can be applied to the AI-based system components. Due to the technical description of the functioning of the system components (cf. Chapter 4) the auditing authority can measure and evaluate the system behaviour by applying corresponding audit metrics and success criteria. When this audit is passed, the last process step of the *Main Audit* stage follows. As concluding step, the auditing authority must define criteria which define the necessity of a re-audit. Typical criteria can be intrinsically motivated, e.g. because of a software update of a system component, or extrinsically motivated, e.g. due to environmental changes in the ODD of a system component.

After the Main Audit stage, when passed, the testing and verification of the present AI-based system is finished. However, as defined in the necessity criteria, a re-audit can be prompted on event- or time interval-basis. If so, the scope of this re-audit must be defined. The re-audit can be narrowed to specific components of a system, reducing the need to re-evaluate the whole system and only re-certify changed components.

4.2 *Concept of a Safety Guideline*

The first process stage *Formalisation* consists of three process steps. In the beginning, the manufacturer must make sure that the present AI-based system is sufficiently modularised. This prerequisite is explained in Chapter 4.1. The manufacturer can lay the foundation of the modularisation early in the life cycle of the system. The advantage is that the audit can be performed module-wise, thus subsequent improvement must not affect the entire system, necessarily, but only specific modules. Then, each module must be given a dedicated ODD. Methods for formalizing an ODD are mentioned in [15] using the operational envelope, also techniques described in [14] can be utilized to create a uniform domain description. In the final step of the process stage *Formalisation*, the manufacturer specifies audit metrics and success criteria by which the functioning of each module is measured and evaluated in the audit. The methodology of a metric for a module strongly depends on the purpose of the given module. Examples, such as the confusion matrix in case of classification problems, are given in [22]. The success criteria on how well the modules perform are expressed by the given metrics. By applying metrics and criteria which are commonly used or required per standard the manufacturer facilitates comparability of the present system.

In the subsequent process stage *Regulations* the manufacturer is advised to examine if his AI-based system is affected by prevailing or imminent regulations. These can be standards such as the NMEA 0183 standard [16], acts like the imminent AI Act [5] or other regulatory decisions.

In the last process stage *Data & Model* the manufacturer provides a description of the used data and the functioning of the present system. This shall benefit a well-performing system and thus a positive verification. Data quality is the first part since it plays a significant role by reflecting a model's potential experience and knowledge through the range of scenarios on which it is tested and developed. The variety of manifestations of bad data quality in general and in ML-based systems, specifically, as well as its assessment, is described in [23]. Subsequently, the applied dataset must be described module-wise by the manufacturer. This is an obligatory step in the preparation for the audit. Based on the dataset description, the auditing authority should be able to procure suitable test data. Therefore, the dataset description must, on the one hand, describe the comprising data, e.g. its values and value ranges, and on the other hand, the statistics of the dataset, e.g. the distribution of certain values applying descriptive statistics [24]. In case of publicly available or acquirable datasets, the manufacturer must report this additionally so that the auditing authority is aware of which datasets not to use. Finally, in the last process step, *IPO pattern*, another obligatory step in preparation for the audit takes place. The manufacturer needs to describe the expected functioning of each module from the AI-based system. To do so the manufacturer shall make use of descriptions based on IPO patterns. More precisely, the functioning of each module is described by specifying output values to their input values.

In the subsequent chapter, recommendations for actions are derived from the proposed framework. These recommendations aim at facilitating the implementation of the process steps proposed in this framework.

5 RECOMMENDATIONS FOR ACTIONS

The following recommendations for actions were derived during the development of the framework for functional verification as outlined from the full-text study *VerifAI*. These recommendations serve as a basis to establish a basis for the collaboration between regulating bodies, to standardise the audit procedures for MASS and identify future work.

5.1 *Location of testing and verification processes in a separate module K*

In consideration of the existing publications of the European Commission as well as the procedures in the MED, it is recommended to introduce a separate module into the existing testing and verification processes. It is obvious to locate the testing and verification processes for AI-based systems presented in this separate audit module. This allows the proposed processes (cf. Chapter 4) to be integrated without having to adapt existing modules.

5.2 *Standardisation of the exchange of information in AI-based systems*

It is recommended to promote the standardisation of information exchange and data sources for the testing and verification of AI-based systems. Standards can significantly simplify and scale the testing and verification processes. Exemplary standard procedures can be seen in [25].

5.3 *Introduction of a model-agnostic testing process*

In order to be able to test the manifold of AI-based systems in a uniform manner and to ensure the future viability of the testing process, the establishment of a model-agnostic testing process is suggested (cf. Chapter 4.1). The focus of the test should be to determine "whether" and not "how" an AI-based system functions properly. This approach enables the feasibility, scalability and comparability of the audit processes.

5.4 *Formalization of the operational design domains of AI-based systems*

To enable uniform testing, it is advised to rely on a standardised formalization of both the description of the operation domain as well as of the measurement and evaluation of functional performance (cf. [14], [15], [13]).

5.5 *Development of an automated data processing infrastructure*

The technical realisation of the testing processes should be based on an automatable data processing infrastructure to ensure scalability and reproducibility. For the data procurement process, it is fundamental to rely on standardised operation domain descriptions of present systems (cf. [14], [15], [13]). Notably, the use of synthetic or augmented data is a promising way to independently obtain the necessary test data at any time without building up long-term data dumps (cf. [17], [18], [19], [20], [21]). A crucial advantage in using synthetic (or augmented) test data is the generation of novel test data which was not used by the manufacturer before.

6 CONCLUSION

Current regulatory procedures are inadequate to assess maritime AI-based systems (therefore referring to MASS) as shown in Chapter 2. New processes have to allow systems with a wide variety of architectures to be tested, verified and brought to market in a safe manner. It is therefore needed to introduce concepts which can be implemented parallel to existing procedures and measures without interfering with innovation or safety. The authors, therefore, propose the introduction of a new Module in the framework of the MED labelled *Module K* consisting of guidelines for the manufacturer of an AI-based system and the regulating body responsible for verifying, testing and approving such a system. The guidelines include steps which should be performed to address concerns arising from bringing these systems on the market whilst keeping the amount of required in-depth knowledge about their internal functions to a minimum, essentially allowing for a black box testing procedure. The proposed methods are a basic outline of how such a methodology could be implemented to allow the verification of MASS. These methods can serve as a guideline to specify future research and narrow down the fields which must be investigated further.

7 FUTURE WORK

Despite the given possibilities for modelling complex dynamics and correlations with the help of large amounts of data, the application of AI with ML methods, especially through deep learning, is problematic. The quality and reliability of the decision-making processes and consequent results of given models are directly dependent on the selection of the algorithms and quality of datasets.

Furthermore, the range of available datasets for testing the models is severely limited, making it difficult to generalise and solve a problem using ML methods. One approach to address that issue is to establish methods and processes in the development phase of safety-critical applications to maintain safety and robustness after deployment. Processes and methods from other areas, e.g. for computer vision applications, could be adapted by transferring findings to the maritime domain. Another important aspect is how to define and justify methods, processes and requirements for datasets and their procurement, since they are crucial for the development of robust systems based on AI, more specifically ML.

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