Shore based Control Center Architecture for Teleoperation of Highly Automated Inland Waterway Vessels in Urban Environments

Arne Lamm[1][a], Janusz A. Piotrowski[2][b] and Axel Hahn[1][c]
[1]*Institute of Systems Engineering for Future Mobility, DLR e.V., Oldenburg, Germany*
[2]*Department of Computing Science, Carl von Ossietzky Universität Oldenburg, Oldenburg, Germany*

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Abstract: The following paper presents an SCC architecture that allows to take over the remote control of one or more ships from the shore side, especially in critical situations, in order to present a concrete solution of a remote control center as proposed in the MASS levels for autonomous navigation. Particular attention was paid to the technical and functional components and requirements specified by the regulations, and the practicability based on decision-making and action execution was investigated. In particular, the three levels of situational awareness were taken into account and the remote control center was finally implemented as a prototype. For the evaluation, the practicability based on the RTT was assessed and the completeness based on the design specifications of common INS was examined.

1 INTRODUCTION

In the context of automation in the maritime domain, remote control is also increasingly important as a fallback solution for such systems. Furthermore, different approaches address the remote control as a pre-step of autonomous vessels or as fallback system for unexpected situations that cannot be handled. With this understanding the term remote control covers both the direct control of the remote-controlled ship and the instruction of an autonomous system that controls and steers the ship. This remote control should be provided by a shore-based control center (SCC), which combines all necessary components for a stable and reliable remote control. Such an SCC can be governed by, for example authorities or authorized operators (IMO, 2018). Further, more than one institution could operate their own SCCs, where for example the shipping company as well as the government have own SCCs, which are used to monitor, control, or ensure the correct and legal operating of a ship. Especially when shipping companies are regarded, the ability of controlling more than one ship is required (MacKinnon et al., 2015). But when remote control is considered, not only the control itself, but also the situation awareness of the remote operator and the communication between the SCC and the ship needs to be considered (Dittmann et al., 2021). The situation awareness addresses the environment perception as well as the internal state of the ship. This situation awareness is provided by using different sensors which are located onboard. While the perception sensors are used to measure the environment, detect target ships, obstacles and ship specific metrics like speed and course. The internal state sensors are used to measure different information about the internal state of the ship like the propulsion system or about the cargo.

Derived from this, the SCC should include the capability of providing a situation awareness and control functionality, to the remote operator. Especially regarding these functions, the Vessel Traffic Service (VTS) at the first impression has similar capabilities. The VTS is a service, which is provided in areas with high traffic, where the VTS uses globally available perception sensor information as well as information from the crew and is authorized to control, manage, and support navigational tasks.

[a] https://orcid.org/0000-0002-8815-3444
[b] https://orcid.org/0000-0001-8934-7040
[c] https://orcid.org/0000-0003-2240-5351

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The difference between the VTS and the SCC is, that the SCC has all internal and perception information from the ship (Dittmann et al., 2021). So, the SCC employee is in an extended understanding a part of the crew (not located onboard), while the VTS is an external authority. Further, a VTS has the ambition to have a macroscopic view of certain situations and areas whereas an SCC has a more microscopic view of the traffic situation, in particular the view from one of the involved vessels within a specific (encounter) situation.

This description shows the need for an SCC that provides both the control function and situational awareness for the remote operator. Furthermore, the SCC need to embed into an overall architecture that enables the remote control and monitoring for several parties.

This paper provides a generic architecture, which enables different parties to remote control and monitor one or more ships, by ensuring the remote control as well as all needed information for situation awareness. Chapter 2 describes the current state of remote control and SCCs in the research domain. This is followed by the detailed definition of situation awareness and their levels, as well as the remote-control functionality. After this the concept for a SCC architecture is presented. In the evaluation the test setup is described, and the delay of control commands are evaluated, followed by the architecture evaluation based on use cases from the AVATAR research project, where the architecture was applied within physical maritime testbed environment called eMaritime Reference Platform (eMIR).

2 RELATED WORK

In the context of remote control and SCCs different approaches exist, which differs in scope and functionality. In particular, the various approaches focus either on remote control and situational awareness or on SCC. In the following, remote control will be discussed first, followed by situational awareness, and then SCC.

2.1 Remote-control and Situation Awareness

Two approaches can be distinguished when considering remote control. One is the control of an autonomous system, and the other is the direct control of a ship. Zhang & Zhang (2021) design a power and remote-control system for monitoring ships in lakes and reservoirs. The remote-control was designed to steer the vessel directly by the operator. In contrast, Son et al. (2004) design an operational control and monitoring system for small unmanned observation ships (UOV). The system was designed to instruct the autonomous system on the UOV by sending navigational and control data. In addition, there also exist approaches which combine both, the control of an autonomous system as well as the direct control. The following approaches include both control possibilities. Dittmann et al. (2021) present an approach for remote-control, using the international regulations of watch-keeping. In their approach the remote control is provided by an autonomous supervisor, which can be instructed from the remote-control-center. Stateczny & Burdziakowski (2019) present an overall architecture for small unmanned surface vessels (USV), where they show the modules of the USV accordingly to (IMO, 2018). They show the hardware architecture with all modules which are needed on the USV. Furthermore, they present the software architecture which include the control and monitoring of the USV. In this architecture the USV is controlled by a mission control system, which is already controlled by the autonomous system and can be overwritten by the control mode. Furthermore, the remote-control can instruct the autonomous system as well as the mission control system. A second architecture, which support the controlling of the autonomous system onboard as well as the direct control, was presented by Guo et al. (2015). The authors design the remote control with two different set of commands. The first set contains commands to send waypoints, or a start and destination point for the autonomous system. The second set include commands where propulsion parts can be steered directly from the remote operator.

The situation awareness, as second part, can be considered from two different viewpoints. The first viewpoint from the remote-control perspective and the second from the SCC perspective. Zhang & Zhang (2021), Stateczny & Burdziakowski (2019) and Guo et al. (2015) determined internal sensor readings and condition of the systems as data which need to be provided to the remote operator. In contrast the MUNIN project, which has developed a technical concept for operation of unmanned merchant ship (Fraunhofer CML, 2016), determined the ECDIS, should be provided for situation awareness for the remote operator in addition to the temporal overview and the internal ship conditions as the main data (Porathe, 2014). Where the ECDIS, by providing the same functionality as onboard, include at least the perception sensors. Further in some situations additional data can be used, including a camera system (Porathe et al., 2014). Dittmann et al. (2021) determined the voyage information (including waypoints), the navigational information including for example weather, position, speed, and distance to next waypoint. Further the object detection from the autonomous system, dynamic information, safety and emergency, propulsion system status, cargo and stability have been identified as relevant information for situation awareness.

2.2 (Shore based) Control Centers

Control centers are basically stations from which remote control can be performed. The concept itself is location-independent and can also be located within direct sight of the remotely controlled object. The SCC is a special control center, which is located on shore and out of sight of the ship. Most approaches address the location-independent remote-control-center, like Zhang & Zhang (2021), Son et al. (2004), Stateczny & Burdziakowski (2019) and Guo et al. (2015). While the MUNIN project design a SCC, which is able to control the vessel from a static location (Fraunhofer CML, 2016). But the remote-control stations in their project are basically used for monitoring and instructing the vessels, while the parts of steering are made in a separate so called situation room, which is designed as a regular ship bridge and allows the operator to steer the vessel directly (Porathe et al., 2014). In general, however, only rough functionality is discussed; in particular, the technical architecture of the control center or SCC is not addressed.

2.3 Integrated Navigation System (INS)

Integrated navigation systems (INS) are increasingly being installed on modern ship bridges. These integrate the tasks such as route monitoring, collision prevention, location determination, voyage planning, but also object identification through radar and AIS target data, as well as ECDIS and ENC reference objects. INS increase the safety of navigation through the improved overall view and a quality and process control. Intelligent alarm management also reduces the number of false alarms and thus the workload of nautical personnel. The goal is no longer to bundle data in one place, but to provide better data. The data provided goes through an integrity check before being displayed in the system. Data (e.g., speed) is measured at multiple points and checked for correctness. Since INS is a collective term, the various versions differ in type and scope. Accordingly, different (multifunctional) workstations can be provided for the various task areas (IMO, 2007) (IEC, 2007).

Since the INS architecture is finding an increasingly broad field of application in shipping and can therefore be regarded as a reference and state of the art. It is characterized by extensibility and compatibility of the components and functionalities. it is crucial that the INS can be used reliably in ship management. The goal of an INS is therefore to bundle and harmonize the heterogeneity and complexity of the systems on the ship and, in particular, on the bridge. The aim is to reduce the range of functions to the essentials and to evaluate the information load in advance. Accordingly, the principles of INS as a state-of-the-art approach to the design of today's ship bridges must also be taken into account in SCCs in order to do justice to the findings of the INS movement to an appreciative extent. Accordingly, the INS should essentially be integrable and replicable in the SCC. For this reason, the functional scope of the SCC architecture is compared to the evaluation of the SCC in order to examine this core requirement and determine the coverage.

2.4 Summary

Regarding the current research in the remote-control domain, two different alternatives can be differed. The first direction addresses the direct steering or instructing autonomous systems of vessels, which are controlled from a mothership or a place in the line of sight, like described by Son et al. (2004), Zhang & Zhang (2021), Guo et al. (2015) and Stateczny & Burdziakowski (2019). In this direction remote-control systems are realized and tested but the situation awareness is not really considered, because the environment is constrained, and the remote-controlled vessel is monitored by the mothership or the remote operator directly. So, the situation awareness is provided using the sensors of the mothership or the remote-control station by the line of sight. The second direction addresses the remote operating of commercial shipment, especially merchant ships, like in the MUNIN project (Fraunhofer CML, 2016) and described by Dittmann et al. (2021). Here the SCC plays a much more important role, but here the remote operator and the human machine interface is more regarded than the technical architecture of the SCC. Accordingly with the architecture, the situation awareness is regarded on a flat level. Summarized, the research lacks in an overall technical architecture concept for the SCC with the integration in the whole remote-control environment, where the vessel can be steered and instructed like described by Son et al. (2004), Zhang & Zhang (2021), Guo et al. (2015) and Stateczny & Burdziakowski (2019) from a SCC, which can be far away, without losing any advantages existing on the mother ship or by operating in line of sight. Further this SCC should be able to provide the remote operator the same situation awareness as on the vessel itself. This can be done regrading parts from Porathe et al. (2014), Porathe (2014) and Dittmann et al. (2021), but needed to extend them, by defining necessary sensors and information.

3 CHALLENGES OF CONTROL CENTER OPERATION

In the following, the challenges that appear with the operation and construction of control centers will be identified and derived. The two functions that have already been defined in the previous chapters and will be taken up and systematically applied to the use case of the (shore based) control center. First, the situational awareness perspective will be highlighted, and the corresponding technical systems will be identified. Finally, the remote-control perspective is highlighted and the conditions for safe operation are defined.

3.1 The Situational Awareness Perspective

To provide consistency in the information relevant for situational awareness (SA), it is necessary to form a unified understanding of the term situational awareness. Several definitions of SA exist. In order to be able to use the definition of terms used by authors such as Endsley (1988), Bedny & Meister (1999) or Smith & Hancock (1995) the terms environment, time and actor are crucial. Situational awareness is therefore about understanding the environment to be interacted with (for a specific and predefined area) through the present conditions by interpreting the conditions from the past and drawing conclusions and forecasts for the future. It is always a matter of taking an individual view and deriving decisions from it. According to Endsley & Smolensky (1998) situational awareness can be divided into three levels. These levels then lead to a decision that results into an action. All three levels must be supported by a control center (Figure 1).

Accordingly, the maritime domain already offers a broad range of technologies and sensors that are necessary for SA and serve as the basis for the digital representation of the different levels of SA.

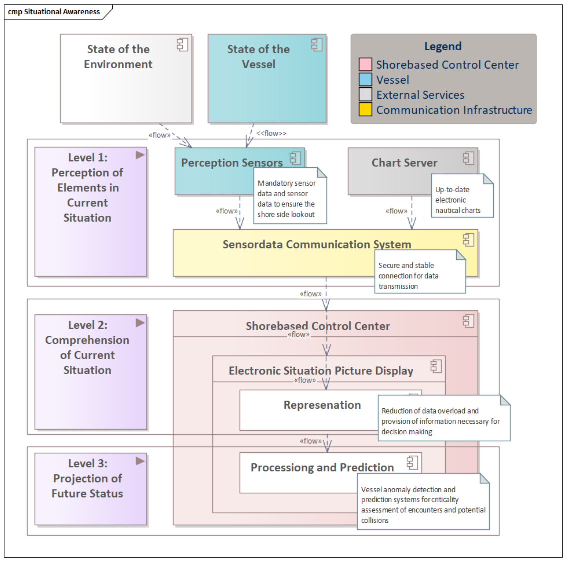

Figure 1: The three levels of situation awareness with the embedded SCC components for situation awareness.

The first level is the perception of surrounding elements in current situation and the internal state and condition of the vessel. Next to the existing sensor information the selection of suitable sensor technologies for the acquisition of relevant information, as well as the processing and extraction of essential attributes, is of primary importance. During data acquisition, objective processing is crucial to be able to represent the observations of reality on a digital level and without loss of information, and to enhance them with meaningful meta-information. The goal is therefore to transmit the (sensor) information that is normally available to the bridge personnel on the ship in real time securely to a remote decision-maker. Furthermore, the question must be clarified which information about the mentioned technologies is missing or necessary for decision making.

In shipping, the assessment of an encounter is the responsibility of the experts who monitor the operation of the ship (Officer of the Watch; OOW) and are accordingly responsible for the safety on board, as well as the ship's command. For control purposes, a situation assessment is made from shore, by independent VTS, in order to contact the ships if necessary. As these two areas of responsibility are still clearly different from each other, a SCC cannot be compared with a VTS center. As already mentioned in the introduction, the SCC is responsible for the microscopic view of a selected traffic user, whereas a VTS center takes a macroscopic view of the overall traffic and traffic management. It has a regulating and controlling role.

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To standardize the procedure on the ship's bridge, the International Chamber of Shipping (ICS) has created the Bridge Procedure Guide (International Chamber of Shipping (ICS), 1998). This contains checklists and guidelines for safe action on the bridge, including voyage planning and monitoring. The issue of situational awareness is also addressed. According to the Bridge Procedure Guide, situational awareness on the ship's bridge includes "knowing where the ship is, where it should be, and whether another ship, an event, or conditions developing nearby pose a risk to the safety of the ship." (International Chamber of Shipping (ICS), 1998). In addition, the Guide provides the following guidance on the use of electronic aids:

- Use of lookout, ECDIS, radar, and visual surveillance techniques to confirm the navigational safety of the vessel and monitor traffic
- Cross-checking information from multiple sources.

Care should be taken to ensure that information available on electronic navigation devices remains clear and relevant to the current situation. Relying purely on electronic aids is not recommended by the guide. From these statements, however, conclusions can be drawn for the second level of the situational awareness framework the comprehension of the current situation. A look-out is crucial in order to get a picture of the current situation via unfiltered representations. Further, a data fusion of the underlying sensor information is crucial to avoid sources of error and missing data.

Based on this information, the navigator evaluates the current situation and checks for anomalies and prospective critical conditions that need to be dealt with and have a direct impact of the own vessel. This process seamlessly transitions to third level, the projection of future status. Based on this information, the navigator can make a decision which results in an action, usually a maneuver, i.e. a steering operation on the vessel.

The essential technologies and their components for efficient ship navigation as well as for the situational awareness levels are largely listed in Regulation 19 ("Carriage requirements for shipborne navigational systems and equipment") of SOLAS Chapter V (IMO, 2020). These technologies should also be available for decision-making of the remote operator.

The following are the essential technologies, without redundancies, for safe and efficient navigation, the components of which are largely based on Regulation 19 ("Carriage requirements for shipborne navigational systems and equipment") of SOLAS Chapter V (IMO, 2020) based on the requirements for all possible vessels:

Accurate positioning is necessary for navigation on the water. Position information is provided using a coordinate system (orthogonal grid), divided into longitude and latitude. GNSS is a collective term for existing or future satellite-based navigation support. The most common implementation of these services is the U.S. proprietary Global Positioning System (GPS) project. To increase the accuracy of positioning, the differential global positioning system (DGPS) method can further help. A reference station (fixed GNSS antenna), whose position has been accurately determined beforehand, calculates the error of the orbit and time system and sends correction data to the available receivers (IMO, 2015). The position navigation and timing (PNT) system must be designed to be resilient to interference for the safety of the ship. For this purpose, position data from various sources are checked and merged into secured information. In addition to the satellites, motion data which might be given out by an inertial measurement units (IMUs) are synchronized with the satellite signals to compensate disconnections or interference (IMO, 2017).

In addition to the ship's position, the ship's course is also crucial for navigation. The two tools approved for determining the north direction in SOLAS are the magnetic compass and the gyro compass. By means of the direction of movement (compass) and speed (log), the ship's command can also perform the approximate location determination without direct measurement (dead reckoning). Furthermore, the heading needs to be provided as well as the rate of turn (ROT), which indicates how the ship is aligned and shows the speed perpendicular to the vessels direction of travel.

On the ship's bridge, all information necessary for safe navigation will be provided. Assistance systems will complement existing systems to relieve personnel and increase safety and efficiency of ship operations. Nautical charts are essential for safe navigation in (unknown) sea areas. Important information such as water depth, coast lines or buoyage, which nautical personnel need for route planning, is recorded in the nautical chart and is constantly updated. Electronic Navigational Charts (ENC) have become established in commercial shipping. These ENCs are available in the IHO-S-57 standard and can be displayed using an Electronic Chart Display and Information System (ECDIS). For the exchange and standardization of hydrographic data, the S-100 standard version 1.0 was published in

2010. From this product family, for example, the S-101 standard will replace the S-57 in the long term. S-100 is a framework document intended for the development of digital products and services for hydrographic, maritime, and GIS (geographic information systems) communities.

Probably the most established technical tool for collision avoidance on the bridge is the radar system, which today is predominantly used in combination with a radar image evaluation device (Automatic Radar Plotting Aid; ARPA). In addition to manual and automatic target detection and tracking, ARPA also determines the course and speed (target movement) of other traffic users. Based on this, Closest Point of Approach (CPA), Time to Closest Point of Approach (TCPA), and Distance at/to Closest Point of Approach (DCPA) are determined and warnings are issued if necessary (IMO, 1995).

Since 2000, AIS has been firmly anchored in SOLAS as an additional system for protection against collisions. Radar data are enriched by electronically exchanged information. AIS is a ship-based radio system that allows ships to exchange detailed information with each other (ship-to-ship). Communication to VTS (ship-to-shore) is also possible.

All information occurring on the ship's bridge must be bundled and displayed in addition to the ENC. By combining the various input devices AIS, charts, radar, echo sounding device and log, the system can process the available information in advance and, if necessary, communicate acoustic and visual alarms to the bridge personnel (automatic voyage monitoring). The functions of an ECDIS system range from general chart management and various planning functions to voyage monitoring.

GMDSS refers to all technical facilities, services and rules for worldwide assistance in emergencies and for securing navigation. This includes the marine radio and NAVTEX (Navigational Text Messages), as well as emergency transponders, satellite systems with ground stations and worldwide emergency response centers (Maritime Rescue Coordination Centers; MRCC). Safety information and immediate weather warnings (high winds, storms or hurricanes) are communicated via NAVTEX to all ships within a radius of approximately 400 nautical miles. In addition to weather warnings, navigation warnings and SAR information are also transmitted via this information system.

Additional to maintain completeness, the ship should be equipped with a daylight signal lamp, a telephone, a bridge navigational watch alarm system and a heading or track control system.

In addition to the sensors, which are used for monitoring the environment of the vessel as well as the navigational situation picture there are several sensors which monitor the internal state and condition of the vessel. In general, they monitor the whole propulsion system, including the engine, rudder, thruster and other operational related systems of the vessel. Regarding the complexity of the engine itself and the existing engine monitoring of vessels in the commercial shipping, the representation and scope of the monitoring of the engine need to be determined for each vessel independently. Same applies for the rest of the propulsion system, like the rudder and the thrusters. The complexity of the monitoring is influenced by the size of the vessel as well as the types of the propulsion parts. While the propulsion monitoring of a small research vessel could be simple the complexity of monitoring the propulsion of a container ship cannot be compared to the small research vessel. So further the propulsion as well as its monitoring is seen as black box, whose complexity differs from ship to ship.

3.2 The Remote-control Perspective

In order to move the control of highly automated and autonomous vehicles to the shore side, not only ship to shore communication needs to be discussed and clarified, but especially shore to ship communication. To propagate possible commands to the ship, a unified and standardized interface must be designed that can be addressed by different entities to take control of remote-controlled vessels at any time and any place. Since the motorization in shipping is characterized by a high degree of heterogeneity, the interface for controlling ships must be completely rethought and the response of the steering system must be interpreted directly on the ship and monitored by the remote operator. According to the MUNIN project results (Fraunhofer CML, 2016), one operator can be used for up to six different vessels, if the operator just instructs and monitors the autonomous system. As a consequence, the operator needs a uniform control interface that works independently of the vessel characteristics, this is also the case in the situation room. The situation room is a specific room which can be used to steer the vessel directly inside the approach of the MUNIN project. This means that for example, instead of the rudder angle, the change in the ship's course or heading is controlled as a steering command and the translation to the ship must be made internally. But further the SCC should include the ability to work on each level of remote control to allow the remote operator instructing the system (if exists) which provide the autonomous functionality or to directly steer the ship. External intervention within a safety-critical system requires that the communication and the ship can be reliably controlled. The challenge is, on the one hand, to secure the authentication between the ship to be remotely controlled and the control center and, on the other hand, to make the communication reliable. Furthermore, if the communication is not reliable as expected, the remote-controlled vessel needs procedures to handle communication interruptions or disconnections. Accordingly, to the Bridge Procedure Guide the remote operator like the OOW should ensure compliance with the COLREGs and should not hesitate to use the different propulsion parts as well as other signalling apparatus to ensure this compliance (International Chamber of Shipping (ICS), 1998). Based on these requirements the one-way transmission time is a special key factor of the remote control, and in an extended understandings also the round-trip time. Regarding the one-way transmission time from the International Telecommunication Union (ITU), which was defined as 400 ms for the upper limit (Telecommunication Standardization Sector of ITU, 2003), sending control commands should not take longer to ensure the fast execution of transmitted commands. Further to ensure the remote operator gets feedback from the remote-control system the round-trip time of the message should not exceeded 800 ms.

4 CONCEPT FOR A SHORE BASED CONTROL CENTER

The previous chapters have provided the basis for the following concept. The insights from the related work and also the derived challenges clearly show that for a shore based control system three subsystems are essential: The ship, the communication infrastructure, and the control center. Since the control and decision center are decoupled from the vehicle, it is mandatory that the system to be controlled (ship) can provide all necessary information by itself and can also process and execute the necessary commands. In the following, the required functions of the individual subsystems of the overall system architecture will first be explained and described in more detail. Finally, the overall architecture is presented (cf. Figure 2).

4.1 Communication Infrastructure

The basis for the reliable remote-control capability is the communication link between the ship and the SCC. This communication link is provided using a centralized communication infrastructure (CCI). This CCI has several advantages, while the most important is that through the centralization of the communications infrastructure, ships can be controlled from multiple SCCs and, conversely, the SCC should be able to remotely control multiple vessels. A distribution also has different advantages like avoiding a single point of failure in this infrastructure, when one SCC crashes. Moreover, the CCI allows several SCCs to monitor and control more than one ship at the same time. The CCI links the vessels with the SCCs and allows the communication of control commands as well as transfer data, which can be monitored. In addition to the system which provides the distribution of messages, the CCI should include a sensor observation service (SOS). The Sensor Observation Service (SOS) is a service for querying real-time sensor data. The offered sensor data includes descriptions of sensors themselves (using SensorML as Modelling Language), as well as the measured values, (in Observations&Measurements (O&M) format). All three solutions are concepts of the Sensor Web Enablement Framework (SWE) defined by the Open Geospatial Consortium (OGC). The SOS can also be implemented transactionally (SOS-T), so that new sensors can be registered via the service interface and subsequently measured values can be inserted. This service should enable the SCC to filter and adjust received sensor data for a specific use case or task, while all other SCC are not affected by this configuration.

4.2 Vessel

The second system to be described is the vessel, which should be remotely controlled. The vessel needs to contain components, which fulfill the requirements to assure the situational picture creation and decision making as well as the remote-control.

The vessel first needs to provide each relevant data for the situation awareness. This data should contain the measurements from the navigational, perception, and internal state sensors, in short, each data which can be measured on the vessel itself and can be used to get the situation awareness. This collection should include each relevant sensor on the vessel, like described in the situational awareness section.

The vessel needs to accept incoming messages and further process them into actuation, depending on the available and provided remote-control level. For this purpose, as a basis the vessel needs to be able to control the propulsion, the engine as well as other actuators on ship. These additional actuation elements can be for example the trim control to adjust the stability of the vessel. The actuation components can be steered with programmable logic controllers (PLC) which are used as an interface between the actuation elements and the system which process the control commands. The system which processes incoming commands, in the architecture called input module, can represent a system with a concrete logic or intelligence that makes decisions and decomposes the commands to the control level and performs a comparison between in- and output, or it can pass the control commands directly to the actuation instance. So, it could be an autonomous function, which navigates and controls the ship fully autonomous, as well as an interface, which just forwards incoming commands to the specific PLCs.

4.3 Shore based Control Center

The architecture of the SCC can be divided into four main components, which ensure the functionality of the SCC. These components are the internal exchange

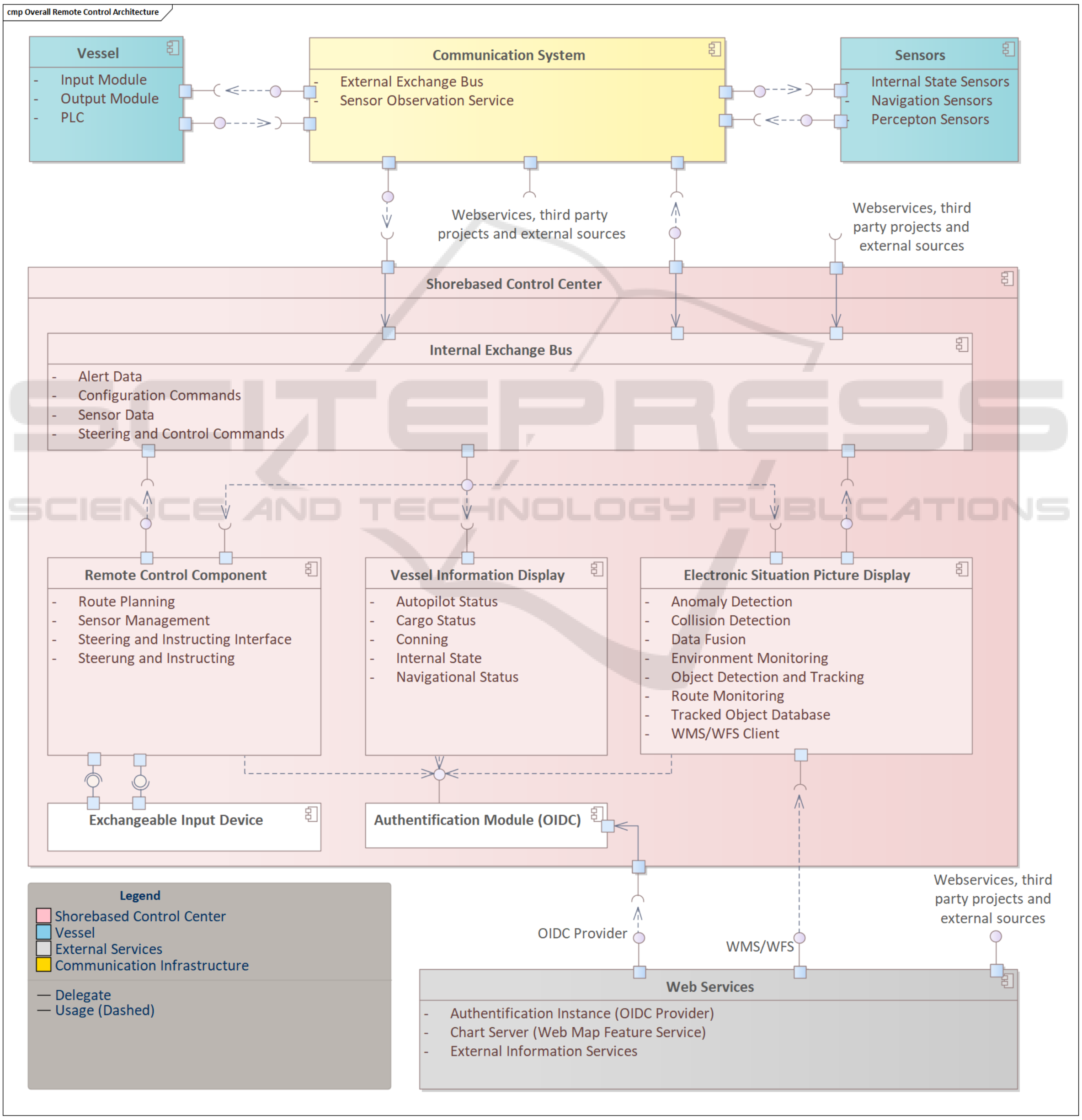

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Figure 2: Overall architecture of the shorebased control center and the interfaces, connections and functions between ship and shore.

bus, the remote-control component, the vessel information display (VID) and the electronic situation picture display (ESPD). The internal exchange bus provides a communication infrastructure within the SCC. This allows the different components to interact with each other. Further the remote-control component provides the necessary functionalities to steer a vessel and planning the journey. The VID and ESPD provide together the situational picture, where the remote operator can observe the navigational, perceptional, and internal situation and state of the vessel. All components should use the same authentication module (e.g., OpenID Connect), to ensure authentication within the whole infrastructure. The authentication can be provided by external services and should not be further regarded.

The internal exchange bus (IEB) provides the inter process communication for the SCC. The IEB is used by the several components inside the SCC to communicate with each other as well as the interface between the CCI and the remote-control center. Messages are forwarded from the remote-control component to the CCI and data from the CCI is distributed to the existing components inside the SCC. Further the actions inside the SCC could be monitored and analyzed.

The second component addresses the remote-control. It must provide a steering and instructing interface, which should be able to process inputs of the remote operator. Further the remote-control component uses an interface for external input devices, to have the ability to connect different input devices to the remote control and also to integrate and expand new steering devices. External input devices can be any kind of physical or virtual controllers, like joysticks, azimuth levers, ship consoles or touchpads, while the external input device component provides the interface between the physical and virtual layer. The steering and instruction interface forward the instructions or steering commands into the main logic, which is provided by the steering and instruction component. The component processes the given inputs and forward them using the IEB. By decoupling the control component from the processing component, it is possible to take over control at different levels. For example, at the strategic planning level, routes can be specified for the vehicle to follow. At a lower level, it is possible to define maneuvers to be performed by the vehicle, for example to avoid an obstacle or to change or adjust the heading by a defined degree. Alternatively, at the controller level, it is possible to actuate the rudder or engine systems directly.

The second part of the remote-control component is the sensor management. The SCC must be able to manage the sensors, from which they get information. At least the steering and instructing interface need to provide the strategic planning, like the route planning. The route planning provides the functionality to create routes, which can be send as strategic command to a remote-controlled vessel. For the consistent route planning nautical data is need, which leads to the second main component of the SCC, the Electronic Situation Picture Display (ESPD).

As mentioned, the situational picture is provided by two components, the ESPD and the VID. The ESPD provides a visualization and the same functionalities as an ECDIS on the ship. The used ENC can be accessed via an external web map services (WMS), there additional information can be retrieved using web feature services (WFS). Using ENC from external services allows the remote operator to access the latest information, warnings, or rules. Additionally, the planning from the remote-control component can be performed using the available data. Further the ESPD can be used for anomaly and collision detection after the data from the IEB is processed. This processing is necessary to improve the quality of the measurements through sensor fusion and use a database to store the tracked objects afterwards. These objects can be used for further analysis or for prediction and planning purposes. The ESPD can be extended to several other services which can use the data to support the remote operator by controlling the vessel and during the decisions making process. Also, the monitoring of the environment must be provided by the ESPD. The information could be provided by the vessel but in addition other information sources could be used, as already mentioned with ENC data. For further measurements different sources can be used and integrated into the architecture.

The Vessel Information Display (VID) visualizes the state information from the vessel, which includes the several measurements. It should provide all information which were described in the situational awareness chapter. Further the navigational as well as the autopilot status can be displayed. The monitoring of cargo is also considered here.

5 EVALUATION

The overall architecture developed is evaluated in several steps. First, the technical feasibility is demonstrated, and the implemented setup is briefly shown. Second, the delay measurements are evaluated. While the MUNIN project already evaluates the applicability of streaming sensor data using the different communication technologies, the evaluation only considers the control commands. Finally, the SCC is evaluated against the function of an INS. The evaluation took place in the maritime testbed environment eMIR in the context of the AVATAR research project. The AVATAR research project is about reactivating strategically useful waterways to relieve road traffic as a transport route. In order to make waterways visible as a more attractive alternative, it is necessary to increase the degree of autonomy for this mode of transport. To demonstrate the feasibility of autonomous inland waterway vessels, the practical feasibility of the various automation levels will be demonstrated. Since the first step towards an autonomous waterborne vessel is teleoperation, and that the remote-control is reliably carried out over land. The used maritime testbed environment eMIR consists of a physical and a virtual testbed (Rüssmeier et al., 2019). The physical testbed contains the research platforms that was used for testing the systems under test. Furthermore, the physical test field also includes the reference waterway, which enables monitoring of the research platforms during tests.

5.1 Setup for Implementation and Testing

To implement the architecture shown, RabbitMQ[4] is used as the basic communication infrastructure. RabbitMQ is a message broker that can provide configurable queues to forward messages to the connected consumers. Here it is possible to create multiple queues for the sensor data as well as remote-control commands. Since it is necessary to keep the bandwidth and the data volume as low as possible, the messages can be serialized with the help of Protocol Buffers[5]. In addition, Remote Procedure Calls (RPC) can be used, so that it can be ensured that the commands were received by the client, and the remote operator receives feedback. For the collection of sensor data, sensors can be used, which in turn can be connected in an NMEA2000 network, for example. NMEA2000 is a bus based on the CAN protocol and can be used to connect devices to the vessels network. From this network, the measurements can be retrieved and read out using libraries such as CANBoat[6], which can be wrapped, and the received messages can be published on the RabbitMQ exchange bus. The IPC of the SCC can be implemented by another RabbitMQ server, both RabbitMQ servers can then be connected to each other using a shoveling approach. In this case, the messages from individual queues are forwarded to the queues of the other server. The authentication can be implemented using OpenID Connect, which can be provided by a Keycloak[7] instance. With the help of Keycloak, identity and access management can be performed. An alternative could be the use of the Maritime Connectivity Platform [8] (MCP), which would provide a token in the same way as Keycloak. The components within the SCC were implemented using Java and JavaFX[9] for the frontend.

As remotely controlled vehicle a small research boat was used. This has the sensor technology required for the evaluation. The flexible, sustainable architecture of the research boat enables the integration and expansion of the functions required for the evaluation, such as the measurement of the round-trip time (RTT) timestamp. In addition, the experimental vehicle provides the possibility of processing incoming control commands using RPC over RabbitMQ that can be processed and interpreted directly by the motor and control unit. The control interface of the research boat was developed to realize the teleoperation of inland ships and formations (platooning). The connection from the research boat was provided via mobile network (4G), while the implementation was focused on coastal areas as well as inland areas, where the coverage of 4G meets the requirements. The implemented VID was able to display all relevant data from the vessel. While the size of the used vessel was small, also the number of installed sensors were limited and manageable. The ESPD within the SCC was able to display the map from an external web map service and to show all detected objects. Further with the remote-control component it was possible to directly control the ship by setting the rudder angle and the relative thrust.

5.2 Applicability Evaluation of the Remote-control

Like described in the remote-control chapter, the overall one-way transmission time of the remote control should not exceed 400ms, while the RTT, should not exceed 800ms considering the one-way transmission time. Several different field tests were

[4] https://www.rabbitmq.com/
[5] https://github.com/protocolbuffers/protobuf
[6] https://github.com/canboat/canboat
[7] https://github.com/keycloak/keycloak
[8] https://maritimeconnectivity.net/
[9] https://github.com/openjdk/jfx

made in a coastal area. The one-way transmission time as well as the RTT was measured performing different maneuver tasks, like turning, evading and driving forward with course adjustments. Further the measurements were performed on several days with different climate conditions. In total 1475 command executions were made, where 584 executions were engine commands and 891 were rudder commands. The size and length of the commands was the same. The allocation between the one-way transmission time from and to the vessel is nearly in all executed commands the same, so it is not further regarded. The allocation of the RTT can be seen in Figure 3.

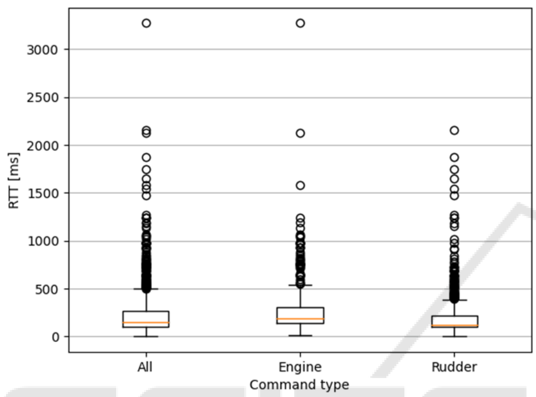

Figure 3: Deviation of control command RTT of different field tests, evaluating 1475 command executions.

The Figure 3 shows that the most command RTT is below 500 ms, which match the requirements of 800 ms for the RTT. Further about 10 percent of the engine as well as the rudder commands are outliers, where a part can be seen as measurement deviations. The RTT of the most command was approx. 105 – 260 ms, which is much lower than the requirement value.

5.3 Comparison with INS

As mentioned earlier, an SCC should include the functionalities and components that are specified by INS so that the essential properties are also available on the shore side. The work of Lund et al. (2018) , has summarized the core components of common INS solutions from various works. The essential seven parts are compared to the SCC architecture in the following to show the completeness of the solution. The seven components are: existing workstations, an overall operating system, sensor integration, networking, radar information, an ECDIS controlled autopilot and a stable internet connection. The first component, workstation, comprises the hardware, which must be seen in connection with the operating system, which is also the second component. In order to mitigate the point of the operation system, it is recommended to use operating system-independent solutions when selecting the software solutions to be used. That results in the fact, that for the SCC it is not required to have a specific operating system allowing safety and time-critical processes to run on real-time capable systems. Visualization solutions of the SCC can run on less critical systems. In a broader sense, the SCC could provide a multi-function display. The sensor integration is provided via the CCI, as well as all other information flows such as radar or steering commands. Steering commands including the activation and control of the autopilot function as well as autonomous systems. Accordingly, the components of the sensor integration, the radar and the ECDIS controlled autopilot are also provided. For the SCC concept a stable internet connection is essential. The connectivity to the internet in the SCC architecture is also considered as well. The seventh and last component addresses the on-board network connection. In the context of the SCC, this takes place on the ship's side and is therefore not considered in the SCC. The connection of the various components on the SCC side is regulated by the internal exchange bus, which can be based on an Ethernet network. Accordingly, it can be seen that the SCC contains all the required components of an INS insofar as they are located in the SCC according to the concept. In summary, it can be said that the SCC fulfills the requirements as a remote INS.

6 CONCLUSION

In the paper, an architecture focusing on the technologies and functions for the realization of a shore-based control center was presented. It was defined based on the requirements derived from the regulations and the decision-making processes on the ship's bridge. In order to support the decision-making process, special attention was paid to the levels of situational awareness to ensure the provision of information at all levels. It was found that essential information could be prepared and accessed in a location-independent manner to support the ship's command and control, which is an essential necessity when decoupling the control center from the ship. It turned out that the existing communication infrastructure is already sufficient to realize a shore-based control center. Only the reliability of the transmission or more concrete the guaranteed transmission and communication between ship-to-shore and vice versa, as well as the resulting concepts

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for the fallback level are crucial for the realization. In order to validate the completeness of the functional scope, a comparison with the INS was aimed to ensure that the design specifications can also be applied to an SCC. Accordingly, further work consists of testing the edge cases in remote control with meaningful scenarios and creating and presenting further technical framework conditions for the reduction of automation risks associated with operation phase.

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