MOSES Shore Tugboat Control Station: Development of a shore-side system to support autonomous tugboat operation

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ABSTRACT

Highly automated and autonomous systems are expected to be supported by monitoring and control stations at shore, where the main challenge is for the remote operator to have an adequate situation awareness of the ongoing operation. In a framework for automating tug-assisted ship manoeuvring and berthing, the EC-funded, H2020 project MOSES has designed a Shore Tugboat Control Station (STCS) as an interface between the actors involved in the process. This paper describes the main functionalities and the interface prototype of the MOSES STCS, also considering requirements from Classification Societies. Based on an analysis of use cases (i.e. operational scenarios), the remote operator needs to have a visual overview of the operation through video feeds and map representations showing the positions and movements of the tugboats and the assisted vessel, an understanding of the weather conditions, and the system availability for the tugboats.

KEY WORDS

Autonomous tugboats, Remote Control Centre (RCC), Situation awareness, Tug assistance, Use cases, Human-Machine Interface

1. INTRODUCTION

With the advancements in maritime autonomy, highly automated ships are expected to be continuously supported by shore-based control centres, where a team of specially trained operators can monitor the status of a fleet of autonomous ships and take over control when necessary. One of the earliest comprehensive concepts for the, so called, Remote Control Centre (RCC) or Shore Control Centre (SCC) was developed in the EC-funded MUNIN project (Porathe, 2014). For maintaining operational safety at an adequate level, the operators at an RCC will need to supervise ship operation and take control when a situation is too difficult for the autonomous system (e.g. to resolve a collision encounter) by depending on real-time data streams from onboard sensors (see Størkersen, 2020 and references therein). However, RCC operation poses a multitude of complex human factors and Human-Machine Interface (HMI) challenges that operators must effectively deal with. Having an adequate situation awareness from a remote location, considering issues such as information overload (Woods et al., 2002) as well as the problems related to overreliance on automation (Lee and See, 2004), misunderstanding in interaction with manned vessels, and delays in decision making (human-out-of-the-loop syndrome), are major challenges for the design of RCCs (Porathe et al., 2014). In a trial study of the MUNIN RCC prototype, Man et al. (2015) concluded that in order to address the challenges in the design of such facilities, which relate to the geographic separation from the vessel, they should not be duplicates of the ship's bridge but be completely re-designed centred around maintaining situation awareness for the operators. In a review of the relevant literature, Ramos et al. (2018) have identified the following factors that affect operator performance in a Shore Control Centre: information overload, situation awareness, skill degradation when overly relying on automation, boredom, and fatigue.

The ambition of the EC-funded, H2020 project MOSES is to increase the efficiency of port operations while maintaining an adequate level of safety by developing a framework for automating the tug-assisted ship manoeuvring and berthing processes, which are currently conducted by manned tugboats with low-level automation. The technologies involved in this framework include an autonomous tugboat swarm that communicates and automatically triggers an automated mooring system once the manoeuvred vessel is in place. The operation is supported by the Shore Tugboat Control Station (STCS), which is a type of RCC as the term is used in the ISO/TS 23860:2022 vocabulary, whose goal is to provide an interface between the tugboat operator, the port, and the Vessel Traffic Service (VTS). Although there have been considerable advancements in the domain of autonomous tugboats since the early 2000s in the fields of perception, decision making, control, modelling, and infrastructure and operation, the latter has mostly included studies on the tug scheduling and berth allocation problems (see Choi et al., 2023 and the references therein). To the best of our knowledge, there are no studies addressing the design of RCCs for autonomous tugboat swarm specifically.

The objective of this paper is to describe the main functionalities and the interface prototype of the MOSES STCS. The methodology that was applied resulted in system requirements (functional and non-functional) by analysing use cases and operational scenarios, as well as identifying Class requirements for remote control and supervision of vessel functions. Specifically, the methodology included the following steps: 1) Determining the goal of the system and its operational context in terms of the actors it needs to interact with, 2) Identifying user needs and requirements based on an analysis of use cases (i.e. operational scenarios) with system sequence diagrams, and 3) Initial design of the interface, taking into account the general requirements from the Classification Societies and those derived from the use cases.

The paper is structured as follows: Section 2 reviews the approaches that have been implemented in the literature regarding design of RCCs for autonomous ships and the relevant requirements from the Classifications Societies. Section 3 describes the STCS concept and its main functionalities. Section 4 describes the results from the analysis of three use cases, one for each of the phases of the manoeuvring process. Section 5 describes the STCS interface prototype that is based on the derived requirements. The paper concludes with a summary of the results from the analysis and the contribution of this work in the domain.

2. DESIGNING REMOTE CONTROL CENTRES FOR AUTONOMOUS SHIPS

The design of RCC concepts for autonomous ships includes different approaches to create HMIs and workflows that are intuitive, efficient, and supportive of human decision-making. In the context of the MUNIN project, various prototype interfaces were created in order to convey situation awareness to the operator monitoring remotely in terms of spatial, temporal, and operational overview (Porathe, 2014). To maintain spatial awareness, maps similar to the Electronic Charts Display and Information System (ECDIS), which is the modern standard equipment for ship bridges, were used. To maintain temporal awareness, the prototypes included timelines in the form of slot diagrams separating the voyage into days or hours and marking tasks for the operator, as well as trend lines that provide time series of important parameters. To maintain operational awareness, a ship status indicator at various levels of abstraction was proposed for understanding the condition of the ship's technical systems, as well as colour coded top level indicators for different ship functionalities. Hoem et al. (2022) developed and implemented a Human-Centred Design (HCD) approach, based on Risk-Based Design (RBD) principles and the Scenario Analysis in the Crisis Intervention and Operability study (CRIOP) framework, to evaluate the HMI of a prototype land-based control centre for an autonomous ferry in its early design stages. Rutledal (2021) implemented the Structured Analysis and Design Technique (SADT) to identify and analyse the functionalities and tasks that need to be performed by an RCC for an autonomous ferry, which is intended as the first step towards the design of the RCC. Veitch et al. (2021) have implemented a HCD approach based on the ISO 9241-210 standard on ergonomics of human-system interaction, which includes defining the operational context, deriving user requirements through expert workshops, prototyping, and evaluating the design. Cheng et al. (2023) developed a method for hazard identification that can provide input to "human-oriented design and development of SCC", which involved extending the Systems Theoretic Process Analysis (STPA) method with explicit modelling of the remote operator's cognitive processes.

In addition to research on design methods for RCCs, Classification Societies have also provided guidance to the technical arrangements in RCC, aimed to facilitate remote control and supervision of vessel functions to ensure that they provide a level of safety equivalent or better compared to the functions being conventionally controlled and supervised from on-board the vessel. Det Norske Veritas has published guidelines for autonomous and remotely operated ships (DNVGL, 2018), which describes RCC arrangements (incl. remote workstations and layout), hazards and barriers (e.g. failures, communication loss, cyber-attacks), the importance of remote situational awareness and remote vessel supervision. Bureau Veritas has issued guidelines for autonomous shipping (BV, 2019), which for RCC describes functional requirements including the following: displaying suitable information, facilitating remote control, providing means of communications with ships and authorities, the ability to easily identify operational abnormalities, having a clear visibility around the ship, and providing the status of essential ship services. In addition, for RCC ergonomics, BV recommends to follow the ISO 11064 standard for control centres. The American Bureau of Shipping has released an advisory (ABS, 2020), which identifies some of the functions of the RCC in autonomous marine operations (e.g. voyage planning and monitoring, maintaining situational awareness, responding to anomalous and emergency situations, and controlling transitions between operating modes). More detailed requirements for RCCs were provided in ABS' guide for autonomous and remote control functions (ABS, 2021). ClassNK have issues guidelines for automated/autonomous ship operation (ClassNK, 2020), which includes general requirements for remote monitoring and remote control with reference to the identification of necessary information to be provided, the importance of the communication network, and examples of hazards (e.g. poor communication and cyber-attacks). Table 1 summarises the main Classification Societies' requirements for RCCs with respect to workstation layout, situation awareness, hazard identification, and data logging.

Table 1: Main requirements for RCCs from Classification Society guidelines

Workstation layout	Two remote operators with separate workstations for remote navigation and engineering functions.
Situation awareness	• Sufficient for analysing prevailing conditions, planning actions, and remotely executing operations. • Real-time information provided by sensor data to substitute human senses. • Equivalent to or better than conventional local situation awareness. • Sufficient overview of status of ship functions (e.g. with a predefined colour code). Instructions on how to sequentially restore functions or how to operate the equipment / functions during extreme conditions should, to the furthest extent, be covered by decision support functionalities or automation.
Hazard identification	• Examples of events and hazards: vessel movements (dynamic and static conditions), ambient conditions (e.g. reduced visibility, strong wind, rough sea state, strong currents, heavy precipitation), fire, high and low temperatures, vibrations • Alarms should only be used when actions are required and should clearly indicate required actions. All navigation related alerts should be managed in accordance with the Bridge Alert Management (BAM) concept of IMO as defined in

	MSC.302(87).
Data logging	Data related to key vessel functions should be electronically logged and stored, the following at a minimum: operational status of key vessel functions including communication links, alerts, manual orders, all data input and output to/from decision support and automation systems.

3. CONCEPT AND MAIN FUNCTIONALITIES

The main objective of the MOSES STCS is to supervise the manoeuvring and docking process of the assisted vessel. To achieve this, the STCS needs to be connected in real-time to all the actors who are involved in the process including (see **Figure 1**): the autonomous tugboat swarm and the personnel onboard (if any), the assisted vessel, the automated mooring units, the VTS, the Port Community System (PCS), and the Meteo/oceanographic service. The remote human operator in the STCS will be able to receive high-level commands from the Pilot on-board the assisted vessel and assume remote control of the autonomous tugboat swarm whenever needed. Another role of the remote operator will be to verify that the autonomous tugboat swarm has achieved its mission (i.e. to bring the assisted vessel in the pre-defined berthing position) after both the swarm and the automated mooring units have automatically signalled the process has been completed.

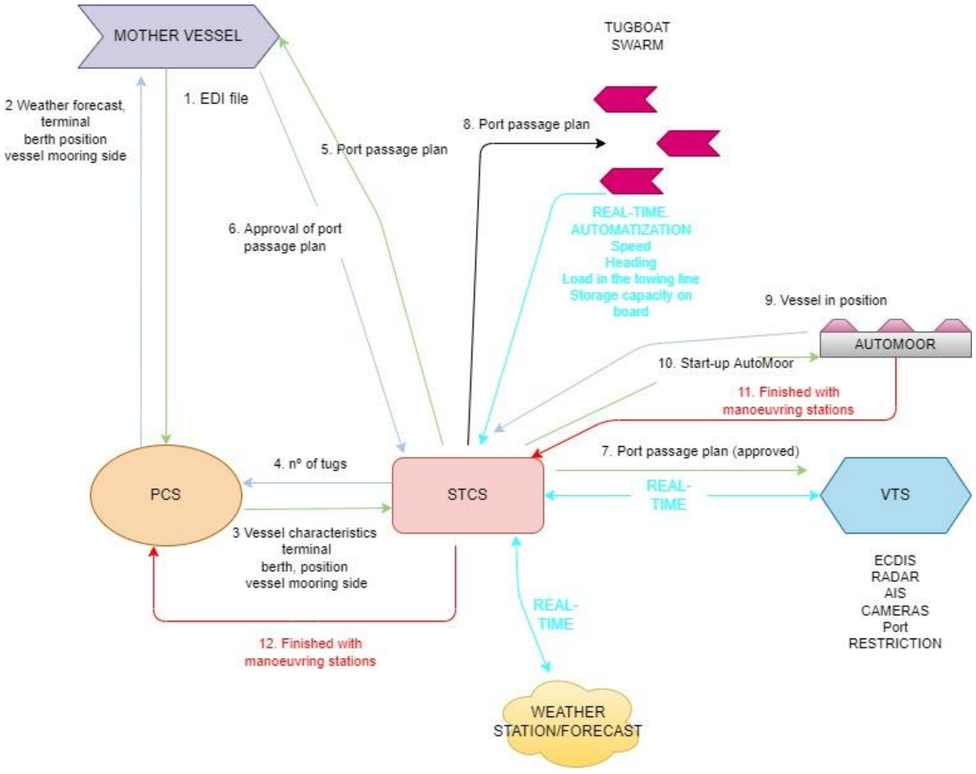


Figure 1: Communication flow between the STCS and other platforms

The interaction of the STCS with the involved actors depends on the phases of the process, which include port arrival, manoeuvring, and mooring the assisted vessel. In the first phase, the STCS communicates with the PCS, which relays the necessary information for planning the manoeuvring. This information includes local conditions and navigational hazards, the ship particulars (e.g. size, number of propellers, number and capacity of thrusters etc.), the ship's operational parameters (e.g. current draught, trim, overall length etc.), details about the allocated berth, the number and required bollard pull of the tugboats, the expected weather and sea conditions, and the port passage plan (as per SOLAS Chapter V Reg. 34). This information will dictate the route chosen to or from the berth and will ensure that planning and execution of all manoeuvres makes suitable allowance for the dimensions of the vessel to, for example, avoid groundings and contact with harbour structures, and allows the STCS to incorporate this information into a comprehensive manoeuvring plan. Knowledge of the current weather conditions, received in real-time from the port weather station, allows the remote operator to be proactive in terms of unexpected changes in wind and/or current conditions.

During the manoeuvring phase knowledge of the port passage plan, exchanged between the STCS, the assisted vessel, and the VTS offers an objective criterion for monitoring the progress and efficiency of the autonomous tugboat operation. In addition, a detailed passage plan will allow timely and unambiguous interventions when deviations occur. The remote operator will monitor the trajectory followed by the mother vessel on the electronic map system installed in the STCS. To check that the trajectory followed by the ship is within the safety parameters, the trajectory followed by the ship shall be calculated by means of triangulation to fixed points (waypoints). In addition, the information provided by VTS is essential for monitoring the progress of the vessel, as well as the relative position of the vessel length (heading) and the mother vessel speed.

During the final approach to berth, the STCS will communicate with the automated mooring units to monitor the relative position of the assisted vessel relative to the quay by using dedicated proximity sensors installed in the units.

Based on the described concept for the STCS, **Figure 2** shows the requirements for achieving the goal of “Remote monitoring and control” by implementing the following main functions: Situation awareness, Mission scenario management, Switch between levels of autonomy, and Fail-safe operation.

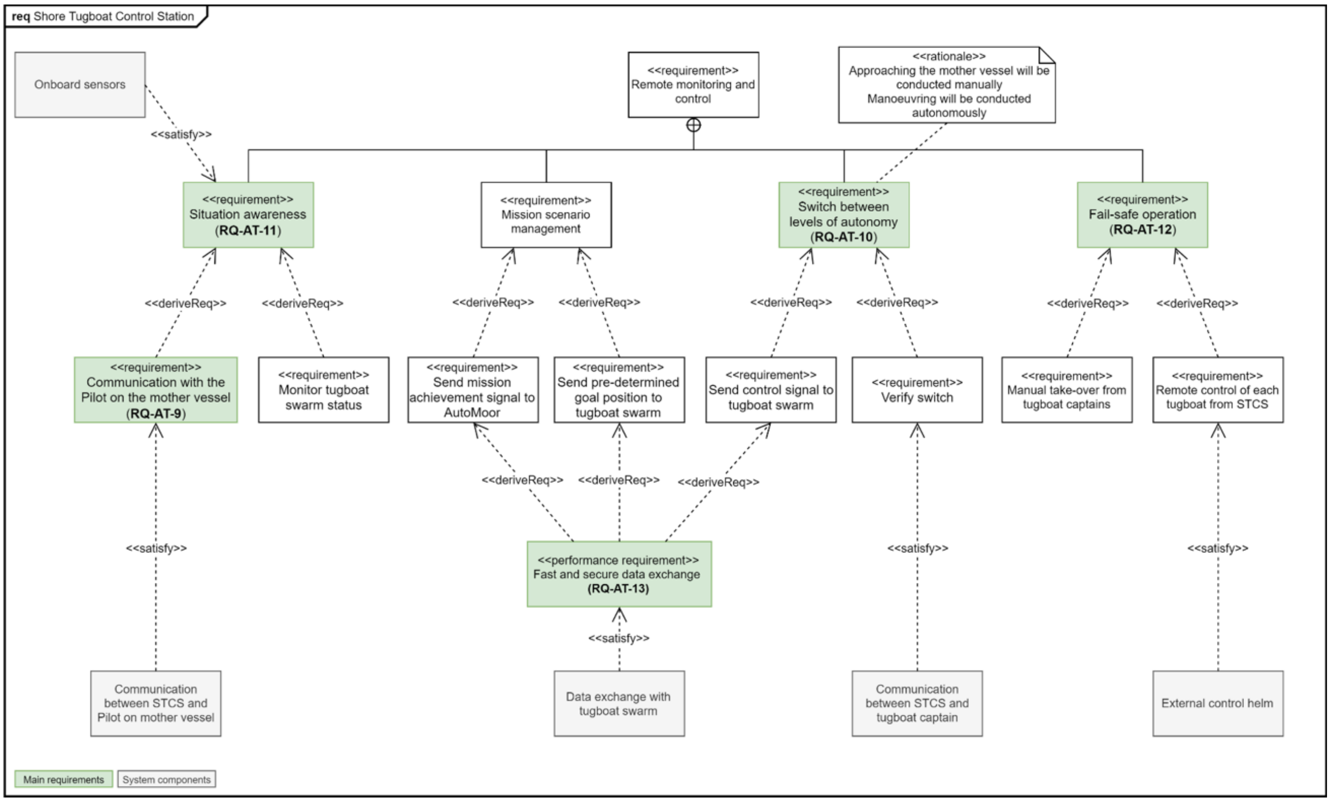


Figure 2: Requirements for the STCS

For the remote operator at the STCS to have adequate situation awareness, real-time data exchanges need to be implemented by integrating the information from the different involved actors. The objective is to efficiently monitor the status of the tugboat swarm, as well as the status of the tugboats relative to the assisted vessel (through conventional means, such as verbal communication via VHF) and the port infrastructure. To manage the mission scenario, the STCS needs to provide the autonomous tugboat swarm with a pre-determined berthing position and, once the process has been completed, send a mission achievement signal to the tugboats and the automated mooring units. Switching between levels of autonomy requires the STCS to send a control signal to the tugboat swarm and to verify the switch with the personnel onboard the tugboats (if any). Finally, achieving fail-safe operation depending on the type of failure requires the STCS operator to be able to assume control of each tugboat remotely by first disengaging autonomous control mode.

The achievement of the STCS' goal strongly depends on bi-lateral, real-time and secure communication (in many cases through wireless interfaces) and therefore it is crucial to ensure the inviolability of the transmitted information, whether due to a cyber-attack or a communication break. Indicators, such as the quality of the wireless connection, can provide the necessary information to the STCS operator to, for example, switch the autonomy level in case of low network quality. These parameters will be configurable by the user to reflect the specific conditions in each port.

4. USE CASE ANALYSIS

The analysis of the use cases resulted in identifying the type of information that needs to be exchanged between the STCS and the other involved actors. Three different use cases have been described using system sequence diagrams, one for each phase of the process, i.e. port arrival, manoeuvring, and mooring.

During port arrival, the PCS operations user can launch the process of generating, approving, and distributing the port passage plan (Figure 3). After the PCS sends the characteristics of the ship, which terminal and dock will arrive at, and which side of the ship will be moored, the STCS operator requests a weather forecast from the meteorological service, prediction of maritime traffic from the VTS. Using this information, the STCS generates the port passage plan, which includes the trajectory to the dock and the maximum deviation limits with respect to that path, calculates the required number of tugboats and sends this information to the PCS. Once approved, the STCS sends the port passage plan to the autonomous tugboat swarm and the VTS.

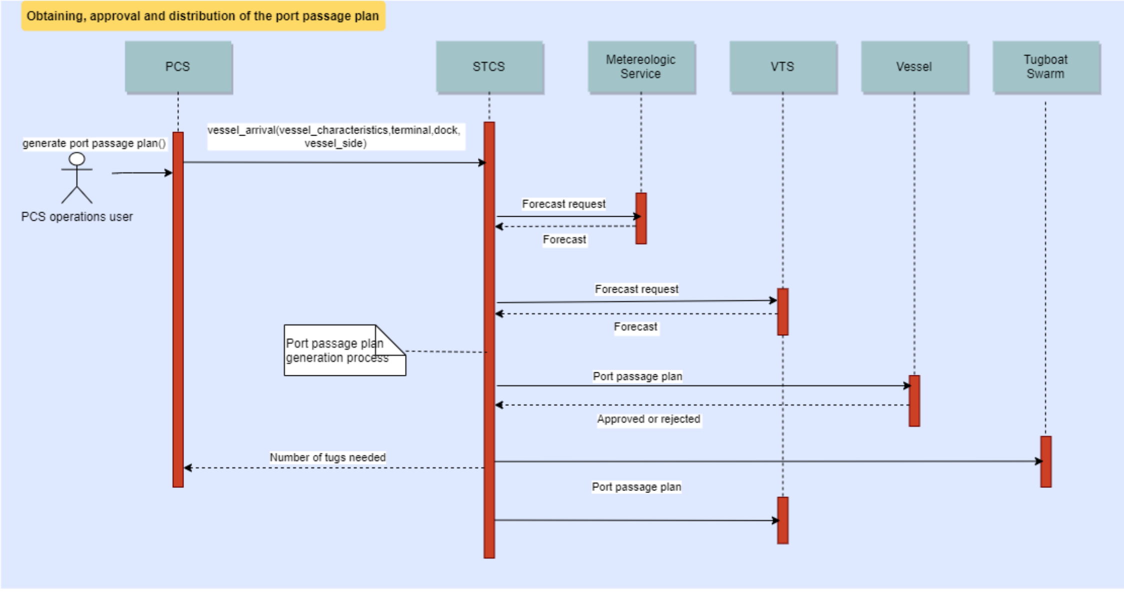


Figure 3: Use case of obtaining, approving and distributing the port passage plan

During the manoeuvring phase, the STCS operator can supervise autonomous towing operations in real-time, and if necessary, transfer control of one or more tugboats to their respective captains, if any (Figure 4). Once this monitoring process starts, the STCS operator begins to receive real-time information on weather data from the meteorological service, the status of maritime traffic in the port from the VTS, and sensors that are on-board the autonomous tugboats. In case an alarm is triggered to indicate hazardous conditions, such as engine failures, poor network connection, or collision risk, an order will be sent to the tugboat in question to assume remote control or transfer control to the captain onboard (if any).

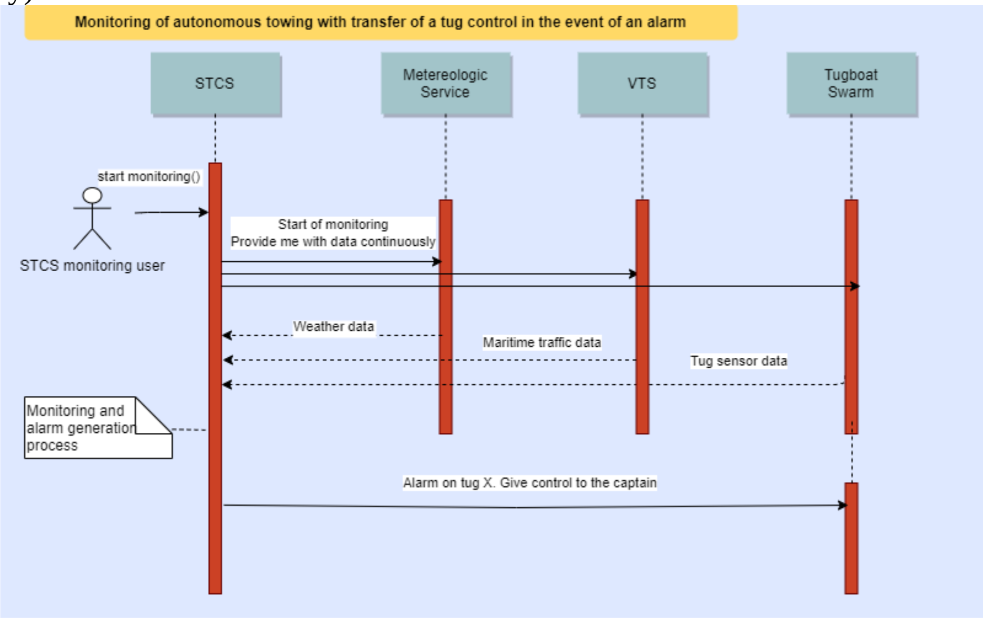


Figure 4: Use case of monitoring of autonomous towing with transfer of a tug control in the event of an alarm

During the mooring phase, the STCS operator can supervise autonomous mooring operations in real-time, and if necessary, change the control of an automated mooring unit on the quay to manual (Figure 5). Once this monitoring process starts, the STCS operator begins to receive real-time information on weather data from the meteorological service, and the status from the automated mooring system. In the event that any of the automated mooring units enters an alarm state, the STCS sends the order to switch to manual control.

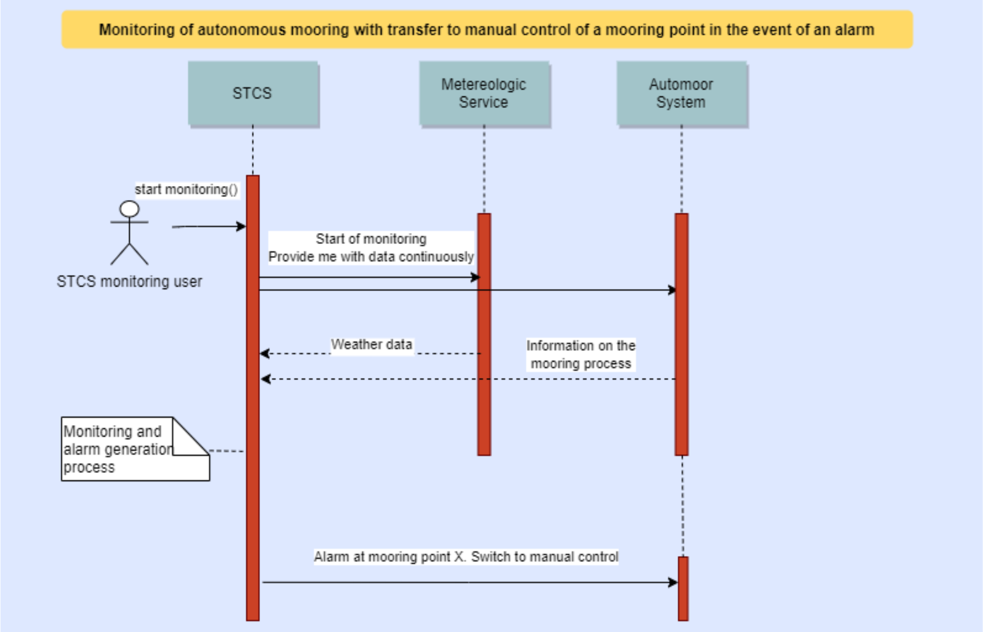


Figure 5: Use case of monitoring of autonomous mooring with transfer to manual control of a mooring point in the event of an alarm

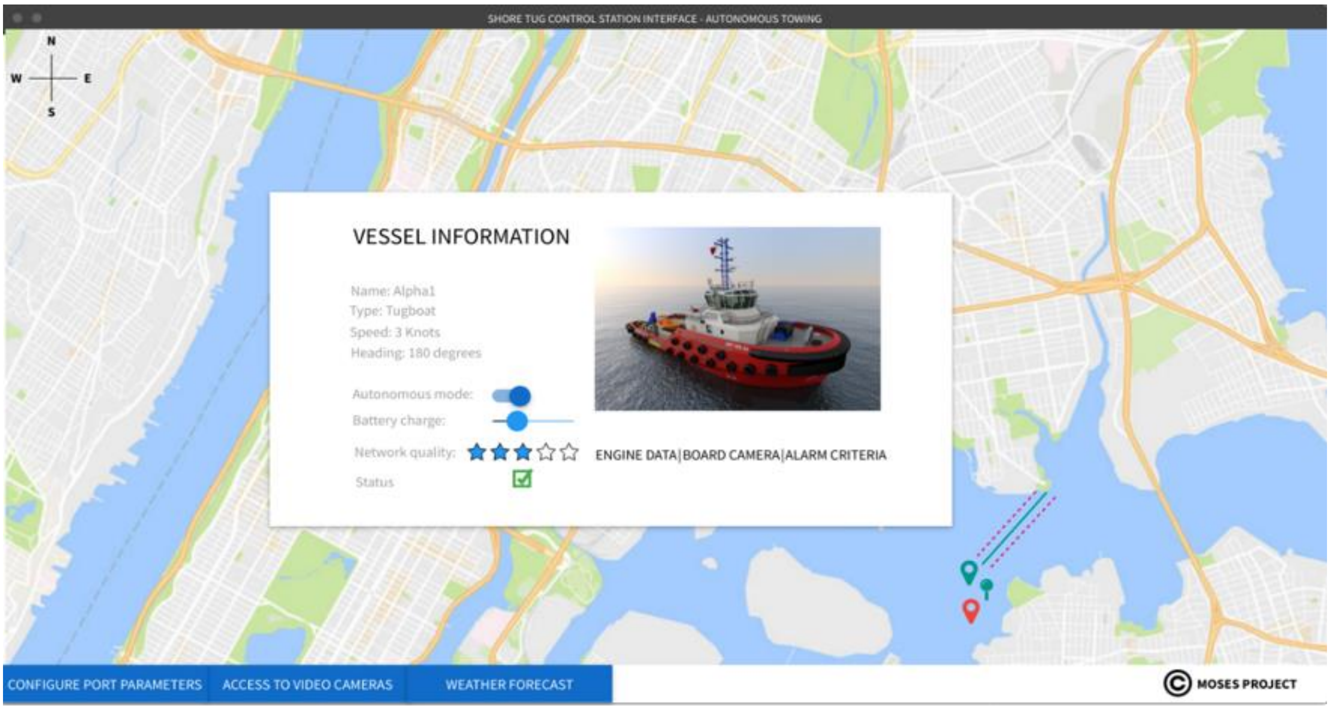
5. SHORE TUGBOAT CONTROL STATION INTERFACE

Given the general requirements from the Classification Societies, the required functionalities for the system to accomplish its mission, and the requirements derived from the analysis of the use cases, the MOSES project has developed an initial design for the STCS HMI. The interface consists of three separate components for fulfilling the following functionalities: 1) supervising the autonomous towing phase, 2) supervising the autonomous mooring phase, and 3) logging operational data and reporting. In addition, the interface will be based on graphic representations of the process on digital maps (similar to ECDIS layouts) where the different information will be displayed, such as the movements of the autonomous tugboats and the assisted vessel in the port, speed, heading, distance to the dock, and deviation from the passage plan.

The STCS interface will include different dashboards for navigation and engineering for each of the two separated workstations that will be physically located at the STCS, one for a navigation watchkeeping officer and another for an engineer watchkeeping officer. The engineering dashboard will be designed to duplicate actual marine automation workstations, which are currently widely implemented on-board vessels for relevant machinery functions (e.g. alarm and monitoring, power management, auxiliary machinery control, etc.). Below is a more detailed description of the navigational dashboard and the aforementioned three separate components.

During the autonomous towing phase, the STCS operator will be able to monitor the evolution of the operation with real-time information about the status of the manoeuvring (Figure 6). In the main map view, the STCS interface will plot the planned route up to the mooring point to be followed by the assisted vessel (continuous green line) and the relevant "safe corridor" (dashed red lines), as well as the position, speed and heading of each tugboat and the assisted vessel (green pin marker) in real-time. If the "safe corridor" is violated by the assisted or another vessel, an alarm will go off. The operational status of the tugboats will be displayed on the map by changing the colour of the corresponding marker, from green when they are working autonomously correctly, to orange when they are manually operated, to red when in an alarm state (e.g. engine failure, poor network quality, collision risk, deviation from the planned route etc.). In case of an alarm, the STCS operator will be able to diagnose the situation by opening a detailed file for each tugboat ("Vessel Information" window), which includes the following information: speed, heading, vessel type, vessel image, network quality, status. After analysing the alarm, the operator may disable the "Autonomous mode" and either assume remote control or transfer control to the tugboat captain (if any). In addition, from this window, the STCS operator can access on-board cameras and engine performance data.

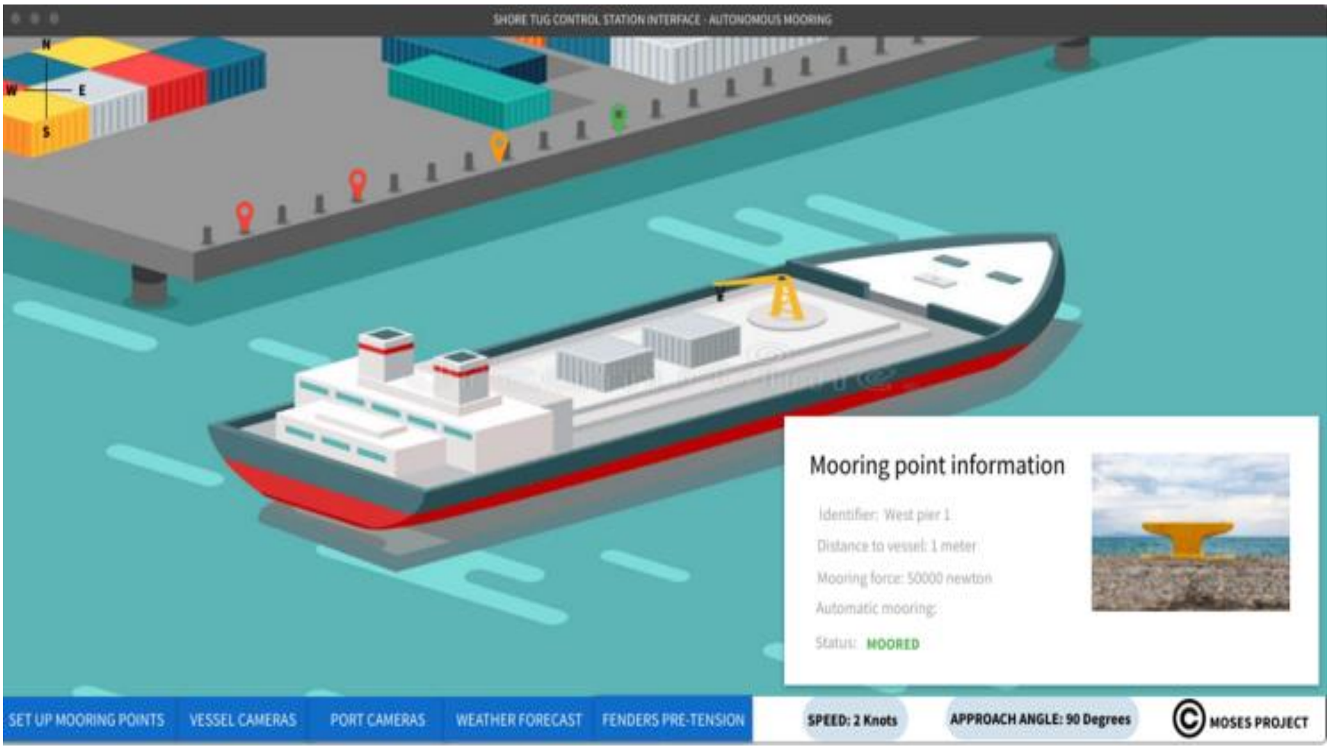
Before the operation starts, the STCS operator is required to configure the following parameters: port security parameters related to the ship's transit ("Configure Port Parameters" option), and parameters for each tugboat ("Alarm Criteria" option in the tugboat's "Vessel Information" pane) including the speed or positioning ranges. If any of the tugboats, deviates from its planned route by a value greater than that indicated in the defined ranges, then an alarm will go off. At any time, the operator will have access to weather information and environmental conditions (e.g. wind speed and direction, port agitation, tidal levels, visibility) through the "Weather Forecast" option, as well as access to the port's video surveillance system ("Access to Video Cameras" option).



Name: Alpha1
Type: Tugboat
Speed: 3 Knots
Heading: 180 degrees
Autonomous mode:
Battery charge:
Network quality: ★★★☆☆
Status ☑

Figure 6: STCS interface component for monitoring the autonomous towing phase

During the mooring phase, when the assisted vessel is close to the dock, the STCS interface will automatically switch to the autonomous mooring view (Figure 7). This view will show real-time information of the assisted vessel's distance to the berth, the angle of approaching and speed for avoiding any potential collision during the process. In addition, the position of the automated mooring units at the dock will be shown through markers with the following colour coding: white at over 5 m distance, orange between 1 and 5 m, red less than 1 m, and green when the ship is securely moored.

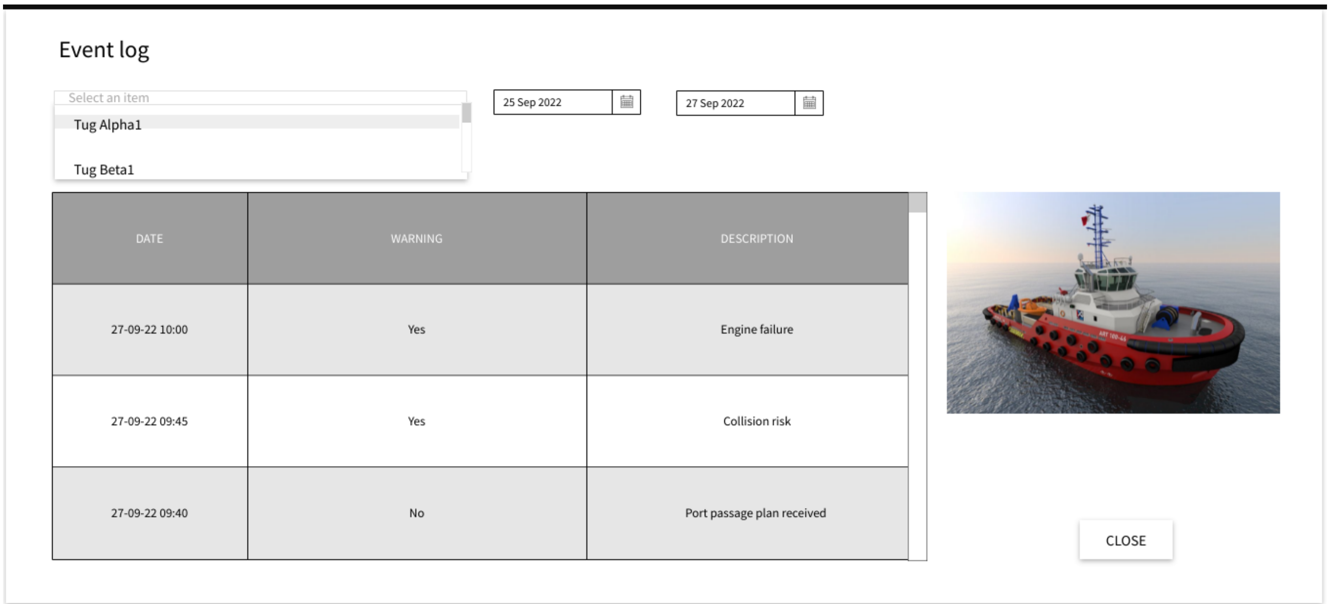


Identifier: West pier 1
Distance to vessel: 1 meter
Mooring force: 50000 newton
Automatic mooring:
Status: MOORED

SPEED: 2 Knots
APPROACH ANGLE: 90 Degrees

Figure 7: STCS interface component for monitoring the autonomous mooring phase

By clicking on each of the markers indicating the automated mooring units, the STCS operator will have access to the following information: identifier and photo, force applied to the unit (in N), and the colour-coded status of the unit with green when the process successfully completes autonomously (“Moored”), or another message in case of failure (e.g. unit power failure, vessel holding force too high, vacuum level too low etc.). In addition, through the corresponding interface options, the STCS operator will have access to the ship’s and port’s cameras, the weather forecast (tide variation, wind speed and direction, port agitation), and the stress values that are being applied to each of the fenders.
Finally, as a complement to the main dashboards, the STCS interface will also include a logging and reporting component, which will allow having a centralized view to look into the events history, whether there are warnings and alarms related to the autonomous tugboats or the automated mooring units (Figure 8).



25 Sep 2022

27 Sep 2022

DATE	WARNING	DESCRIPTION
27-09-22 10:00	Yes	Engine failure
27-09-22 09:45	Yes	Collision risk
27-09-22 09:40	No	Port passage plan received

Figure 8: STCS interface component for logging operational data and reporting

6. CONCLUSIONS

This paper described the initial design of a prototype interface for the MOSES Shore Tugboat Control Station (STCS), which is intended to support the operation of the autonomous manoeuvring and docking scheme that is developed in the project. The MOSES STCS will effectively act as an interface between the autonomous tugboat swarm, the PCS that provides information about planning the vessel arrival, the VTS that monitors maritime traffic in the port area, the Meteorological Service that provides weather conditions and environmental information, and the automated mooring system. The elements and layout of the interface was defined from system requirements derived from the analysis of three use cases, one for each phase of the manoeuvring process, of the interactions of the STCS with other actors involved in the process using process sequence diagrams, as well as requirements from relevant Classification Societies’ guidelines.
The results suggest the importance for the remote operator to have a visual overview of the operation through video feeds and map representations showing the positions and movements of the tugboats and the assisted vessel. The remote operator also needs to have a good understanding of factors, such as the weather conditions and the system availability of the tugboats and the automated mooring system to effectively monitor the evolution of the operation and maintain an adequate safety level. In addition, secure and fast real-time communication between the STCS and the other actors involved in the process is crucial for the STCS to achieve its mission.

The MOSES STCS interface prototype consists of three components for supervising the towing phase, supervising the mooring phase, and logging operational data and reporting. Furthermore, in accordance with the requirements from Classification Societies, the interface will include separate dashboards for the navigation and engineering functions. The engineering dashboard will be designed to duplicate marine automation workstations and therefore has not been further described in this paper. The STCS interface provides the remote operator with easy access to all information that is necessary for obtaining situation awareness about the developing operation, including detailed information about the status of the technical systems of the tugboats, the deviation of the tugboats and assisted vessel from the planned port passage plan, access to the video camera feeds and the weather forecast, the distance to the dock, the status of the automated mooring units, as well as colour coded alarms to identify off-nominal conditions. All the information will be logged to provide the data required for diagnosing developing hazardous situations and for analysing operational data after the operation has ended.

This paper aims to contribute to the ongoing discussion about the role of remote operators in RCCs, what type of information should be exchanged with other systems, and how they should be designed in terms of layout and information accessibility to effectively support autonomous maritime operations.

7. ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 861678. The content of this document reflects only the authors' view and the Agency is not responsible for any use that may be made of the information it contains.

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