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LEAS: An AI-based Demonstrator as Decision Support Tool for Traffic Monitoring at VTS Centers

T. Stach & P. Koch
Fraunhofer Centre for Maritime Logistics and Services CML, Hamburg, Germany

ABSTRACT: Maritime traffic is prevalent worldwide, with particularly high density in coastal waters. To ensure safety and efficiency, Vessel Traffic Service (VTS) centers monitor and coordinate maritime traffic. For this purpose, VTS centers utilize various sensor and communication technologies such as radar, Automatic Identification System (AIS), electro-optical systems or radio communication. Additionally, any Vessel Traffic Service Operator (VTSO) is motivated to utilize a Decision Support Tool (DST). The LEAS project addresses emerging challenges at VTS centers. One key challenge results from the continuous evolution of maritime traffic, in particular, its ever increasing automation and autonomization. Another key challenge is the growing shortage of skilled workers. Consequently, it is crucial to process increasing volume of maritime traffic data while maintaining or improving safety and efficiency. DSTs at VTS centers must be adapted to these emerging challenges, accordingly. In the LEAS project, we develop and evaluate a demonstrator which represents a DST. This demonstrator is being developed in close collaboration with VTSOs to address these challenges. Most notably, it has a situation detection which makes use of Artificial Intelligence (AI) methods and displays relevant information in an intuitive Human-Machine Interface (HMI). The demonstrator is evaluated using simulated traffic scenarios in the German Bight and Baltic Sea, with VTSOs as test subjects. This paper provides an overview of the project and demonstrator. First, we introduce the key requirements for the demonstrator and discuss their impact on the system architecture. Next, we present its AI-based situation detection. We explain the underlying formalism of the situation detection and resolution as well as its implementation in the demonstrator. Finally, we evaluate the capabilities and limitations. The paper concludes with an outlook to future work with focus on potential deployment at DST at VTS centers.

1 INTRODUCTION

Maritime traffic plays a substantial role in global trade. More than 80% of world trade volume is transported by sea [1]. In coastal waters the maritime traffic density is particularly high. To ensure safety and efficiency of the maritime traffic, so-called Vessel Traffic Service (VTS) has been established [2]. VTS centers world-wide monitor and coordinate maritime traffic. To do so they rely on various communication and sensor technologies. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) provides guideline concerning technical requirements for VTS systems [3]. In Tab. 1 the most common communication and sensor technologies are summarized. Based on the given technologies a Vessel Traffic Service Operator (VTSO) can obtain situational awareness of his designated VTS territory.

To enhance the situational awareness of the maritime traffic the IALA motivates VTSOs to use

Decision Support Tools (DSTs) [4]. Accordingly, a DST should support the VTSO by various means:
– "provide alerts and indicators"
– "reduce the workload"
– "enhance efficiency"
– "be accurate and in real time"

Table 1. Communication and sensor technologies of VTS centers as defined by IALA in Guideline G1111 [3].

Technology	Provided Information
Radar	Direction and distance to target and its motion direction and velocity.
AIS	Static, dynamic and voyage related information about target.
Environmental monitoring	Hydrological (e.g. height of tide) and meteorological (e.g. visibility) conditions.
Electro-optical systems	Images or videos at daylight or during night-time.
Radio communications	Verbal communication, specifically over VHF radio. Contains background information on coordination and navigation decisions.
Radio direction finders	Bearings of targets in vicinity.

As pointed out in a previous article, current VTS systems and DSTs have many technical limitations [5], [6]. VTS centers collect a high volume of multimodal data through communication and sensor technologies (cf. Tab. 1). However, there is no known VTS system or DST which fuses the multimodal data stream and creates a holistic situational awareness. For example, AIS data could be fused with VHF radio communication to provide more contextual information on arising situations.

Instead VTSO rely on manual tools such as creation of threshold-based, spatio-temporal alerts. From differences in regulatory and physical properties of VTS territories, differing traffic patterns result. Thus, substantial experience is mandatory with respect to each VTS territory. Also, here Machine Learning (ML)-based techniques could have been by applied. For example, automatized statistical analyses and extraction of traffic parameters can represent human experience to some degree.

The urgency for novel DSTs is exacerbated by external factors. On the one hand, VTS is facing constant evolution of maritime traffic, in particular, increasing automatization and autonomization. On the other hand, the shortage of skilled workers at VTS centers is increasing as stated by cooperating VTS centers in Travemünde and Warnemünde and incident investigation reports [7]. This creates a growing gap between the ever-changing monitoring and coordination tasks and available skilled workers. The growth of this gap impairs the safety and efficiency of maritime traffic. Already today, there are avoidable incidents [7].

The project LEAS aims at filling this gap. The outcome of the project is a demonstrator which represents a next- generation DST for VTS centers. Through the integration of state-of-the-art technologies, such as ML-based data processing and fusion, the demonstrator aims at giving a deeper and more holistic situational awareness. This is primarily achieved by the Artificial Intelligence (AI)-based situation detection and resolution module which is presented in this paper. Furthermore, the utilized techniques facilitate scalability to multiple VTS territories and extensibility of integratable data streams and detectable situations. Due to the implemented formalism not only situations are adaptable and intuitively interpretable. Also, situations are automatically combined with each other. This lowers the number of false alerts and cognitive workload. Thus, the focus on true alerts is improved.

The remainder of this article is organized as follows. In Ch. 2 related works are presented and compared to our work. Then, the superordinate project of this work is presented in Ch. 3. Subsequently, in Ch. 4 our demonstrator is discussed in detail. This chapter represents the main part of this article and is divided into several sub-chapters. Finally, this paper ends with a conclusion of the results to date and gives an outlook to future work.

2 RELATED WORKS

An extensive survey on (anomalous) situation for maritime traffic monitoring purposes has been carried out by us in a preceding work [8]. Thus, here we limit related works to articles published from year 2020 onwards to ensure novel approaches. Also, the focus lies on rather holistic approaches and advanced technological readiness than highly specific solutions.

Xiao et al. provide requirements for a framework for a next- generation VTS system [6]. According to the authors, it should be equipped with AI-based functionalities such as forecast of traffic-dense hot spots, creation of knowledge bases (based on pattern extractions) and the incorporation of Electronic Nautical Charts (ENC) into automated decision support. The next-generation VTS system should aim at further automating maritime traffic management, inter alia, by reducing the involvement of a human in the loop and repetitive labour.

Evmides et al. propose a framework which focuses on processing big data in real-time [9]. It considers collecting, processing, storing and analyzing AIS data. Additionally, so-called intelligent services are utilized. They cover, first, measurements based on descriptive statistics, second, behaviors of vessels with respect to spatially defined polygons and, lastly, collision detection based on linear extrapolation vessels motions.

In [10], [11] the authors propose a traffic management priority index. This priority index aims at indicating which situation requires focus most urgently. In the [10], it is calculated by, first, clustering vessels and, second, applying fuzzy logic to assess the hazard level for given clusters, i.e., situations. The priority index is grouped according to the hazard level into attention, threat, danger or collision. In the work of [11], the priority index represents a value between 0 and 1. It is calculated taking into account geometrical relations such as closest point of approach (CPA), time to closest point of approach (TCPA), encounter angles and others.

Zhang and et al. propose a methodology which consists of few steps [12]. Firstly, similarly to [10] vessels are clustered. Secondly, for each cluster the collision risk calculated by taking into account the vessels attributes and Convention on the International Regulations for Preventing Collisions at Sea

(COLREGs). Lastly, given on the calculated collision risk a network model detects vessels with high levels of risk. The authors state that this methodology is adaptable to various port regions, i.e., territories.

The approaches in the related works show starting points for increasing the situational awareness. However, the approaches are highly specific and do not consider multimodal processing. In contrast, our demonstrator covers aspects which have been proposed by the related works. Xiao et al. bring up relevant requirements for a DST [6] which independently have been identified and implemented in project LEAS. This includes the incorporation of ENC or creation of a knowledge bases. Evmides et al. most importantly address the challenge of real- time capability of a system which collects, processes, stores, analyzes and, lastly, applies intelligent agents to a large volume of (live) data [9]. However, the authors primarily mention AIS data whereas the demonstrator presented in this work considers further data sources. In [10], [11] a priority index is proposed. Our demonstrator sorts situation criticality according to their hazard level through explicitly defined levels. Moreover, our holistic approach in which a variety of situations can be detected and combined, adapts situations criticalities. This leads to a lower number of false alerts.

3 PROJECT

The project goal is the development of an AI-based DST for shore-based monitoring and steering of mixed maritime traffic [13]. Mixed traffic refers to traffic consisting of fully autonomous, semi-autonomous and conventional participants. The demonstrator incorporates the following goals and innovations:
- extensive support for VTSO through AI-based methods
- adaptation of Human-Machine Interface (HMI) with consideration of AI-based modules
- early detection of relevant hazardous situations
- consideration of mixed traffic
- creation of simulation possibilities for training of (hazardous) situations with mixed traffic

The resulting demonstrator is evaluated by VTSOs from German VTS centers Travemünde and Warnemünde.

To achieve these goals project partners with complementary expertise take part in the project which are Fraunhofer CML, Fraunhofer FKIE, DLR-KN, DLR-KI, HSW - University of Wismar and Bergmann Marine as of today [13]. The project is completed in 40 months. In Fig. 1 the work package (WP) structure of the project is briefly illustrated. The work packages are executed roughly in order from top to bottom as sequentially depicted by the arrows. Only exception is WP7 which covers legal research and is executed during the entire project time.

At the time of preparation of this article, the demonstrator is being evaluated. Thus the project is in its final stages.

With respect to the project WP structure, the focus of this paper lies on:
- WP2: Traffic Management Concept and System Architecture, i.e., data fusion and preparation
- WP4: AI-based Systems and Modules for Decision Support, i.e., anomaly detection and hazard escalation
- WP5: Demonstrator for AI-based Modules for Decision Support with innovative HMI, i.e., integration of AI modules into demonstrator and demonstrator into VTS simulator

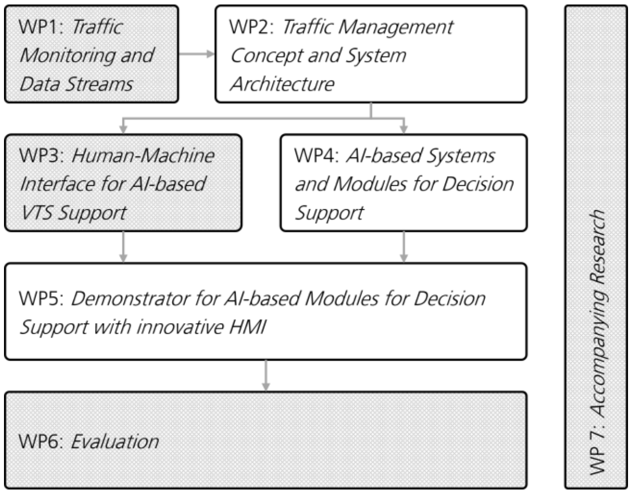

Figure 1. WP structure of the project LEAS. This paper focus on the work packages illustrated by boxes with white background.

The final results including the evaluation of the demonstrator by VTSOs as test subjects will be presented in a subsequent publication.

4 DEMONSTRATOR

In this chapter, the demonstrator is presented and explained in detail. First, an overview of the system architecture is given. The abstract system architecture template and the actual implementation are explained. The architecture plays a significant role concerning the modularity, hence, extensibility to multimodal operation of the demonstrator. Then, the module for the situation detection and resolution is presented.

This is the core when it comes to the situation awareness of the demonstrator. They underlying formalism and its implementation are explained. Also, an excerpt of currently detectable situations is given. This chapter concludes with capabilities and limitations of our approach.

4.1 *System Architecture*

The system architecture abstractly consists of
- data sources,
- the data fusion module,
- various AI modules and
- the HMI.

The connections of the composites are illustrated in Fig. 2. The system architecture is designed accept various data sources (illustrated in Fig. 2 with shaded background). This enables the DST to work multimodally and facilitates changes of the system environment. With that approach it has been effortless to switch demonstrator's environments between a VTS simulator or recorded traffic scenarios. To do so, a central data fusion module processes incoming data from various data sources, such as AIS data inside a National Marine Electronics Association 0183 (NMEA) data stream, radar data, VHF radio communication or ENC, which typically are available at VTS centers (cf. Tab. 1). The data fusion module works object- oriented in that sense that each ship target represents an object. It identifies tracks, and, if applicable, fuses ship targets. The data fusion is able to fuse targets which are given by AIS and radar data sources. Furthermore, the data fusion allows for object-oriented annotation. Inherently, it evaluates and annotates applicable rules and actions according to COLREGs based on the relative motion of any specified own ship and ship target [14].

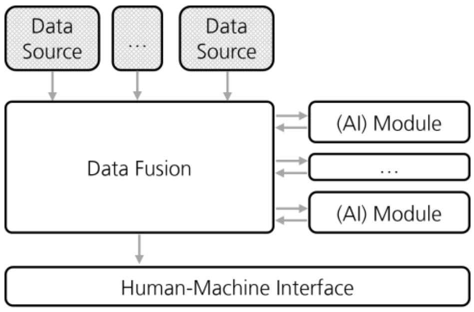

Figure 2. High-level demonstrator system architecture abstractly illustrating interfaces.

The pre-processed data then can be requested by any (AI) module as well as by the HMI. The connected modules then can return their results by annotating the given objects. Through this mechanism the modules are able to exchange information and the HMI is able to request the fused ship data which can be AIS and radar data as well as the results from the connected modules.

The presented demonstrator relies on that system architecture. The specific implementation is illustrated in Fig. 3. In the context of the project LEAS a VTS simulator and an external microphone serve as data sources. The VTS simulator delivers AIS data encapsulated in NMEA sentences. Moreover, recordings of the encapsulated AIS data can be accepted by the data fusion. The data then is processed by the data fusion which creates objects out of the ship targets. Due to the data source agnostic approach which relies on standards such as NMEA any VTS which supports an NMEA interface.

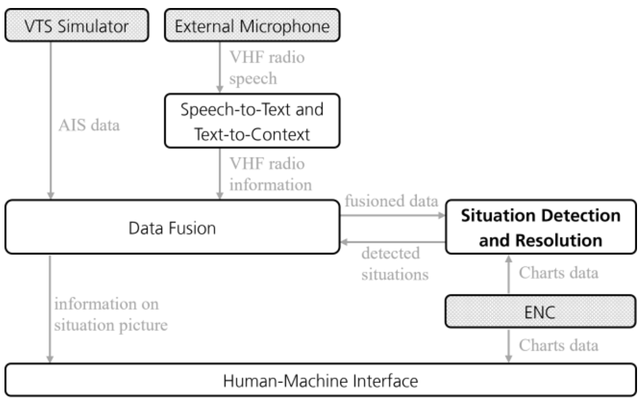

Figure 3. Low-level demonstrator system architecture depicting situation detection and resolution and its relevant interfaces.

All depicted modules of the demonstrator run on a Dell XPS notebook. It is equipped with 20 CPU cores and 64 GB of RAM. The situation detection and resolution module is running with a frequency within an order of magnitude of one second. A significant acceleration of the demonstrator can be expected when the modules are optimized for performance which has not been the focus so far.

The microphone can be used to imitate VHF radio communication. A dedicated module transcribes the spoken communication and then annotates it to any ship target.

This paper focuses on the module for the situation detection and resolution which is presented in detail in the following chapter.

4.2 *Situation Detection and Resolution*

The AI module *Situation Detection and Resolution* (see Fig. 3) relies on the formalism which has been introduced by Stach et al. in the previous paper [5]. In the following it is briefly introduced. However, for more details, readers are referred to the previous paper.

The formalism consists of three hierarchical spaces: the object space $\mathbb{O}$, the measurement space $\mathbb{M}$ and the situation space $\mathbb{S}$. In Fig. 4 these hierarchical spaces, their representations and interrelations are illustrated.

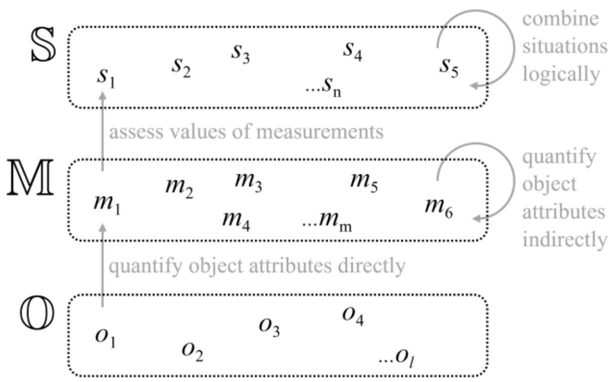

Figure 4. Illustration of formalism based on how the situation detection is implemented.

The object space $\mathbb{O}$ contains objects o_i which are participants, i.e., vessels, or actors, e.g. physical or regulatory obstacles, in maritime traffic. Objects have attributes which can be determined directly or indirectly. The determination of the attributes is called measurement mi within the formalism. For example, position is a measured quantity of a vessel and the directly determined measurement value are the latitude and longitude values. By contrast, the CPA value of a pair of vessels is an indirect measurement since it is based on other measurements such as position, Speed over Ground (SoG) and Course over Ground (CoG). The situation space $\mathbb{O}$ contains situations s_i which are assessments of measurements or logical combinations of existing situations. A specific situation is introduced when a measurement fulfils the situations criteria. This mechanism is illustrated in Fig. 5 left.

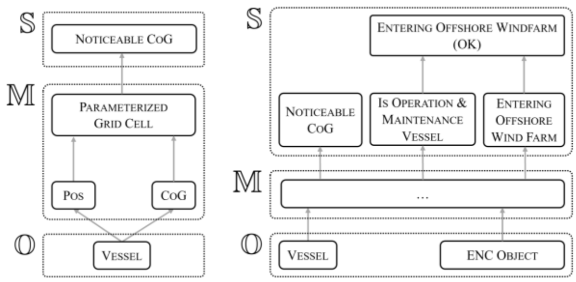

Figure 5. Hierarchical diagrams according to the used formalism for traffic situations *Noticeable CoG* (left) and *Entering Offshore Wind Farm (OK)* (right) based on the introduced formalism.

Here, position and CoG of a vessel are measured. Based on its position, the vessel is assigned to a statistically parameterized grid cell. The CoG is taken into account to verify if it matches the defined intervals of the grid cell. If the CoG of the vessel does match the defined intervals, then the situation *Noticeable CoG* is introduced.

Situation criteria can also be based on the logic combination of multiple situations instead of the assessment of measurements. This facilitates intuitive combination of situations, introduction of situations with broad contextual consideration and reduction of too generic situations. This mechanism is illustrated in Fig. 5 right. There, a vessel and an ENC object are taken into account. For the sake of simplicity, the measurement space is skipped in the illustration. In the situation space, initially the situations *Noticeable CoG, Is Operation & Maintenance Vessel* and *Entering Offshore Wind Farm* are introduced. In other words, given the vessel position an unusual course is detected (since it seems to be leaving a traffic separation scheme (TSS) lane). However, the vessel is an operation & maintenance vessel and its course is oriented towards an offshore wind farm. Combining these pieces of information it becomes apparent that the operation & maintenance vessel is on its way to its designated wind farm. Given that context, the vessels course is usual and the situation *Noticeable CoG* can be dissolved.

Lastly, it should be noted that this formalism inherently captures the causes for any situation in a transparent manner. This facilitates the determination of a resolution of the situation which is achieved by no longer satisfying situation criteria. Following the illustrations in Fig. 5, the causes and potential starting points of resolutions are determined by going through the diagrams from top to bottom.

In the presented demonstrator this formalism is implemented based on a hybrid architecture: an expert system with rules which utilize ML techniques. The expert system is implemented using the Python library *experta* [15]. Various subclasses of objects, measurements and situations are introduced. In each cycle of the expert system, situations or either initialized or dissolved depending on whether their criteria are fulfilled or no longer satisfied.

Each situation is assigned a criticality level following the suggestion by the IALA which are with ascending order of hazard level [4]:

1. caution
2. warning
3. alarm
4. emergency alarm

The specification of the hazard level of each situation is defined considering insights from VTSO and ergonomical approaches. For example, to reduce the false or distractive alerts, the situation *Entering Offshore Wind Farm* has the hazard level *warning* whereas the context-enriched situation *Entering Offshore Wind Farm (OK)* has the reduced hazard level *caution* (cf. Fig. 5). However, the hazard levels can be adapted easily if needed.

In the following, an excerpt of types of detectable situations is given.

4.2.1 *COLREGs*

Based on AIS data COLREGs are assessed for each vessel- vessel combination as proposed by Constapel et al. in [14]. As a result, the situation detection and resolution module annotates each vessel with the tags crossed, crossing, giveway, head-on, overtaken, overtaking, safe or standon with regards to any other vessel, if applicable. The identified COLREGs situations can be incorporated into the situation resolution. Further details on the processing of COLREGs assessments are explained in [14].

4.2.2 *Area-related*

In our implementation, the situation detection and resolution module is directly connected to a ENC server (see Fig. 3). This enables the extraction of ENC objects. In accordance with the projects evaluation traffic scenarios, point objects like AtoNs or area objects such as military practice areas, offshore wind farms, anchorage areas, TSS lanes or separation zones and depth contours are extracted and taken into account. The position and course of any vessel then is put into relation with the extracted ENC objects. Thus an area approach or penetration can be detected and considered for further context information (cf. Fig. 5).

4.2.3 *SoG- or CoG-related*

The SoG and CoG of each vessel is assessed in relation to empirically (manually) defined or statistically determined criteria. Empirical criteria can refer to either speed rules or minimum speed required for manoeuvrability. Statistically determined criteria make use of historical data. For the presented demonstrator, AIS data has been indexed following a hexagonal grid with the Python library *H3* [16] and then the distributions of CoG and SoG have been approximated by Gaussian mixture models [17]. Based on these Gaussian approximations confidence intervals have been determined according to which the CoG or SoG of a vessel is considered either normal or anomalous, i.e., *noticeable*.

4.2.4 *Collision Risk*

A collision risk situation is detected based on CPA and TCPA measurements. Analogous to SoG or CoG-related situations, CPA and TCPA values are assessed in relation to empirically (manually) defined or statistically determined criteria.

The measurements of CPA and TCPA are applied not only on pairs of vessels but also between vessels and objects other than vessels, e.g., aid to navigations (AtoNs) which are automatically extracted from ENC.

4.2.5 *VHF*

Spoken radio communication, i.e., over VHF radio, can be transcribed applying the automatic speech recognition system *OpenAI Whisper* [18]. Then contextual information can be extracted from the transcribed communication. The demonstrator covers basic, however, common and relevant cases such as green-to-green agreements or mayday calls.

4.3 *Capabilities and Limitations*

4.3.1 *Agnostic towards Data Source*

The presented demonstrator offers many capabilities which have not been covered yet by other works (cf. Chapter 2). From VTS center to VTS there can be various communication and sensor technologies as data sources available (cf. Tab. 1). Beyond the usage of a standardized AIS or radar data interface, the system architecture of the demonstrator facilitates the integration of further data sources. This ensures that the demonstrator is applicable at most VTS centers independently from their available data source. The integration of other data sources than AIS or radar increases the level of information on the monitored maritime traffic. This in turn increases the accuracy of the situation detection and resolution so that false alerts are reduced. The integration of VHF radio communication as data source and its automatized processing in a DST is a novel functionality.

4.3.2 *Transparency and Interpretability*

The underlying formalism of the situation detection and resolution module as well as its implementation into a hybrid expert system offers many advantages. First and foremost, it makes the functioning of the DST inherently transparent and its output interpretable. This is a crucial feature because it makes the VTSO the functioning and output of the DST understandable This increases trust and acceptance into the DST. In case of doubt, unclear or apparently wrong decisions can be traced. The modular design of the situation detection and resolution module also allows for easy adaptions and extensions. For example, situation criteria can be adapted or situations introduced resp. removed whenever needed. Moreover, it facilitates future validation and verification of the DST [19], [20].

4.3.3 *Extensibility*

Even though the situation detection and resolution is an expert system, fundamentally, its rules can be based on cutting-edge techniques such as ML. By this hybrid approach the demonstrator remains transparent and still enables the utilization of novel and promising techniques. The presented demonstrator utilizes ML-based techniques in the cases of, first, SoG or CoG-related assessment and, second, VHF transcription (see Ch. 4.2). In particular, the SoG or CoG-related assessment based on automatic statistical parameterization enables the application in various VTS- territories with differing traffic patterns.

4.3.4 *Intuitive Abstraction*

Lastly, due to its hierarchical abstraction from objects to measurements to situations the formalism facilitates the intuitive combination of situations. This particularly helpful as soon as territories with highly specific or novel traffic patterns need to be monitored. Based on our experience with the project, the situation space enabled easy exchange about additions or adaptions of detectable situations with project partners and VTSO with less technical background.

4.3.5 *Reliance on Standards*

The demonstrator relies on standards such as NMEA for AIS data streams. This may be seen as a limitation but, however, facilitates the integration into different VTS centers.

5 CONCLUSION & FUTURE WORK

All in all, the presented demonstrator delivers a more holistic range of functionality and a higher Technology Readiness Level (TRL) than related works (cf. Ch. 2). It fulfils some of the requirements for a framework for a next- generation VTS system as proposed by Xiao et al. [6]. The demonstrator has been developed from scratch which made it possible to design a system architecture which aims at scalability and explainability. Thus, given the compliance of common standards such as NMEA data streams, the demonstrator can be implemented at any VTS simulator or actual center. Moreover, its situation detection and resolution module is capable to adapt to territory-dependent traffic patterns.

During the preparation of this paper, the usability of the demonstrator is being evaluated following evaluation processes described in DIN EN ISO 9241-210. This is performed through interviews and questionnaires with VTSOs during and after the individual trials. Every trial consists of three traffic scenarios which are approx. 20 minutes long and include various hazardous traffic situations. Different aspects of usability of the demonstrator are considered which are, inter alia, task appropriateness, conformity of expectations or transparency. The functionality of the demonstrator has been evaluated during the development and pretrials. It was tested and verified that the demonstrator is able to detect every hazardous situation (see situation types listed in Ch. 4.2.) in the given traffic scenarios.

Their feedback will flow into future iterations of the demonstrator. More complex traffic scenarios can be evaluated using the European Maritime Simulator Network (EMSN). Moreover, improvements will focus on expanding its contextual understanding to support a broader, more dynamic situation detection. The objective is to move from isolated rule-based detections to a comprehensive situation-context model that enables real-time, multimodal awareness and allows VTSO to interact with the system in a declarative, human-centric manner.

5.1 *Improvement of speech-to-text and text-to-context*

One major direction of development is the improvement of VHF speech-to-text and, subsequently, text-to-context capabilities as introduced in Chapter 4. This, on the one hand, refers to the improvement of the speech-to-text functionality in general. As addressed by Martius et al. this poses a challenge since maritime radio communication data is scarce [21]. The authors propose to enrich training data by synthetic data. On the other hand, VHF radio communication should not be treated as isolated textual input. Rather it will serve as a fully integrated component in the broader situation awareness model. Utilizing methods as shown in [22], fusing VHF radio communication with AIS will allow the system to correlate further situations than the green-to-green agreement or mayday call such as

– outputs from the situation and detection module, in general,
– current port call schedules and berth allocations and
– broadcast safety or navigational messages.

This can be fused into a coherent and queryable context model which allows VTSOs to issue high-level queries in natural language similar such as:

– "Highlight vessels with increased CPA risk that have not yet responded on VHF radio."
– "Are there any critical situations near scheduled arrivals within 30 minutes?"
– "List all vessels inside a restricted area without a valid permission."

This approach aims to simplify the interaction model for VTSO, enabling them to explore complex situational combinations without the need to manually correlate disparate data sources.

5.2 *Use for Training Purposes*

In addition to supporting operational decision making, such a system has great potential as an embedded learning tool. As VTS centers increasingly recruit personnel directly from academic training into operational roles, often without prior seafaring experience due to the ongoing shortage of qualified maritime professionals, this type of intelligent support tool can help facilitate learning on the job. By making situational context, navigational standards and situation indicators transparent and accessible, it enables inexperienced VTSOs to gain domain knowledge organically during real- world surveillance tasks.

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