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AUTOFLEX

[D4.5] IWW AUTONOMY PACKAGE

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EXECUTIVE SUMMARY

This deliverable presents the AUTOFLEX inland waterway autonomy package developed through Tasks 4.5 and 4.6. The work combines Maritime Robotics' SeaControl, SeaSight and remote operation capabilities with a Mission Exchange Model (MEZ) for transferring the information required to plan, assign and execute autonomous inland waterway missions. The intended concept places mission scheduling, operational supervision, intervention requests and fallback handling in the Remote Operation Centre (ROC), while the onboard Autonomous Navigation System (ANS) executes the approved mission and reports status and requests back to the operator.

The MEZ was developed through requirements workshops, a gap analysis of existing maritime and inland waterway standards, definition of extended data models, and a proof-of-concept demonstration. Existing route-exchange standards, particularly RTZ and S-421, were found to provide a suitable basis, but extensions are required for inland waterway operations. These include action points, operational-mode transitions, strict schedules, lock and bridge passages, mooring information, cargo data, infrastructure constraints and planned responses from the ROC. A subset of the model was successfully demonstrated with the OtterX USV in Trondheim, where the vessel followed a predefined route, notified the ROC at action points, stopped to await operator confirmation and resumed autonomous navigation after bridge clearance. An RTZ Route Planner was also developed and its MEZ-extended route output was successfully parsed and displayed in the Maritime Robotics Vehicle Control Station.

Task 4.5 addressed the situational-awareness capability required for autonomous operation. Therefore, situational awareness systems, were installed on an IWW vessel MS Sorrento operated by project partner DFDS. Camera, AIS and LiDAR data were collected during operations of the Sorrento barge during their normal operation on the Ghent–Terneuzen Canal and used to establish a structured workflow for annotation and training of real-time visual object-detection models. The proposed perception pipeline combines complementary camera, radar, AIS and LiDAR information to improve object classification, ranging, tracking and detection of non-cooperative targets. The deliverable further describes the planned installation of the SeaControl onboard system, SeaSight sensors, dedicated radar, Vehicle Control Station and scalable ROC capability on the IWW vessel MS Letitia which will be further investigated during the validation and demonstration campaign in WP 6.

The work achieved the main objective of defining and demonstrating the core elements of an autonomy and remote-operation package for inland vessels. The vessel MS Sorrento was selected and successfully equipped with parts of the developed situational awareness package and data before further optimization could be collected. The full scope of the developed situational awareness package and the functionality of the developed MEZ will be demonstrated on another IWW vessel, MS Letitia within the scope of WP 6.

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LIST OF ABBREVIATIONS

Abbreviation	Description
ANS	Autonomous Navigation System
CA	Consortium Agreement
IWT	Inland Waterway Transport
IWW	Inland Waterway Transport
MASS	Maritime Autonomous Surface Ships
MEZ	Mission Exchange Model
MR	Maritime Robotics
OBS	On Board System
ROC	Remote Operation Centre
SAS	Situation Awareness System
SOTA	State-of-the-art
TCO	Total Cost of Ownership
USV	Unmanned Surface Vehicle
VCS	Vehicle Control Station

1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

This deliverable relates to tasks T4.5 and T4.6 in the AUTOFLEX project. The purpose was the development of an high-level system enabling inland vessel automation and autonomy.

In Task 4.5 the automation and autonomy package concept for MR (SeaControl and SeaSight), was established and tailored for uncrewed inland vessels at CCNR autonomy level 3¹. Under this concept, the majority of operations, such as mission scheduling, intervention requests, and fallback recovery, were designed to be planned and controlled from the Remote Operation Centre (ROC).

To address critical situational awareness challenges, the task focused on vital object classification requirements, defining specific object categories and interaction strategies for the autonomous navigation system. Additionally, the navigation system was upgraded to support the execution of digital missions (later developed in T4.6), with a particular focus on successfully managing the complexities of oncoming traffic, canals, and locks. To fulfill the task, sensors for situational awareness were installed on an inland vessel and used in the development and training of algorithms for classifying objects into object categories. The work focused on gathering datasets at different viewpoints, illumination conditions, and with object variations, which ensured high-quality training and testing data.

Task 4.6 established the ROC concept, centered around a digital mission package for autonomous vessels. This digital package consolidates all data required for the autonomous navigation system to execute a transport job, including routes, schedules, and specific transit requirements like bridges and locks. Additionally, the task defined methods for both assigning these missions and securely transferring them from the ROC to the vessel.

¹ <https://www.ccr-zkr.org/12050000-en.html#03>
IWW Autonomy Package – PU



2 PROPOSAL OF A MISSION EXCHANGE MODEL

2.1 BACKGROUND FOR THE MISSION EXCHANGE MODEL

This chapter describes the work done to define a draft standard for a Mission Exchange Model. The work is done as part of *Task 4.6 Remote control centre* concept. The Mission Exchange Model (MEZ) describes the information that is needed by the autonomous ship to execute its navigation task, e.g. the route, the schedule, the bridges and locks to pass, and other relevant information. The information is sent from the ROC (Remote Operation Centre) to the ANS (Autonomous Navigation System) to ensure that the autonomous navigation of the MASS in inland waterways is performed according to the input from the ROC operator.

The results were also published in the paper “A Mission Exchange Model (MEZ) for Autonomous Inland Waterway Navigation” that was presented at the ICMASS conference in Hamburg in 2025 [1]. The current deliverable report provides several updates done based on further evaluation of the proposed model. The Mission Exchange Model was also presented to the standardization committee *IEC TC80/WG17 Common Maritime Data Structure (CMDS)* at its April-meeting in 2026, in London. This committee is relevant for the standardization of the MEZ, since it is responsible for the development of the route exchange standard *S-421 route plan based on S-100*, which is also named *IEC63173-1 ED2: Maritime navigation and radiocommunication equipment and systems - Data interfaces - Part 1*. This standard is used as the basis for the MEZ standard, with some extensions.

This chapter describes the requirements to the Mission Exchange Model (MEZ), investigate existing and relevant standards that cover mission data, and propose a format for such missions to be sent from the ROC to the ANS.

2.2 MOTIVATION FOR THE MISSION EXCHANGE MODEL

Humans will be involved in the operation of autonomous vessels for the foreseeable future, irrespective of whether the autonomous vessel is capable of navigating inland waterways (IWW) without continuous human supervision for certain parts of the voyage. The established principle of autonomous navigation, somewhat simplified, is that a) the Situation Awareness System (SAS) provides the Autonomous Navigation System (ANS) with the required information to perform navigation tasks, such as positioning, traffic and other objects identifications, b) to navigate autonomously, the ANS must determine if the actions it currently executes, such as docking or transit, can commence as planned, or if corrective actions such as speed and course changes are required, and c) that the operator intervenes if deemed necessary or requested by the ANS, or otherwise monitor the operation - Figure 2-1 shows the environments for IWW mission planning and execution based on the principle of autonomous navigation. This principle emerged very early in autonomous vessel development [1], and is reflected in the ongoing IMO MASS Code development and international standardization [2], as well as within the first commercial IWW applications.

Although the ANS should be capable of making decision on its own, it cannot determine its own purpose, that is, what it is supposed to do. Thus, it falls upon humans to tell the autonomous vessel what it is supposed to do, when it is supposed to do it, where it is supposed to be at given times, and what navigational constraints it must consider. This is the mission,

and that is assigned to the autonomous vessel by a remote operator that resides in ROC, before leaving the departure port.

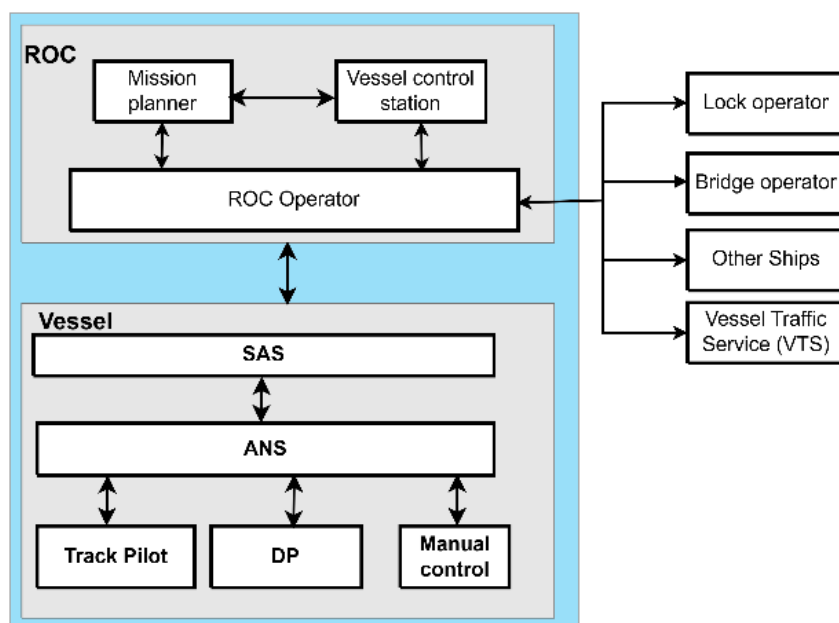


Figure 2-1: Environment for IWW Mission Planning and Execution

2.3 RELATED WORK ON ROUTE PLANNING AND AUTONOMOUS NAVIGATION

In manned maritime transport, one core task of navigation is voyage planning, which serves as the backbone of safe navigation. Voyage planning is linked to SOLAS Regulation 34 [3], with IMO Resolution A.893(21) giving guidelines on how to execute this task [4]. The plan itself typically consists of amongst others: Plotting of the intended route, safe speed, necessary speed alterations, minimum clearances, and course alteration points. Since 2015, this is electronically supported by a route plan exchange format, which is called RTZ, and standardized by CIRM [5], and also standardized in IEC 61174:2015, Edition 4 [6]. This was tested for vessel-shore interaction capabilities by the STM project [7]. An extended version of RTZ, named S-421 and developed by IEC as IEC63173-1:2021 [8] is added to the IHO S-100 framework of standards. Also, during the ISTS-project, a converter from the RTZ-format to the S-421 format was implemented [9]. Routes in RTZ and S-421-formats are described by geographical waypoints, allowed cross track errors, schedules, and optionally by a simple turning radius between legs. On open sea, such voyage plans can be executed from a track pilot supervised by an officer of the watch. In inland navigation, similar processes apply, yet less formalized.

For Autonomous and Inland Navigation, additional specific data elements need to be covered, which are not yet included in the given voyage planning data format, including 1) Specific geometries: The meandering nature of (natural) IWW requires more complex route planning than static turning radius. State-of-the-art track control systems for IWW do typically work with rotation speed regulation instead. 2) Infrastructure interactions: Pausing and waiting during a voyage at IWW infrastructure such as bridges and locks, are more common on the voyage than in maritime. Those do typically affect the schedule, which cannot be totally preplanned. 3) Changing autonomous operations: In contrast to manned shipping, different modes of operations (autonomous and remote) as well as different degrees of autonomy (CCNR 0-5) are possible during different parts of the voyage and need to be planned.

Significant efforts have been put into studying autonomous navigation systems where the focus has been on the ROC [10], [11], [12], [13], the Guidance, Navigation and Control (GNC) methods of the ANS [14], [15], [16], [17], and support functions of ROC and other shore-based personnel for anomaly detection [18], [19]. However, less attention has been given to how the ROC should communicate plans, and changes of plans, to the ANS. This includes the definition of the mission that the ANS shall execute, and how it should be exchanged between the ROC and the ANS.

The review in [20] investigates the current advancements on autonomous mission planning and management for autonomous underwater vehicles and aerial vehicles. While a high-level architecture for a typical mission planning and management system is presented, the mission exchange model is not discussed. The review of mission planning in [21] discusses the decomposition hierarchy of the USV (Unmanned Surface Vehicle) mission into specific goals, tasks, and behaviour, however, neither the mission creation nor a data model for transferring a mission from a control centre to the USV is discussed. Robust mission planning for Autonomous Marine Vehicle fleets is proposed in [22], where the planner translates mission goals to tasks that are distributed over the fleet of autonomous drones. However, a mission exchange model is not discussed. An AI planning module for executing the autonomous vessel mission, intended as a translator between the mission and the path and motion planning unit, is proposed in [23]. However, neither the mission creation nor the mission exchange model is discussed. Temporal mission planning for Maritime Autonomous Surface Ships (MASS) is proposed in [24], where a temporal AI planning is used to create the control tasks for the GNC. It takes goals and actions as inputs, but the mission exchange model, that would contain these goals and actions to be communicated between the ROC and the vessel, is not discussed. While the literature seems to focus on the planning problem from the perspective of translating mission goals into tasks, no studies address the data model for transferring the mission to the ANS.

The Mission Exchange Model proposed here will be based on existing standards for route plan exchange (RTZ for current usage [5] and S-421 for further usage [8]) and standards for IWW navigation (currently IENC 2.4 [25], and future S-401 [26]), as well as class terminology for autonomous operations (as e.g. DNV Autoremove [27] or CCNR [28]), to be easily adapted by existing technologies. The mission exchange model will contain all the information that the autonomous vessel will need to execute a mission, including relevant information about the cargo, departure and arrival berths, the route to navigate (with any restrictions such as shallow draft), with the related schedule, bridges and locks to pass, and the allocated positions in the lock chambers and at the berth derived from the Inland ENCs.

2.4 MISSION PLANNING PROCESS

Figure 2-2 describes the message exchanges related to the planning, execution and updates of a mission, related to the environment shown in Figure 2-1. The process starts with the ROC operator describing the mission, including the route and waypoints, planned speed over ground, time schedule, cross track distance for each leg, if the ANS or the ROC operator is in control for each leg, information about the lock passing and bridge passing, and information about when the ANS should notify the ROC operator and what situation to report on. The Mission planner in the ROC will create the Mission Exchange Message according to the Mission Exchange Model, and this will be sent by the ROC communication interface using the ANS-ROC communication carrier.

The ANS will need to validate the mission, and it will then send the approval back to the ROC operator. Then, the mission is ready for execution by the vessel. The ANS can either

execute the mission by sending the set points to the Track pilot or DP system, or it can instead hand over the control to the ROC operator, dependent on the instructions in the mission. During the execution of the mission, the ANS will continuously send statuses and feedback to the ROC operator, according to the mission, and to what is already defined by the ANS. For each request, the ROC operator must evaluate the request and act as needed. This may be to take over the control of the vessel from the ANS, to contact lock or bridge operators, or to handle certain requests that requires updates of the mission plan. During the execution of the mission, external actors like lock or bridge operators may also give warnings or information to the ROC operator that may lead to updates of the mission plan.

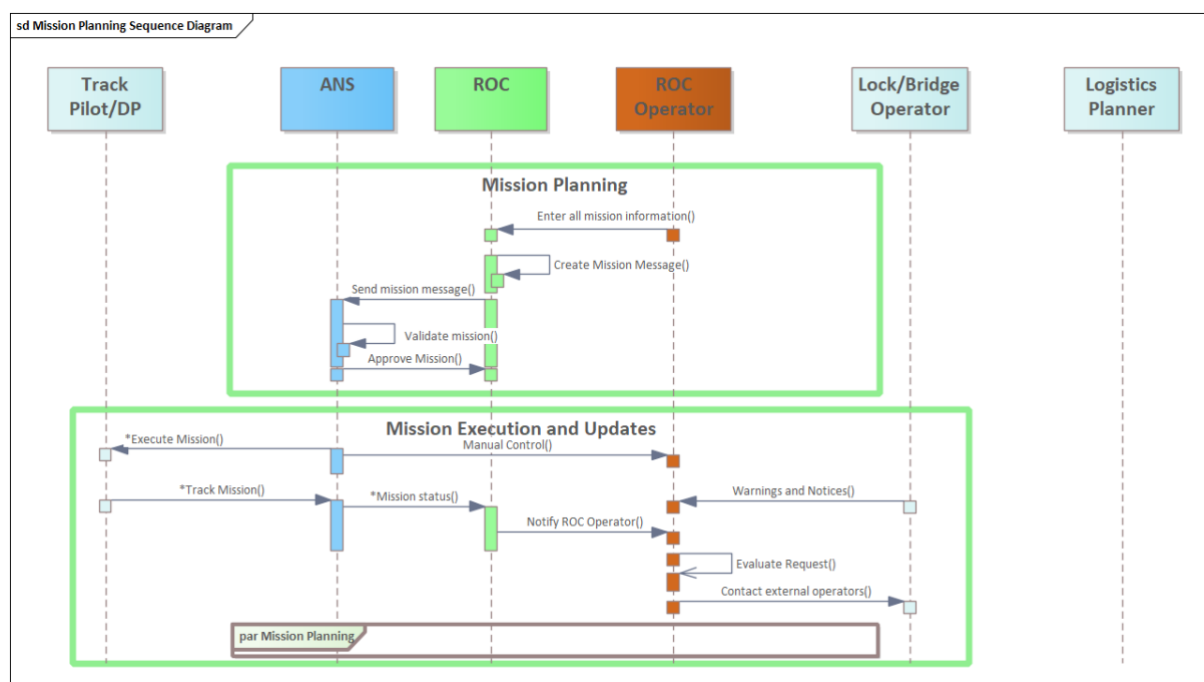


Figure 2-2: Mission Exchange Message sequence diagram

2.5 DEVELOPMENT METHODOLOGY

2.5.1. OVERVIEW

To develop the mission exchange model, a case study method was applied. The case study was designed to be carried out over four phases, with each phase having a specific purpose:

- **Requirements:** In the first phase, requirements to the mission exchange model were elicited in a series of online workshops with joint industry and research organisations, see Section 2.5.2.
- **Gap Analysis:** Secondly, based on the identified requirements, a review of existing data models and standards applicable to inland waterways, but also standards for sea-going vessels were carried out. It was investigated which parts of these existing standards could cover which of the requirements to the Mission Exchange Model, and which gaps still existed, see Section 2.5.3.
- **Extended Data Models:** Thirdly, new data elements were proposed, that are extensions to the existing models and standards to cover the mission exchange data between the ROC and the autonomous vessel that are not already covered. These extensions are proposed as UML classes that can be further implemented as messages on XSD-format or other formats, see Section 2.6 .

- *Demonstration:* Fourthly, and finally, a part of the mission exchange model was implemented and demonstrated on a scaled demonstration vessel (OtterX) as proof-of-concept, see Chapter 3.

2.5.2. REQUIREMENTS TO THE MISSION EXCHANGE MODEL

The requirements to the Mission Exchange Model were collected during online workshops with project partners and can be summarized as follows:

- The mission exchange model covers data needed to be sent from the ROC to the ANS to define the navigation from a departure berth in a terminal to the arrival berth in the arrival terminal.
- The mission exchange model covers data needed to be sent from the vessel to the ROC regarding situations detected by the vessel that needs attention by the ROC operator.
- The mission data model does not cover data sent between the ROC and the lock/bridge or other shore-based infrastructure.
- The vessel travels a fixed route, from a departure port to an arrival port. The vessel will need information about the mission before it leaves the departure port.
- Details on the communication protocol between the ROC and ANS are not part of the mission exchange model.
- The vessel does not have interface to the RIS (River Information System), as this is handled by the ROC.
- The vessel is assumed to be on at least level 4 of automation (high automation) according to the CCNR definition of levels of automation in inland navigation [29], where the vessel is capable of operating between two successive locks.
- The ANS sends status information continuously to the ROC for the ROC operator to monitor the sailing and also to get sufficient situational awareness in those cases where the ROC operator needs to take over control or to update the mission.
- The vessel is able to handle situations in its vicinity through its autonomous navigation system and situational awareness functionalities.
- A mission update is sent from the ROC to the ANS when changes to the mission are needed. This avoids problems with latency of communication.
- The vessel notifies the ROC when it enters a fallback state, which needs to be handled by the ROC.

Another important part of the mission is to ensure that the handover between the ANS and the ROC operator is correctly handled, i.e., to ensure that sufficient information is available among the mission data to send notifications between the vessel and the ROC operator. This includes pre-planned actions defined by the ROC operator that must be performed by the vessel, for instance the mission may contain certain waypoints where the vessel shall stop, notify the ROC, and await acknowledgement or further instructions before proceeding, such as bridges that needs to be opened before passing. This can also be the case where the vessel shall do a transition between two voyage phases that require the ROC operator to either do an action or to verify information before the vessel can proceed. One example is that the remote operator must communicate with a lock operator via VHF before entering the first lock chamber. Another example is to visually verify that the berth is clear before initiating automatic mooring. A third example of an action point is a point where a pre-planned transition from one operational mode to another is performed, e.g., from automatic navigation to ROC operator-controlled navigation. This transition of operational mode may for instance be needed when the vessel is about to enter a lock.

2.5.3. GAP ANALYSIS OF EXISTING STANDARDS

IWW traffic is not regulated through IMO by COLREG or SOLAS, but by regional and national regulations. For Europe, CEVNI (European Code for Navigation on Inland Waterways) regulates the navigation of most of Europe's rivers, canals, and lakes [30]. Therefore the regulations of inland ENC were analyzed. However, also definitions from IMO, to reuse as much of existing definitions as possible.

For information that is specific for inland waterways, e.g., for locks, bridges, and the signaling requirements when sailing on rivers and canals, information from the iENC regulations was used.

The Mission Exchange Model is described as data types and data elements in a UML model based on the IWW use case (first step), a walk-through of the following standards (step 2), and a gap analysis of these:

- The S-421 standard (IEC 63173-1:2021) on route exchange [31] is reused when it comes to the definitions of routes, legs, waypoints, action points, and the schedule with some simplifications to reduce the complexity of the final data model.
- The current Inland ECDIS Standard Edition 2.4 [32] and the iENC Feature catalogue [25] were used to identify specifics related to the IWW sailing, lock passing and bridge passing, that is not covered by S-421.
- The upcoming S-401-standard for Inland Electronic Navigational Charts [33], [26] was used when it comes to information about port features.
- The EDIFACT message BAPLIE regarding the bayplan/stowage plan describing container related data on weights and dangerous goods [34] was used when it comes to cargo information needed by the IWW vessel.
- The reference model and list of data elements as described in the IMO compendium [35] was used when it comes to static information about the vessel.

2.6 DESCRIPTION OF THE MESSAGE EXCHANGE MODEL (MEZ)

2.6.1. OVERVIEW

Figure 2-3 gives a simplified overview of the interaction between the ANS onboard the vessel that is used during the mission execution and the person in the ROC that follows up on the vessel.

The rounded boxes show different activities handled by the ROC operator and the vessel. The arrows show transitions between these activities.

1. Green boxes: Initially, the ROC operator plans the mission for a vessel. The operator uses the mission planning tool to set up the route, timetable, and action points. The mission message is generated and sent to the vessel for approval and execution. During the voyage, the ROC operator can also update the mission based on input received during the monitoring or the controlling of the vessel.
2. Blue boxes:
 - a. After the initial planning of the mission has been done, the ROC operator works in one of two modes: Remote control of the vessel or monitoring the vessel.
 - b. The vessel either controls the sailing by executing the mission or it is passive while being remotely operated by the ROC operator.

Either the vessel or the ROC operator must be accountable for the operation of the vessel, but not both at the same time. This means that when the vessel is executing the mission, the ROC operator will monitor the vessel. When the ROC operator is remotely controlling the vessel, the vessel is manually controlled and the ANS is not used.

3. Light yellow boxes:

- a. The vessel must continuously send its statuses and requests to the ROC for further processing by the ROC systems and the ROC operator.
- b. The ROC operator must interact with external persons and systems, both during monitoring and during remote control operation.

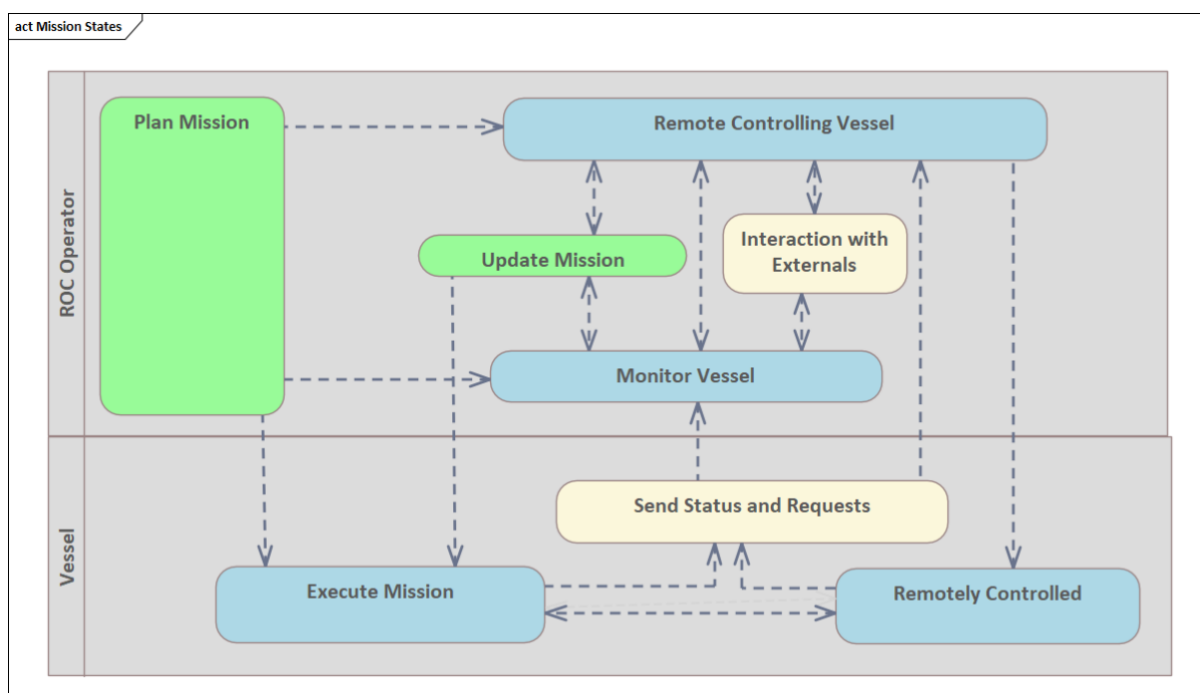


Figure 2-3: Phases and Interactions between Autonomous IWW Vessel and the ROC Operator

The Mission Exchange Model contains of two parts: A) *Mission planning data*, that is needed for the planning of the mission, and is sent from the ROC to the ANS, and B) the Mission execution data that is sent from the vessel (ANS) to the ROC during vessel operation.

A) *Mission planning data* that are sent from the ROC to the ANS to inform the ANS about the details of the passage from the berth in the departure port to the berth in the arrival port. This describes the planned mission to be approved and executed by the ANS:

- *Planned route and planned actions*, Section 2.6.2.
- *Planned schedule with planned actions*, Section 2.6.3.
- *Mooring*, Section 2.6.4.
- *Planned autonomy level*, Section 2.6.5.
- *Cargo*, Section 2.6.6.

B) *Mission execution data* that are sent from the ANS to the ROC during execution of the mission. This information comes in addition to the sensor data sent from the vessel to the ROC, see Section 2.6.7.

In addition, there is information about infrastructure, that is, bridges, locks and overhead cables, Section 2.6.8.

Figure 2-4 gives an overview of the S-421 route exchange standard that the MEZ model builds on. Further, Figure 2-5 gives an overview of the preliminary S-421 model with its attributes that are used by this version of the MEZ. Version 2 of the S-421 will be approved later in 2026, and for the usage together with the MEZ model, these classes should be replaced with the newly approved S-421-model.

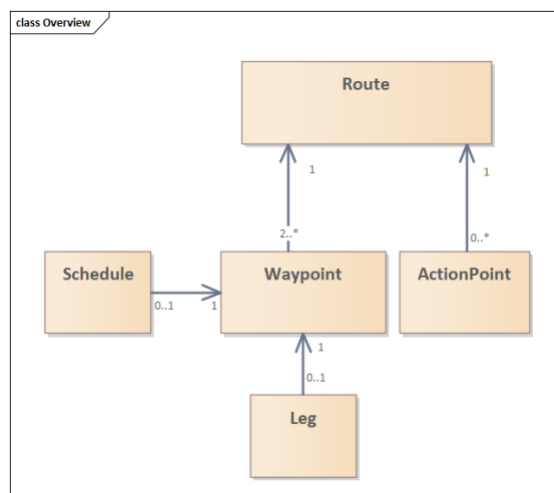


Figure 2-4: S-421 Route Exchange Overview



Figure 2-5: S-421 Route Exchange classes (simplified version)

2.6.2. PLANNED ROUTE AND PLANNED ACTIONS

Figure 2-6 shows the UML classes representing the data for planning the route legs and for specifying action points. The light brown boxes are classes from the simplified S-421 Route Exchange, while the green boxes represent additional classes defined to cover the IWW mission planning. **Class** names are written in bold, while *attribute* names are written in italic. An *attribute* in class **Class** is written as **Class.attribute**.

- **Geometry:** The mission exchange model will allow action points that are either a point, a circle with a position and a diameter, or a user defined space geometry. Several action points can be defined for each route. They are linked directly to the route, and not necessarily to a waypoint. The following extra data is needed for the mission exchange model compared to S-421:
- **Extra data related to RouteActionPoint:**
 - The enumeration **RouteActionPointRequiredAction** is extended with a value for **MissionAction** to indicate that the action point is used in relation to a mission plan.
 - The attribute **RouteActionPoint.routeActionPointRequiredActionDescription** in S-421 is a string. In this proposal, further description of the action point on a mission was added by changing the type of this attribute to the enumerated type **RouteActionPointDescriptionType**. This is useful to explain the type of action related to a specific route action point. This can be for instance a radio calling-in point, an area indicating a traffic signal station for a bridge or lock passing or port entry and departure, or an area indicating that communication with VTS, locks, bridge etc. can be done. These values are derived based on the Encoding Guide for Inland ENC's [32]. In addition to this comes action point types to entering or existing a geometry, or other notifications on arrival or departure times. Examples are to notify the ROC operator when entering (ATA) or leaving (ATD) the action point area, notify about the expected arrival time (ETA) or expected departure time (ETD), or to instruct the ANS to notify the ROC operator when a green light or unknown object is detected. The value of attribute **RouteActionPoint.routeActionPointTimeToAct** is used to describe the point in time when the notification should happen, for instance how long before the ETA or ETD should be given.
 - **RouteActionPoint.ActionPointPlannedOperationalMode** of enumerated type **ActionPointPlannedOperationalModeType** is added to the **RouteActionPoint**. This is used by the ROC operator to plan whether it is the ROC operator or the ANS that is in control during the operation at a certain action point.

the **RouteScheduleElement** referring to the **RouteWaypoint** (as in the proposed 2.0 version of S-421).

- Both **RouteWaypointLeg** and **RouteActionPoint** have an extra attribute **ROCPlannedResponseToShip** of enumerated type **ROCResponseToShipType**. This is the description of what the ROC operator should do in response to the action from the ship. It is the planned response that the ROC operator defines as part of the mission planning. Typical values are to send acknowledge to the ship, contact bridge or lock operator, approve green light, contact VTS or port authority, or to notify the ship that the ROC operator will go to high attention mode or low attention mode, or that the ROC operator plans to take over the control of the ship (remote control) at this point in the mission. These planned actions by the ROC operator are described either on a leg or on an action point.

2.6.3. PLANNED SCHEDULE WITH PLANNED ACTIONS

Figure 2-7 shows in green the extra data type that is needed to describe the time schedule for the waypoints in the route that are part of the mission, namely the **StrictMissionScheduleType**. The light brown box shows the data type from the S-421 route exchange standard, namely the **RouteScheduleElement**.

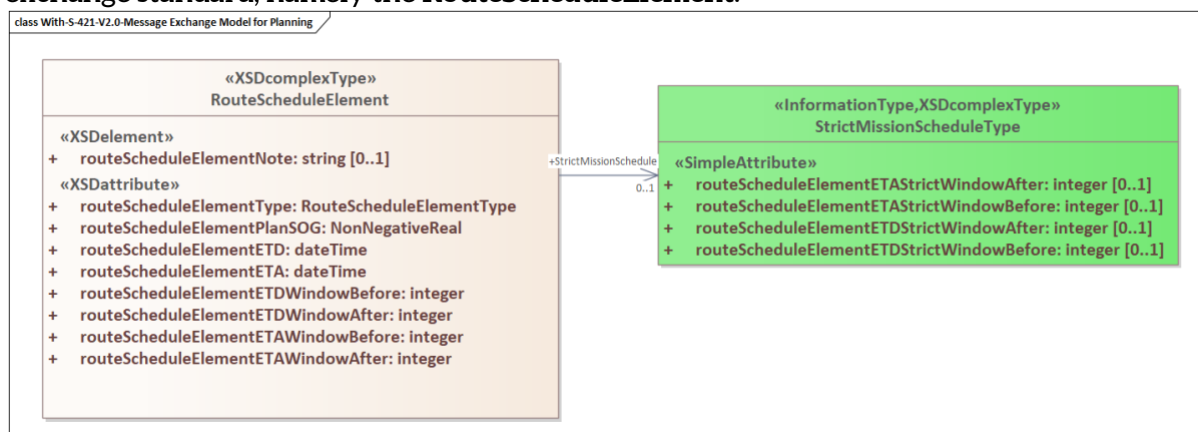


Figure 2-7: Planned schedules on waypoints

The **RouteScheduleElement** describes the ETA to the waypoint, the ETD from the waypoint, and a time interval in number of minutes before and after the ETA and ETD. It also includes the planned speed over ground to be used when approaching the waypoint. The time intervals for entering and leaving a waypoint are the planned time intervals that the ANS onboard need to adhere to. However, it will also be useful for the ANS to know the strict limits of the time intervals for each waypoint when executing the planned route. These restrictions may for instance happen due to closing hours of the locks and bridges, or because of the tide that makes it necessary to reach a waypoint or leave a waypoint no later than at a specific point in time. These restrictions are described in the data type **StrictMissionScheduleType**.

2.6.4. MOORING

For a mission to be completed, the ANS needs information about the mooring position and how to moor and unmoor the vessel. For this information, some of the descriptions in the standard S-131 on Marine Harbour Infrastructure can be used. These data types are further described in [36]. Figure 2-8 shows the types for **Berth** and **BerthPosition** as examples on how these can be defined in the MEZ.

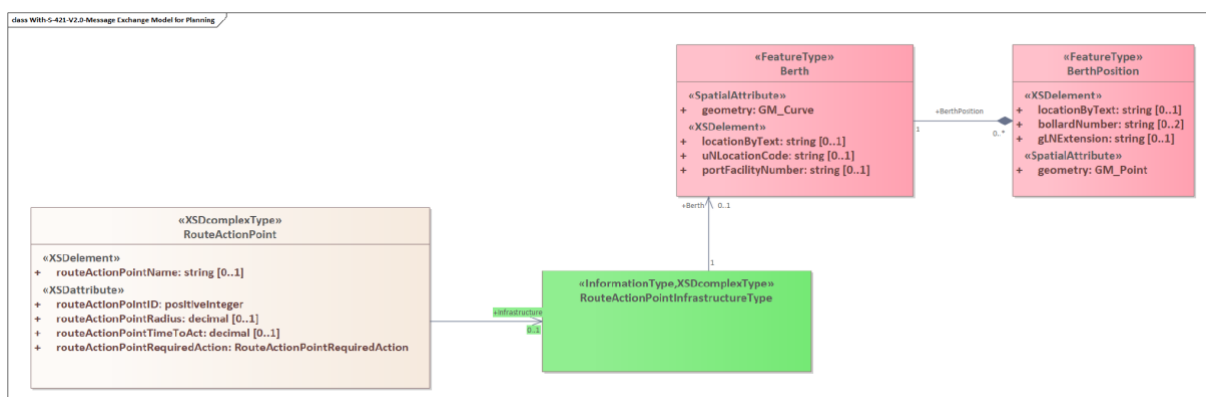


Figure 2-8: Data types for Berth and BerthPosition

2.6.5. PLANNED AUTONOMY LEVEL

According to the Central Commission for the Navigation of the Rhine [29], the level of autonomy for IWW is one of the following modes of operation: No automation, steering assistance, partial automation, conditional automation, high automation, or full automation. However, the mission plan will need a simpler definition of the autonomy. Therefore, the planned level of autonomy is described by the information shown in Figure 2-9. This gives an overview of the data types needed to describe the planned level of autonomy for a whole route (*DefaultOperationalMode* of type **DefaultOperationalModeType**), for a leg (*LegPlannedOperationalMode* of type **LegPlannedOperationalModeType**), and for an action point (*ActionPointPlannedOperationalMode* of type **ActionPointPlannedOperationalModeType**). The operational mode is described by who is in control and a notification deadline. The notification deadline is the maximum time (in minutes) that the vessel will wait for a response from the ROC operator, before the vessel goes to a fallback state. The autonomy level is described by who is in control of the vessel: This can be either the *ROC operator* or the *ANS onboard* the vessel. This party is both controlling the vessel and is also accountable, which means that this party is capable of getting sufficient situational awareness in time to operate safe. At each point in time, only one party can be in control.



Figure 2-9: Data types for planned autonomy levels

2.6.6. CARGO

Cargo data may be needed as a part of the Mission Exchange Message in some cases. If present, the Cargo data is related to the whole route, and may contain the following information, Figure 2-10:

- The stowage location onboard the vessel
- The ID of the container
- The UNDG number, hazard class and extra descriptions in case of dangerous goods
- The weight of the container

Also related to the container data, is the height of the vessel if stacked one, two or three on top of each other. This data can be given as part of the vessel static data at the Route level.

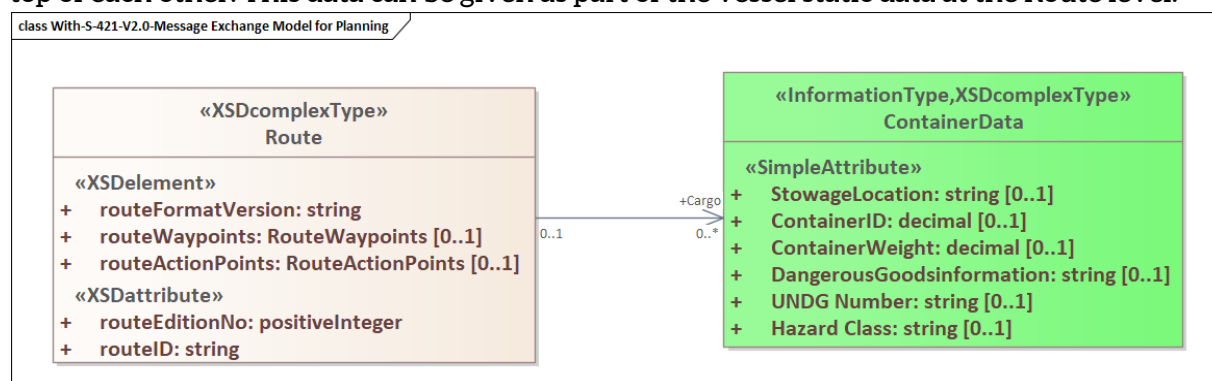


Figure 2-10: Data types for Cargo

2.6.7. MISSION EXECUTION DATA

This section describes the data that is needed for the ANS to send to the ROC to notify about the execution of the mission. This execution data comes in addition to the other ANS status data that is sent to the ROC. Figure 2-11 shows the data model for the data that is needed to be sent from the ANS to the ROC. The following data types are added to the existing classes in the S-421 data model:

- **Route:**
 - Information about **ShipDynamicData** can be added to hold information about the vessel's movement at the time of reporting from the ANS to the ROC. This is defined as described in the IMO Compendium [35] with addition of the position.
 - **ShipActualMissionData:** This data type is used to send actual information from the ANS to the ROC to indicate whether the ANS has approved the mission, started the mission, or requested an update of the mission.
- **RouteActionPoint:**
 - **ShipActualRequest:** This data type is used to send actual information from the ANS to the ROC related to a specific action point. This can be a notification that the vessel will enter or leave the area related to the action point. The type of this area is one of those listed in the enumeration **RouteActionPointDescriptionType**. The notification can be sent when actually entering or leaving the area, or it can be sent in advance. Then, the actual time for entering or leaving the area, is indicated by ETA and ETD, respectively. An example is that the ANS can send a notification to the ROC, saying that the vessel will arrive at a Communication Area Lock (see **RouteActionPointDescriptionType**) at the time ETA. The ANS can also

request the ROC to confirm a green light, to check an object that the SAS is not able to identify, or it can be to notify about an ETA or ETD to an action point.

- **RouteScheduleElement:**
 - The ANS can also give statuses on the schedule to the ROC and request a new schedule. This is done by the data type **ShipRequestNewScheduleType**, where the new ETA and ETD to the waypoint can be given. Alternatively, information about how the time window will be violated, can be given as indicated in the enumeration **ShipRequestScheduleReasonType**.
- **RouteWaypointLeg:**
 - Also, the ANS needs to give information about the current position to the ROC operator, to allow the ROC operator to assess the situation and to take action, for instance to take over control of the vessel. This information is related to a certain leg, as described in **ShipActualWaypointLegRequest**. The actual position can be given by latitude and longitude. Alternatively, the position can be an indication of whether the vessel is outside the crosstrack distance (outside *PortXTDL* or *StarboardXTDL*), meaning that the ROC operator may not need to take over immediately, but instead have time to handle the situation in some other way. If the vessel reports to be outside the fallback corridor (*PortCL* or *StarboardCL*), the ROC operator needs to take immediate action, since the vessel has moved into a critical area compared to what has been planned for this leg.



Figure 2-11: Mission execution data

2.6.8. INFRASTRUCTURE DATA

It will also be useful for the execution of the mission, to have information about bridges, locks and overhead cables that must be passed during the voyage. Figure 2-12 gives an overview of this. This data model is set up based on the manually created classes based on information from the Inland ENC Harmonization group Draft Encoding guide for Inland ENCs, 2024, [32].

In addition it may be necessary to know the sequence of lock basins to enter as described in **LockNavigation**.

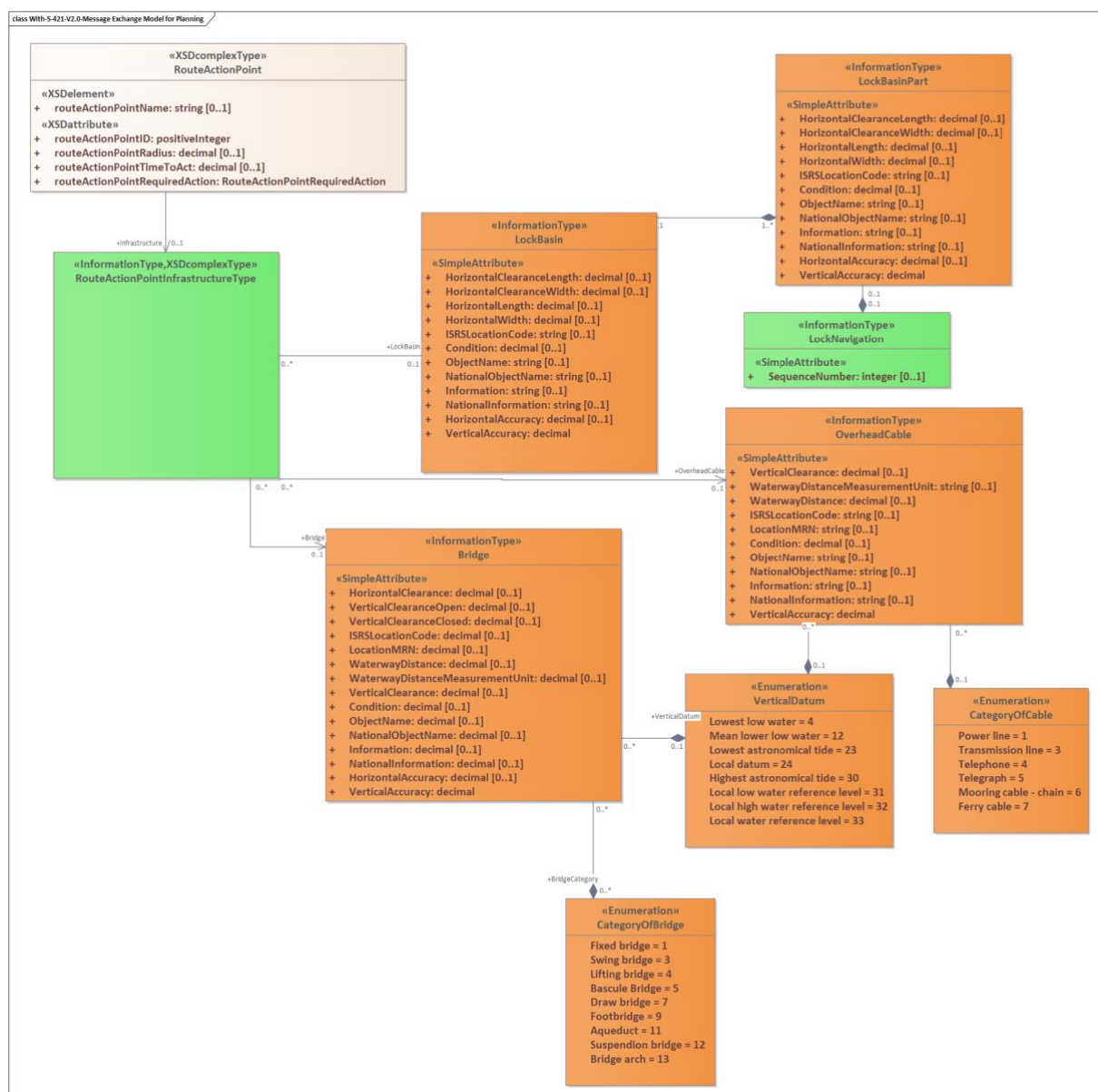


Figure 2-12: Data model for bridge, lock and overhead cable information

3 DEMONSTRATION OF THE MEZ ON AN USV IN THE TRONDHEIMSFJORD

3.1 DEMONSTRATION SETUP

The MEZ will be implemented by Maritime Robotics and tested during the demonstration event of the AUTOFLEX project.

As part of the preparations for this demonstration, a subset of the MEZ was tested during a scaled demonstrator with the ROC and the USV OtterX from Maritime Robotics [37], in a small canal in the Trondheim city centre in Norway.

The scaled demonstration aimed at validating navigation according to a mission as follows, Figure 3-1: Navigate from a starting point along a predefined track. At action point 1, notify the ROC that the bridge operator must be contacted for opening the bridge. Continue navigation to action point 2, stop and hold position until confirmation is received from the ROC that navigation can commence. Continue navigation to action point 3, stop and hold position for further instructions.



Figure 3-1: Mission for the demonstration

3.2 REPORT FROM DEMONSTRATION WITH OTTERX

The demonstration was conducted on June 13th 2025. All planned features and objectives were successfully demonstrated. The initial conditions of the demonstration were that the OtterX was positioned at the planned starting point and confirmed to be in correct operational state, Figure 3-2.



Figure 3-2: USV OtterX and ROC ready for demonstration

The demonstration was started by the ROC uploading the Mission Exchange Message to the OtterX, Figure 3-3. Then, the ROC initiated the mission by giving a command to the OtterX. The OtterX started tracking the route autonomously, at the pre-defined speed, while the ROC operator continuously monitored the execution of the mission. Upon reaching action point A1, the OtterX notified the ROC that it needed to contact the bridge operator for negotiating bridge opening, triggering a prompt to the operator, see Figure 3-4. The ROC contacted the bridge operator via phone and coordinated the bridge opening. Meanwhile, the OtterX proceeded to action point A2 where it stopped and held position, awaiting confirmation from the ROC that it could continue tracking the route, see Figure 3-5. The ROC operator visually confirmed that the bridge was open and light signal indicated clearance, before sending a

continue mission command to the OtterX, Figure 3-6. The OtterX resumed autonomous navigation along the preplanned route. Upon reaching action point A3, after clearing the bridge, the OtterX stopped and held position, awaiting further instructions from the ROC, Figure 3-7.

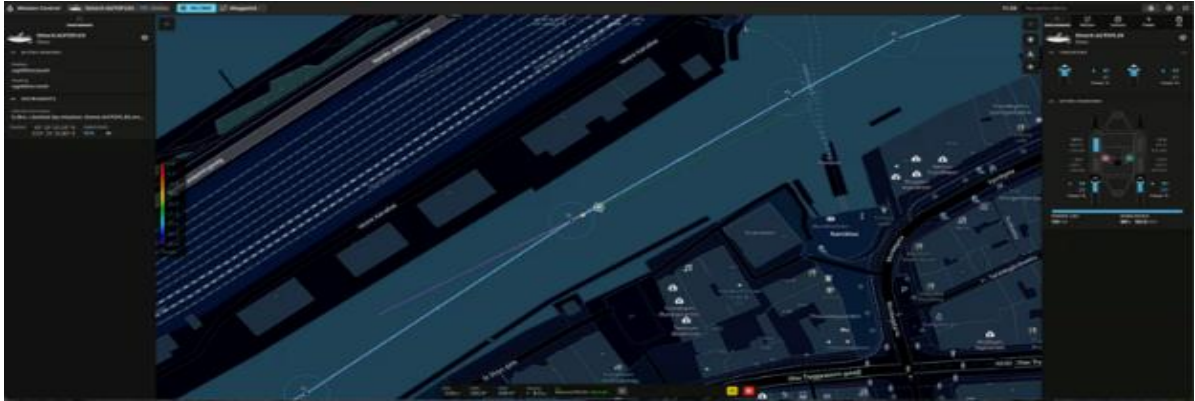


Figure 3-3: Mission plan loaded and ready



Figure 3-4: Prompt notification to ROC operator, OtterX position and action point A1



Figure 3-5: Prompt displaying that OtterX is awaiting confirmation to proceed. OtterX at A2 position



Figure 3-6: Operator using onboard SeaSight camera to confirm bridge opening and clear for passage.



Figure 3-7: OtterX autonomously navigating to final action point A

A short video from this demonstration is available on the Maritime Robotics YouTube channel: <https://www.youtube.com/watch?v=FjLLTvTgqr0>.

4 Sensors for situational awareness

4.1 OVERVIEW

The autonomy package relies on a multi-sensor perception pipeline that combines optical camera data, radar, Automatic Identification System (AIS) information, and LiDAR point clouds to build a robust and redundant picture of the vessel's surroundings. Each sensor contributes complementary strengths: the camera provides dense visual context and supports classification of object type, radar provides long-range detection and tracking of objects largely independent of weather and light conditions, AIS provides cooperative identification and kinematic data for equipped vessels, and LiDAR provides accurate range and bearing measurements independent of lighting conditions and without reliance on cooperative signalling.

As part of **Task 4.5**, a suite of relevant sensors and a situational awareness package were installed and operated on the **MS Sorrento** (MMSI: 205289590) from November 2024 to January 2026 (see Figure 20). The vessel regularly services the Ghent-Terneuzen route and surrounding waters.

The package included:

- SeaSight 360 camera system
- Ouster LiDAR
- On-Board Computer with remote communication
- AIS/GPS Antenna



Figure 4-1: Situational Awareness package installed on MS Sorrento

It should be noted that radar data was not available in the dataset collected from the region where the demonstration will take place, as the data collection vessel (Sorrento) was not

equipped with a radar at the time of data collection. Radar is nonetheless included in the sensor package description below, since it forms part of the intended onboard sensor suite and its data handling is described here for completeness. It will also be part of the full scale demonstration on MS Letitia.

4.1.1. CAMERA DATA

Raw video is captured continuously from the panoramic camera system at a fixed frame rate and resolution, and stored together with a precise timestamp for later synchronization with the other sensor streams. To build a dataset that is representative of real operating conditions, footage is collected across a range of scenarios, including varying light levels (daylight, dusk, overcast), sea states, vessel traffic densities, and distances to target objects. Individual frames are extracted from the recorded video at set intervals or triggered by events of interest, and these frames form the basis for the image dataset used in the annotation and training process described below.

4.1.2. RADAR DATA

The radar included in the sensor package supports built-in object tracking, meaning that in addition to the raw radar image (the plot of returned echoes), the radar itself produces a set of tracked targets, each with an estimated position, course, and speed derived from successive scans. Both the raw radar image and the tracked target data are intended to be logged, together with a timestamp for synchronization with the other sensor streams. Storing the tracked target output, rather than only the radar image, allows the tracking already performed onboard the radar unit to be reused directly in the perception pipeline, without needing to re-derive target motion from the raw image alone.

As noted above, radar data is not present in the dataset already collected from the demonstration region, since the vessel used for that data collection (Sorrento) was not fitted with a radar. The description above reflects the intended data handling for the radar once it is available as part of the full sensor package.

4.1.3. AIS DATA

AIS messages received on board are logged in parallel with the camera and LiDAR streams. Each AIS message provides identifying information (MMSI, vessel name, and vessel/cargo type where reported) together with kinematic data such as position, course over ground (COG), speed over ground (SOG), and heading. Because AIS positions are given in absolute geographic coordinates, they are converted into a range and bearing relative to the ownship position at the corresponding timestamp, so that they can be directly compared against visual and LiDAR detections expressed in the vessel's own reference frame. AIS logging is timestamped using the same reference clock as the other sensors to allow precise temporal alignment.

4.1.4. LiDAR DATA

The LiDAR sensor produces a continuous stream of point clouds describing the range and bearing of reflective surfaces around the vessel. Point clouds are recorded together with a timestamp and are later associated with a fixed extrinsic calibration that describes the LiDAR's position and orientation relative to the camera and to the vessel's own coordinate frame. This allows LiDAR returns to be projected into the camera's field of view, and

conversely allows visually detected objects to be assigned a distance estimate from the corresponding LiDAR returns.

4.2 IMAGE ANNOTATION FOR VISUAL OBJECT DETECTION

To enable automatic detection and classification of vessels and other relevant objects in camera imagery, a subset of the collected frames is manually annotated. Annotation consists of marking each object of interest in an image with a bounding box and assigning it a class label from a predefined taxonomy (for example: vessel, buoy, person in water, or other maritime obstacle). This produces a labelled dataset in which each raw image is paired with a corresponding annotation file describing the location and class of every relevant object present.

The annotation process follows a structured workflow:

- **Class taxonomy definition:** object categories relevant to the operational domain are defined in advance, so that annotations are applied consistently across the dataset.
- **Manual labelling:** annotators use a dedicated annotation tool to draw bounding boxes around each object and assign the correct class.
- **Quality control:** a sample of annotated images is independently reviewed by a second annotator to check consistency and catch labelling errors, and ambiguous cases are resolved against the agreed taxonomy definitions.
- **Dataset splitting:** the final labelled dataset is divided into training, validation, and test subsets, ensuring that images from the same recording session are not spread across multiple subsets, to avoid overly optimistic performance estimates.
- **Augmentation:** standard image augmentation techniques (such as brightness/contrast variation, horizontal flipping, and scaling) may be applied to increase the effective size and diversity of the training set without requiring additional manual annotation.

The resulting labelled dataset is used to train a modern, real-time, single-stage deep learning object detector. Single-stage detectors of this kind process an entire image in one pass through a convolutional neural network and directly output bounding boxes and class predictions, which makes them well suited to real-time operation on embedded hardware such as the onboard compute platform used for video processing in the sensor package.

The following figures show representative examples of raw camera frames alongside their corresponding annotated versions, illustrating the bounding boxes and class labels applied during the annotation process.

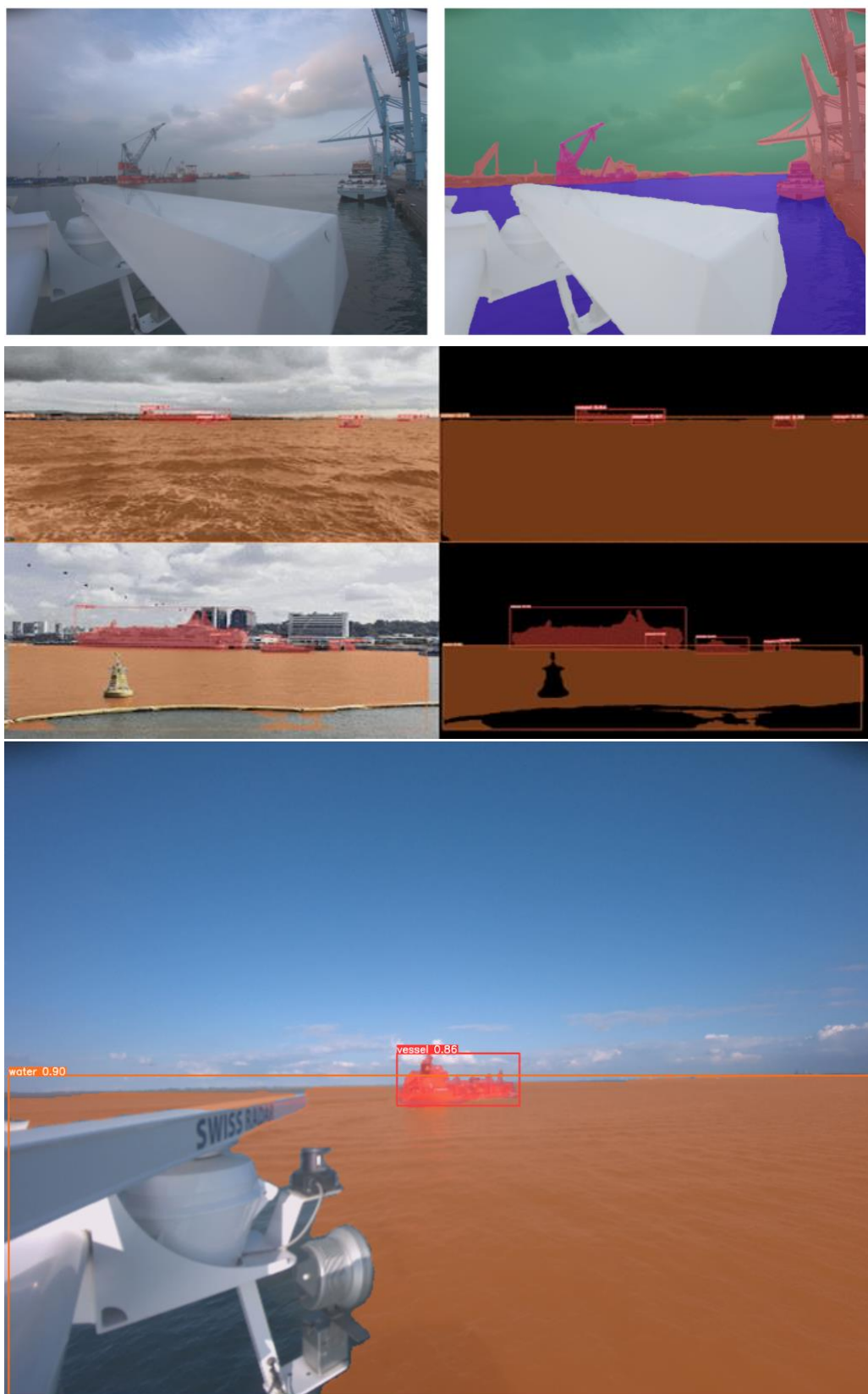


Figure 4-2: Examples of raw camera frames used in the annotation process

4.3 COMBINING VISUAL DETECTIONS WITH RADAR, AIS, AND LiDAR

INFORMATION

Once objects have been detected and classified in the camera imagery, this information can be combined with radar, AIS, and LiDAR data to produce a more complete and reliable situational picture than any single sensor could provide on its own.

Visual detections combined with LiDAR: using the extrinsic calibration between the camera and the LiDAR sensor, LiDAR points falling within a detected object's bounding box can be used to estimate the object's distance and bearing relative to the vessel. This adds a metric range estimate to an otherwise image-based detection, and also allows LiDAR returns that do not correspond to any visually classified object to be flagged as unidentified obstacles requiring further attention.

Visual/LiDAR detections combined with radar tracks: the tracked targets produced by the radar's own tracking function can likewise be expressed relative to the ownship and matched against visual and LiDAR detections within a similar range and bearing window. Because radar tracking already provides an estimated course and speed for each target, a successful match gives an additional, independent kinematic estimate for a detected object, and helps maintain track continuity for objects that are temporarily outside the camera's field of view or occluded, since radar coverage and range typically exceed those of the camera and LiDAR.

Visual/LiDAR/radar detections combined with AIS: AIS-reported positions, once converted to a range and bearing relative to the ownship, can be matched against visual, LiDAR, and radar-tracked detections that fall within a similar range and bearing window at the same point in time. A successful match allows a detected object to be associated with the additional identifying and kinematic information carried in the AIS message (vessel identity, course, and speed), increasing confidence in the classification and providing early indication of the target's intended movement. Objects that are detected by camera, LiDAR, or radar but cannot be matched to any AIS report are treated as non-cooperative targets, i.e. objects without an active or correctly functioning AIS transponder, and are handled accordingly by the perception pipeline.

Together, this combination of sensor modalities allows the perception pipeline to cross-validate detections across independent data sources, improve classification confidence, and maintain awareness of both cooperative (AIS-equipped) and non-cooperative objects in the vessel's vicinity, forming the basis for the situational picture used by the autonomy functions. The extensive datasets gathered during operations on the Ghent–Terneuzen Canal, a vital and highly congested inland waterway for commercial cargo transport, served as the foundation for the machine learning development withing the AUTOFLEX project. By training models on these vast volumes of real-world data, advanced algorithms specifically optimized for real-time object detection in dense inland shipping environments can be developed. The accompanying figures showcase selected frames from the vessel's voyages, demonstrating the algorithm's capability to accurately map and identify potential hazards and traffic along this critical cargo route.

5 TESTING AND MEZ DEMONSTRATION ON IWW VESSEL

5.1 THE DEMONSTRATION VESSEL MS LETITIA

The full-scale demonstration activities in the AUTOFLEX project are planned to be carried out on board the inland container vessel MS Letitia (see Figure 5-1), operated by the HTS Group and sailing under the German flag for its subsidiary MTS Duisburg. The vessel was selected as the AUTOFLEX demonstration platform because it is already equipped with the Argonics argoTrackPilot track-keeping system, providing an established and field-proven automation interface onto which the AUTOFLEX autonomy functions can be integrated and validated.

MS Letitia is a modern inland container vessel of 135 metres length and 17.10 metres beam, with a cargo capacity of six container rows abreast. The hull was designed and built by Rensen-Driessen Shipbuilding, and the vessel was outfitted by Olthof Marine Group in Capelle aan den IJssel, with delivery in November 2024. The vessel operates on a fixed trade between Rotterdam/Antwerp and Duisburg.



Figure 5-1: Picture of MS Letitia (source: <https://www.rensendriessen.com/ships/letitia>)

The vessel features a hybrid zero-emission propulsion arrangement: two 1.6 MW electric main motors supplied by Oswald, a 1.2 MW hydrogen fuel cell installation, and a battery capacity of 1.03 MWh, enabling fully electric or hydrogen-electric operation on its regular route. Four diesel generator sets are installed solely as backup for contingency situations. Through this configuration, MS Letitia is the first fully zero-emission inland vessel operating on the Rhine, and forms part of the RH2INE initiative for a hydrogen-based green corridor on the Lower Rhine.

Beyond its propulsion concept, the vessel was designed and prepared for autonomous navigation from the outset, with an extensive sensor outfit including cameras, radar and high-precision positioning. This readiness has already been demonstrated in practice: within the EU-funded MAGPIE project, MS Letitia completed an autonomous terminal-to-terminal

voyage in the port of Rotterdam, sailing from Amaliahaven on the Maasvlakte via Europoort and the Nieuwe Waterweg to Waalhaven.

The combination of a proven track-keeping system, and an operator experienced with automation trials makes MS Letitia a well-suited platform for demonstrating the AUTOFLEX autonomy concept under realistic operational conditions. The following sections describe the Maritime Robotics onboard system (OBS) installed on the vessel for this purpose, covering its architecture, sensor integration and interfaces to the existing vessel systems.

Table 5-1: Key particulars of the selected demonstration vessel MS Letitia

Particular	Value
Vessel Name	MS Letitia
Type	Inland container vessel (motor freighter)
Length overall	135.0 m
Beam	17.10 m
Container capacity	Six rows abreast
Owner / operator	HTS Group / MTS Duisburg (German flag)
Hull	Rensen-Driessen Shipbuilding
Outfitting	Olthof Marine Group, Capelle aan den IJssel (delivered November 2024)
Main propulsion	2 × 1,600 kW electric motors (Oswald)
Energy system	1.2 MW hydrogen fuel cells; 1,030 kWh battery; 4 diesel generator sets (backup only)
Trade route	Rotterdam/Antwerp – Duisburg
Track-keeping system	Argonics argoTrackPilot

5.2 MARITIME ROBOTICS INSTALLATION ONBOARD

To execute the demonstration, certain product installations are required. The core developments being demonstrated are the Maritime Robotics sensor package and autonomous controller. However, their operation relies on an advanced track pilot and position pilot.

Because the vessel was pre-equipped with the necessary Argonics system during its construction phase, this foundational infrastructure is already in place.

Figure 5-2 below illustrates the equipment layout onboard the *Letitia*, where the blue line represents the network.

- 1) Argonics system (autopilot) - the vessel's integrated system
- 2) Maritime Robotics onboard Vehicle Control Station (a laptop PC)
- 3) Maritime Robotics SeaSightX camera modules
- 4) Furuno Radar DRS4D-NXT
- 5) Maritime Robotics SeaSightX edge compute module
- 6) *OBS-Computer: No longer applicable, moved to position 8*
- 7) Fiber Switch
- 8) Rear facing SeaSightX camera modules with LiDAR. Maritime Robotics SeaControl PC and Radar PC (On Board System), 4G/5G router and GNSS antenna

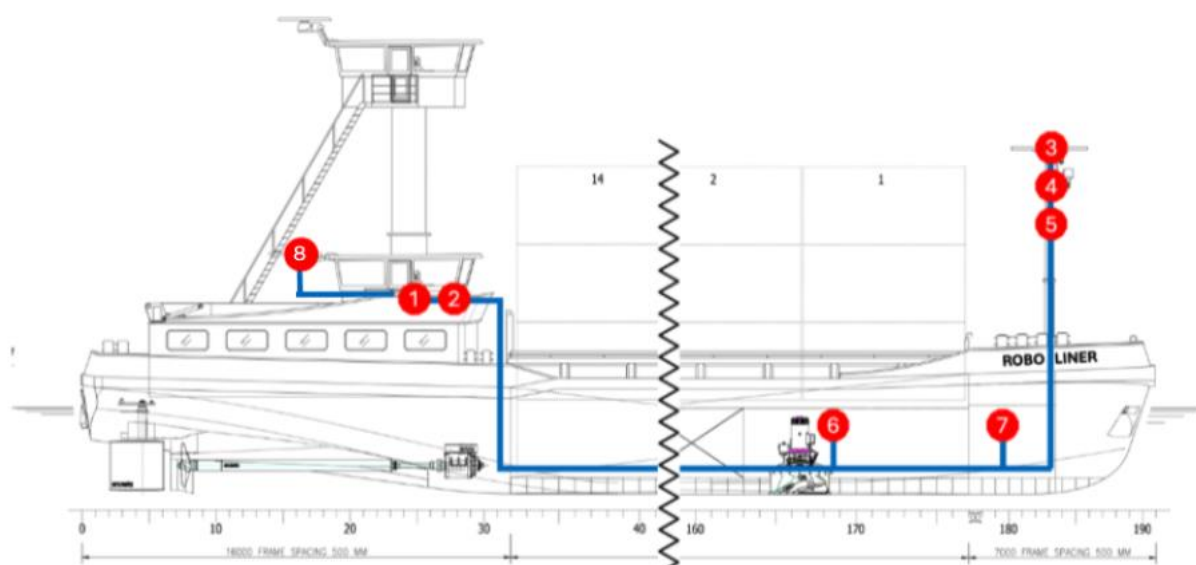


Figure 5-2: The equipment layout on board the Letitia

5.2.1. SEACONTROL ON-BOARD SYSTEM (OBS)

The OBS comprises software and hardware that allows the vessel to navigate automatically based upon control input from the operator. The OBS contains higher-level control and guidance control algorithms, interface to navigation sensors and means to control the vessel through low-level control systems.

5.2.1.1. *Interface to 3rd party low-level control systems*

Low-level control and safety functions will be achieved through an interface to 3rd party DP/maneuvering and Autopilot systems, which may also provide aut docking and autotransit functionality. The low-level control system interface also interconnects the Integrated Automation (and Alarm) System (IAS), providing access to most of the instrumentation onboard, especially the essential vessel components relevant for autonomous navigation.

5.2.1.2. *Navigation Sensors*

The SeaControl OBS provides an interface to navigation sensors for own-ship state and environmental forces estimation. The navigation sensors may be provided by the vessel's system integrator and installed by the shipyard. The typical navigation sensors interfaced are Compass, GNSS-INS, MRU, and Wind sensors. These sensors provide information that is fused with information from SeaSight exteroceptive sensors for situational awareness, described below.

5.2.2. VEHICLE CONTROL STATION (VCS)

The Maritime Robotics VCS software allows the operator to control the vessel either onboard or over a remote communication link. The software has a built-in chart engine with sensor input and audio/video system capable of providing the operator with the necessary information for perception of the elements in the environment, comprehension of the current situation, and projection of future status (the 3 levels of situational awareness) to be able to operate safely. VCS will be available as a scaled down version onboard, running on a laptop. More details about the VCS software are described under the chapter describing ROC.

5.2.3. SEASIGHT FOREMAST

Four SeaSightX camera modules will be installed on the foremast of the vessel. The modules are mounted on a bracket that has been custom-designed and purpose-built for this particular vessel, ensuring a secure and stable installation adapted to the geometry and structure of the foremast. The compute module will be mounted on top of the bracket holding the radar.

The mounting position has been carefully calculated to provide the camera modules with maximum visibility of the surrounding traffic and sea areas around the vessel. This elevated placement ensures an unobstructed field of view, which is essential for reliable situational awareness and for the perception functions of the autonomous navigation system during the demonstration activities.

The installation is temporary in nature. The bracket has been specifically designed so that the installation does not cause any permanent damage or structural modification to the vessel. Upon completion of the demonstration activities, the equipment and bracket can be removed, restoring the foremast to its original condition.

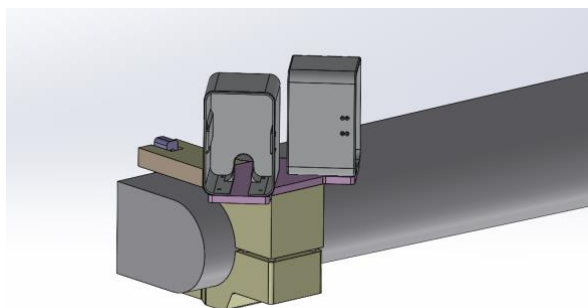


Figure 5-3: The SeaSightX camera module

5.2.4. RADAR FOREMAST

A X-band Radar dedicated for Situational Awareness will be installed in the foremast of the vessel. The unit is mounted on a bracket that has been custom-designed and purpose-built for this particular vessel, ensuring a secure and stable installation adapted to the geometry and structure of the foremast.

The mounting position has been carefully calculated so that the radar lobe does not interfere with the vessel's existing navigation radar. The placement has been assessed and approved, ensuring that the additional radar can operate without degrading the performance or coverage of the certified navigation equipment already in use on board.

The installation is temporary in nature. The bracket has been specifically designed so that the installation does not cause any permanent damage or structural modification to the vessel. Upon completion of the demonstration activities, the equipment and bracket can be removed, restoring the foremast to its original condition.

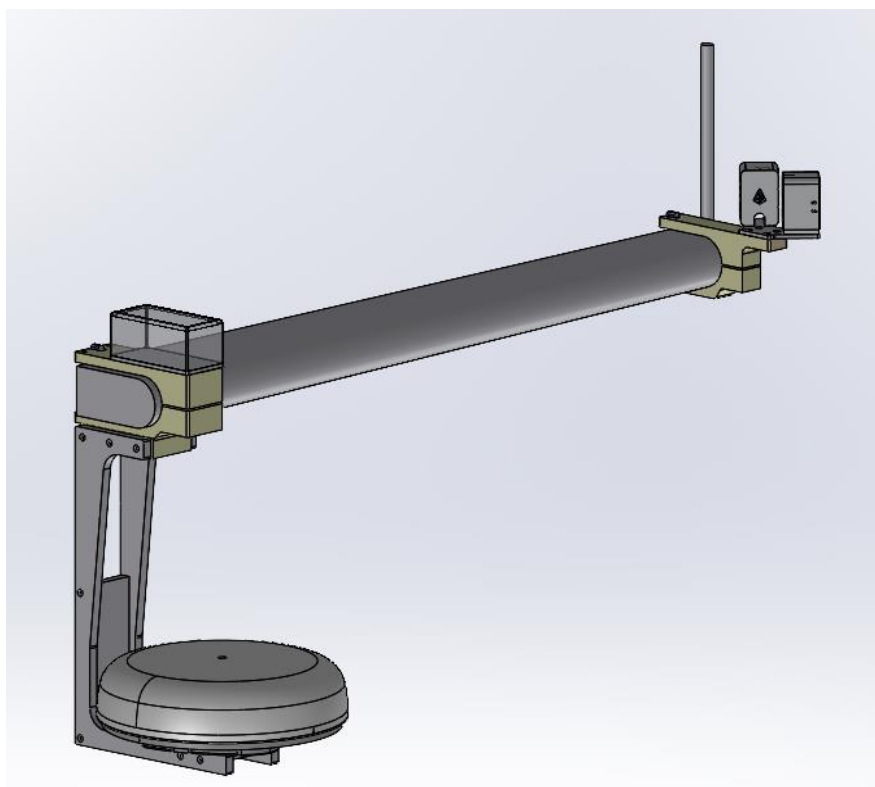


Figure 5-4: The radar foremast

5.2.5. SEASIGHT CL WITH LIDAR AFT MAST

SeaSight CL is a compact, integrated 360-degree camera unit with an embedded lidar sensor, designed to provide close-range situational awareness around the vessel.

The unit is equipped with high-resolution electro-optical (EO) cameras covering the full 360-degree field of view around the vessel. The panoramic image is presented to the operator with digital pan, tilt and zoom functionality, allowing any sector around the vessel to be inspected in detail without any moving parts. The absence of mechanical pan-tilt mechanisms increases reliability and reduces maintenance requirements, while still offering the operational flexibility of a traditional PTZ camera.

In addition to the camera array, the unit incorporates a lidar sensor providing accurate three-dimensional detection and ranging of objects in the immediate vicinity of the vessel. The lidar complements the camera-based perception by providing precise distance measurements independent of lighting conditions, which is particularly valuable during close-quarter maneuvering, berthing and unberthing operations, and for detecting small objects on the water surface close to the hull.

The SeaSight CL is installed as a self-contained unit, fully independent of the SeaSightX camera installation in the foremast. This independence serves two purposes. First, it provides sensor redundancy: the two installations are separated both physically and functionally, so that a fault affecting one installation does not degrade the other. Second, the two systems have complementary coverage: the foremast installation provides long-range panoramic overview of the surrounding traffic and sea areas, while the SeaSight CL provides detailed close-range awareness around the vessel itself.



Figure 5-5: The SeaSight CL with LIDAR aft mast

5.3 REMOTE OPERATION CENTER (ROC)

The Remote Operations Center (ROC) concept developed by Maritime Robotics is founded on a principle of flexibility and scalability. Rather than prescribing a single fixed configuration, the ROC has been designed as a modular concept that can be realised at any level of ambition, ranging from a single laptop providing basic remote control capability, up to a fully equipped, dedicated control room (see Figure 5-4) ashore with multiple operator stations. The underlying software and system architecture remain the same across all configurations; what varies is the physical realisation, the number of displays, and the ergonomic environment provided to the operator.



Figure 5-6: ROC screen setup offers flexible display of situational awareness and control tools

At the upper end of the scale, normal operations are conducted from a well-equipped ROC room on shore. Such a room is fitted with several dedicated screens, each presenting a distinct element of the operational picture. A typical configuration includes a dedicated chart display presenting the electronic navigational chart with the vessel's position, planned route and surrounding traffic; a radar display presenting the radar picture from the vessel; an EO (electro-optical) video display presenting the panoramic daylight camera feed; an LWIR (long-wave infrared) video display presenting the thermal camera feed for low-light and night operations; a display for the feed from the PTZ (pan-tilt-zoom) camera, allowing the operator to visually inspect objects or areas of particular interest; and a conning screen presenting the essential vessel parameters such as heading, speed, propulsion status and rudder or thruster feedback, together with the alarm list providing a consolidated overview of active alerts and system warnings. This multi-screen arrangement gives the operator a comprehensive and continuously updated situational awareness, comparable to, and in some respects exceeding, what would be available on the bridge of the vessel itself.

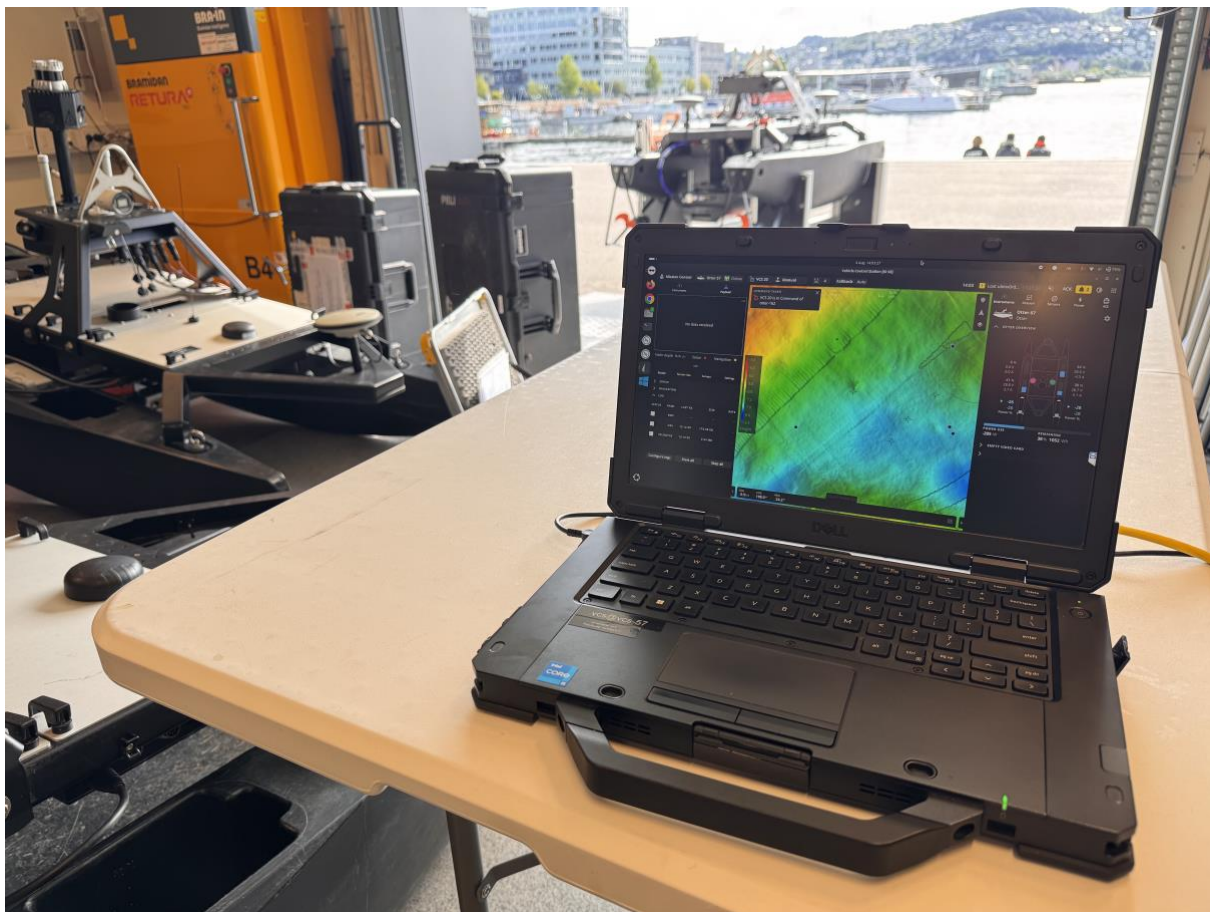


Figure 5-7: Operating vessel missions from a laptop anywhere makes remote control flexible and convenient

At the other end of the scale, the same vessel can be monitored and controlled from a single laptop. In this minimal configuration, the operator accesses the same underlying data streams and control functions, presented in a condensed form on a single display. While this configuration does not offer the same ergonomic qualities as a dedicated control room, it provides full functional capability, and it demonstrates a key property of the concept: the ROC is defined by its software and its connectivity, not by any particular physical installation.

This flexibility serves several operational purposes. First, it allows the ROC to be dimensioned according to the operation at hand. A demonstration campaign, a survey operation and a permanent commercial service have very different requirements, and the ROC can be tailored accordingly without changes to the underlying system. Second, it provides inherent redundancy. The laptop configuration can serve as an emergency solution: should the primary ROC become unavailable, whether due to power failure, loss of connectivity at the shore facility, or any other disruption, control of the vessel can be re-established from a laptop at another location. This layered approach ensures that the loss of any single control facility does not imply the loss of the ability to monitor and control the vessel. Third, the same flexibility supports mobile and deployable configurations. The ROC can be established in temporary premises, in a containerised solution, or on board another vessel, wherever suitable connectivity can be provided.

In summary, the ROC should be understood as a concept and a capability rather than a specific room. The operator organisation is free to choose the physical realisation that best matches its operational needs, safety requirements and available infrastructure, from the minimal single-

laptop setup to the full multi-screen shore control room. The functional core, however, is common to all of these realisations, and is provided by the Vehicle Control System (VCS), Maritime Robotics' software suite for remote monitoring and control, which is described in the following chapter.

5.4 VEHICLE CONTROL SYSTEM (VCS)

The Vehicle Control Station (VCS) shows relevant telemetry and status data received from the USV over the selected available communication link. It allows the operator to define reference states in order to maneuver the vessel using the modes of operation, as described in the OBS section.

If the selected communication link drops out and communication can't be reestablished within a certain time interval, the system will enter a defined fallback state. The design of VCS and OBS facilitates an effective way of controlling a USV remotely by cleverly exposing all relevant features in an integrated vehicle control software. This enables scalability and support for both single compact screen (Grab bag) and multi-screen (Bridge and ROC) setups. An operator can therefore be presented with a familiar user interface when moving between stations, and several operators can cooperate in complex operations while referring to the same VCS features at different locations, e.g. on-board, at ROC, and on a mother/support vessel, significantly enhancing operational safety.

VCS design is based on the Open Bridge design Guidelines, which is built on modern principles of user interface and workplace design, and human-centered design practices, adapted to maritime context and regulations. An overview of the VCS user interface is shown below followed by a brief description of the main components. More information and the use of all features can be found in the VCS User Manual.

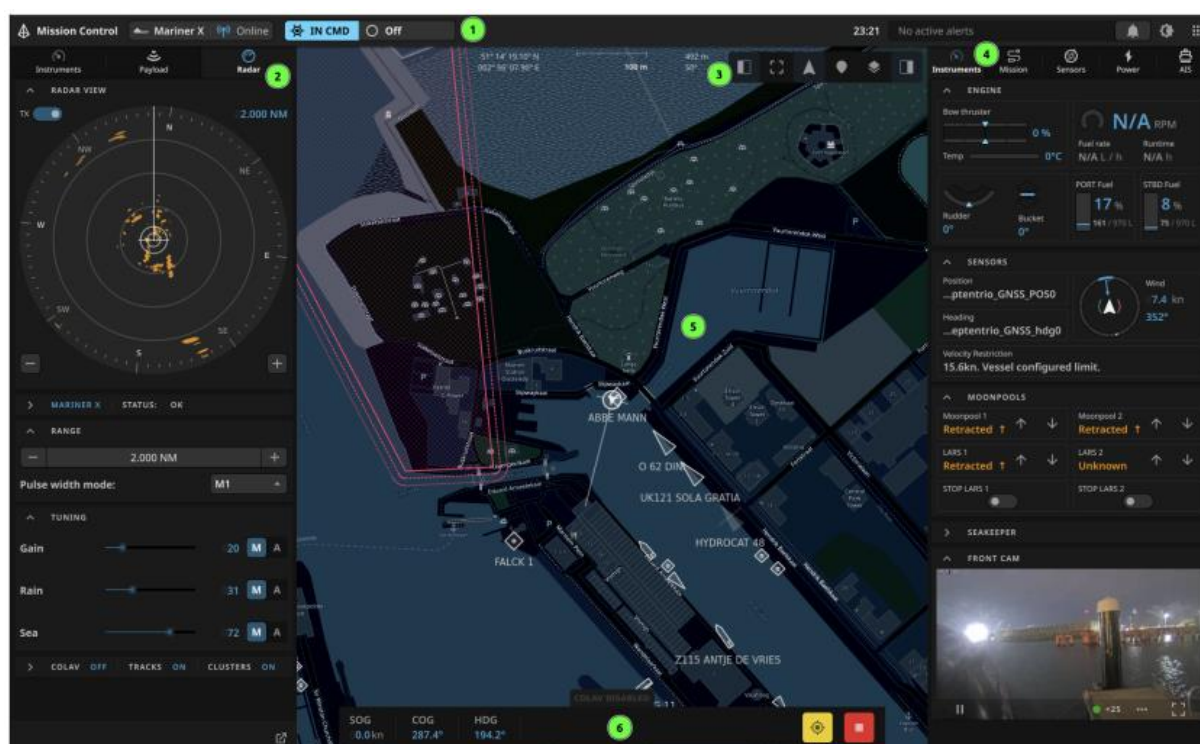


Figure 5-8: The VCS (Vehicle Control System) design

Table 5-2: The components of the VCS design

Component	Description
Topbar (1)	Provides a consistent way for accessing critical functions. On the left side it shows the name of the current window (Mission Control, Conning, etc.), the vehicle and communication channel selector, and the USV operating mode selector. On the right side it shows current time, alerts, color palette selector, and the application launcher.
Left side panel (2)	Contains one or more tabs showing information about integrated sensors and payloads onboard, mission planning, or objects selected in the map view.
Toolbar (3)	Provides easy access to functions commonly used together with the map. Includes buttons for showing and hiding the side panels, managing radar tracks, centering the map on the USV, managing points of interest, and configuring which map layers to show.
Right side panel (4)	Similar to the left side panel, it contains one or more tabs showing at least the "Instruments" tab.
Map view (5)	Shows where the USV is located in the world, what it is doing, what the surroundings look like, and much more. This is the centerpiece of the VCS application and is where most things related to driving the USV happens. Different user interface controls are exposed depending on the USV's active operating mode.
Navigation panel (6)	Shows the current Speed Over Ground (SOG), Course Over Ground (COG), Heading (HDC), and allows setting setpoints for these values if the USV is in an operating mode that supports it. Depending on the mode, additional options are made available in a popup window.

6 RTZ ROUTE PLANNER TOOL

As part of Task 4.6, Fraunhofer CML developed the RTZ Route Planner, a desktop application that enables ROC operators to create, edit, and export mission-compliant route files in the RTZ format extended with MEZ action point data. The tool was developed in Python using the PyQt5 framework and provides a graphical interface that bridges the gap between route planning practice and the MEZ data structure described in Chapter 2. While the preceding sections of this chapter describe the data model and format underpinning the MEZ, the Route Planner provides a concrete implementation through which an operator can compose a complete mission package ready for transfer to the ANS.

6.1 OVERVIEW AND PURPOSE

The RTZ Route Planner addresses a practical need identified during the development of the MEZ: existing route planning tools do not support the MEZ extensions for autonomous inland waterway navigation, in particular the action point concept, scheduled ETAs and ETDs per waypoint, and the ROC notification requirements. The Route Planner provides a standalone tool that supports the full MEZ planning workflow without requiring integration into an existing ECDIS or navigation system.

The tool was developed by Fraunhofer CML and validated against the Vehicle Control Station (VCS) of the Maritime Robotics SeaControl system. A test route covering the Ghent–Terneuzen Canal (Kanaal Gent–Terneuzen), a key inland waterway stretch relevant to the AUTOFLEX project, was used to verify that routes exported from the tool are correctly parsed and displayed in the VCS, including waypoint coordinates, cross-track tolerances, waypoint schedules, and action point radii.

Figure 6-1 shows the Route Planner interface with the Ghent–Terneuzen test route loaded. Waypoints are shown as numbered markers; the MEZ action points at Sas van Gent Bridge, Sluiskil Bridge, and Terneuzen Lock are indicated by circular trigger-radius overlays.

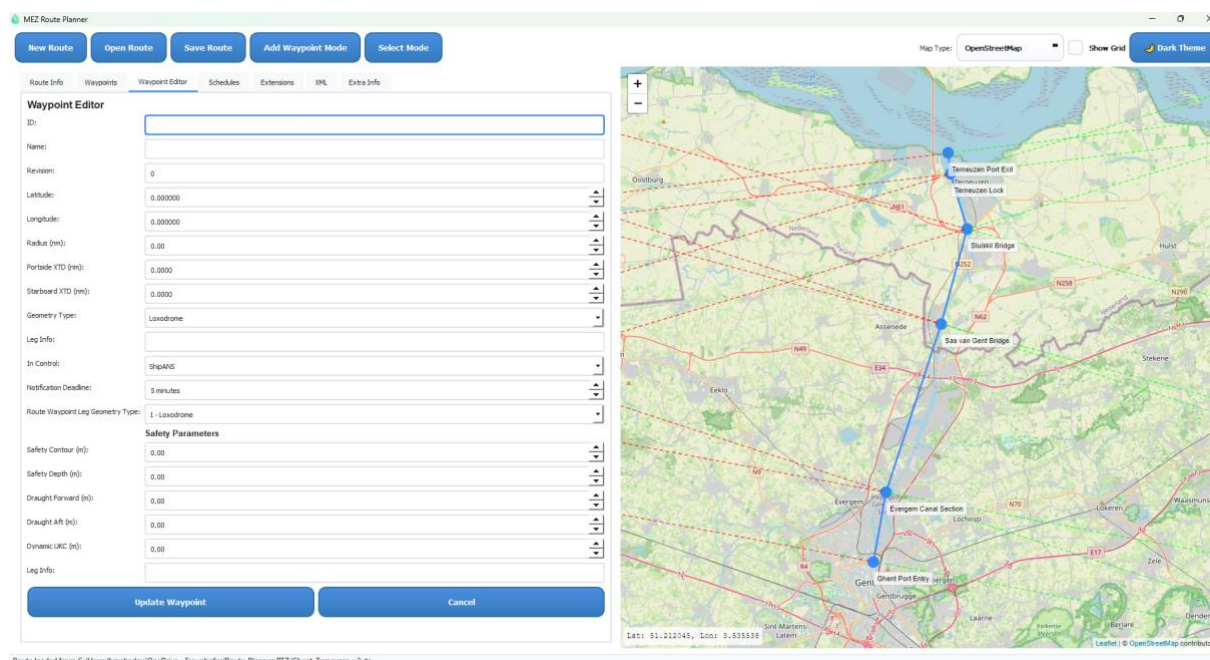


Figure 6-1: RTZ Route Planner — map view with Ghent–Terneuzen route and MEZ action point overlays

6.2 KEY FEATURES

The Route Planner provides an interactive map-based interface built on the Leaflet web mapping library, rendered inside the application via an embedded browser widget. Operators can place waypoints on the map by clicking or by entering coordinates manually, and can edit all route parameters through a structured waypoint table. The application supports the following capabilities:

- **Waypoint management:** Add, edit, reorder, and delete waypoints with geographic coordinates, port/starboard cross-track distance tolerances (in nautical miles), and turning radius (in nautical miles). Waypoints are rendered on the map with a route line connecting them.
- **Schedule entry:** Per-waypoint ETA and ETD can be specified in ISO 8601 datetime format. These are stored as routeScheduleElement attributes in the exported RTZ file, consistent with the MEZ planned schedule data model described in Section 2.6.3.
- **Action points:** Any waypoint can be designated as a MEZ action point. For each action point, the operator specifies a trigger radius (in nautical miles), a required action description for the ANS, and the ROC operator response expected when the vessel reaches the action point. These fields correspond to the routeActionPoint extension defined in the MEZ. The action point location defaults to the linked waypoint coordinates and is also stored as a GM_Point geometry for compatibility with the MEZ spatial data model.
- **Infrastructure data:** Infrastructure elements such as bridges and locks can be imported from a JSON file and displayed on the map as overlay markers. Once loaded, the operator can associate infrastructure data with specific waypoints to include it in the route extension output.
- **Export and import:** Routes can be saved and loaded in the extended RTZ format. The tool also provides an XML preview tab allowing the operator to inspect the raw file

before export. The application can be distributed as a self-contained Windows executable compiled with PyInstaller, requiring no separate Python installation.

6.3 OUTPUT FORMAT

The exported file follows the RTZ schema (IEC 61174) with MEZ extensions encoded within the routeExtensions element. Each waypoint leg carries a routeWaypointLeg element with port and starboard cross-track tolerances in nautical miles. Waypoints with schedules carry a routeScheduleElement with ETA and ETD attributes. Action points are encoded as routeActionPoint child elements of the waypoint extension, containing the trigger radius, required action description, planned ROC response, and GM_Point position geometry at six decimal places of coordinate precision.

Figure 6-2 shows an excerpt from the RTZ+MEZ file exported by the Route Planner for the Ghent-Terneuzen route, illustrating waypoint 3 (Sas van Gent Bridge) with its per-waypoint schedule and the corresponding MEZ action point encoded in the extensions block.

```
<?xml version="1.0" encoding="utf-8"?>
<route xmlns="http://www.cirm.org/RTZ/1/2" version="1.2">
  <routeInfo routeName="Ghent to Terneuzen" routeAuthor="Fraunhofer CML"/>
  <waypoints>
    ...
    <routeWaypoint routeWaypointID="3"
      routeWaypointName="Sas van Gent Bridge"
      routeWaypointTurnRadius="0.100000">
      <geometry><position>
        <coordinates>51.229389</coordinates>
        <coordinates>3.807460</coordinates>
      </position></geometry>
      <routeScheduleElement
        routeScheduleElementETA="2026-04-26T10:00:00Z"
        routeScheduleElementETD="2026-04-26T10:30:00Z"/>
      <routeWaypointLeg
        routeWaypointLegPortXTDL="0.0540"
        routeWaypointLegStarboardXTDL="0.0540"/>
    </routeWaypoint>
    ...
  </waypoints>
  <extensions>
    <extension name="MEZ" manufacturer="Fraunhofer" version="1.0">
      <routeActionPoints>
        <routeActionPoint routeActionPointID="1"
          routeActionPointRadius="0.100"
          waypointId="3">
          <routeActionPointRequiredActionDescription>
            Bridge passing
          </routeActionPointRequiredActionDescription>
          <ROCPlannedResponseToShip>
            Contact Bridge Operator
          </ROCPlannedResponseToShip>
          <GM_Point><position>
            <coordinates>51.228266</coordinates>
            <coordinates>3.803633</coordinates>
          </position></GM_Point>
        </routeActionPoint>
      </routeActionPoints>
    </extension>
  </extensions>
</route>
```

Figure 6-2: Excerpt from the RTZ+MEZ file exported by the Route Planner (Waypoint 3: Sas van Gent Bridge)

This output format was verified against the Maritime Robotics Vehicle Control Station (VCS). The VCS correctly parsed the MEZ-extended RTZ file, displaying the waypoints on its chart, resolving the action point trigger radii, and presenting the ROC operator notifications at the appropriate geographic positions during the Ghent–Terneuzen test route demonstration. The RTZ Route Planner and the corresponding example route file for the Ghent–Terneuzen Canal are available to AUTOFLEX consortium partners via the Fraunhofer CML SharePoint.

Figure 6-3 shows the route as displayed in the Maritime Robotics Vehicle Control Station (VCS) after loading the exported RTZ file. The VCS correctly resolves the waypoint positions, cross-track tolerances, and action point trigger radii, and presents the ROC operator notification at the Sas van Gent Bridge action point during route execution.

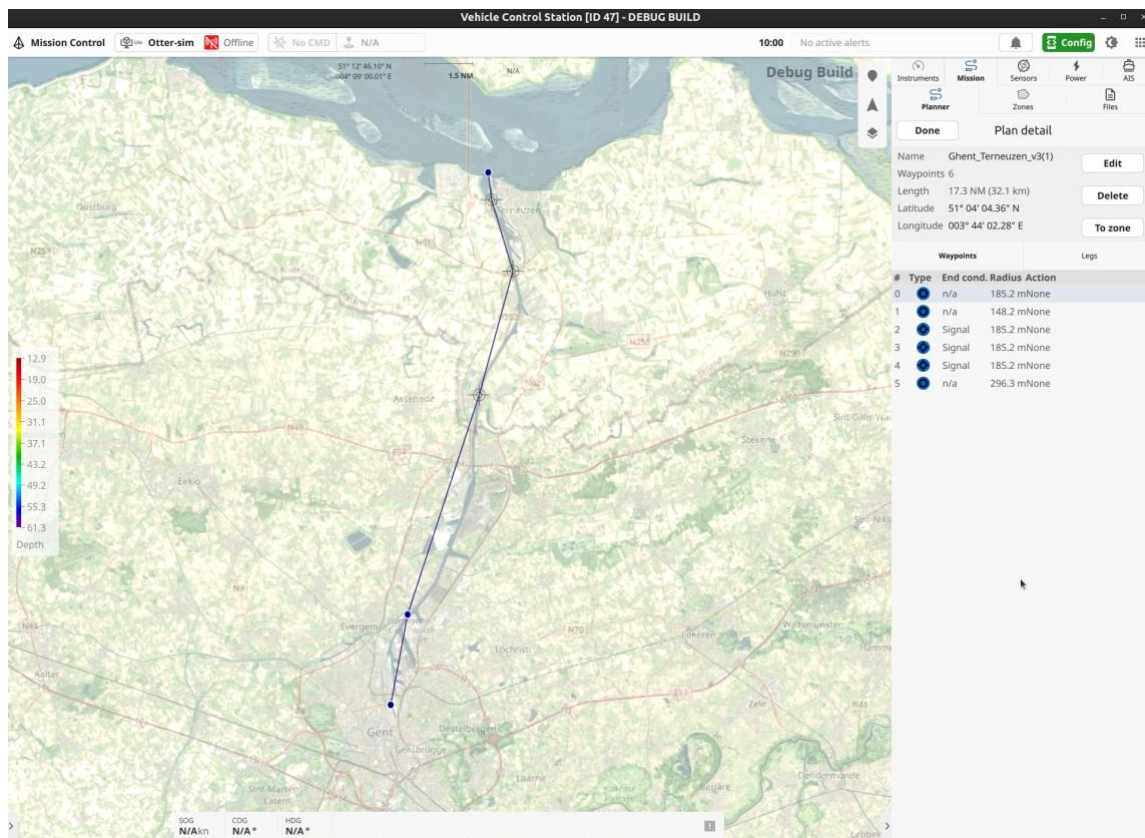


Figure 6-3: Ghent–Terneuzen route loaded in the Maritime Robotics Vehicle Control Station (VCS)

7 CONCLUSION AND FURTHER WORK

7.1 MISSION EXCHANGE MODEL

A Mission Exchange Model has been developed for use by the ROC when sending the description of the route, schedule, and lock and bridge passings to an IWW vessel. The work shows that existing standards for route exchange currently used by sea-going vessels are a good starting point when defining the data needed for autonomous IWW vessels. It also shows that extensions to these models are needed, to cover the specific details of IWW navigation.

Parts of the MEZ were demonstrated on an USV in a canal in Trondheim, Norway, showing the successful application of the principles, which would need further development in order to cover all the data needed for a complete mission.

One part of this task was to develop and demonstrate a Mission Exchange Model (MEZ) for communication between a Remote Operation Centre (ROC) and autonomous inland waterway vessels. The model provides a structured method for exchanging mission-related information, including route descriptions, voyage schedules, lock transits, bridge passages, and other operational instructions required for autonomous inland waterway navigation.

The analysis shows that existing route-exchange standards developed for maritime navigation provide a valuable foundation for mission exchange in inland waterways. However, the study also demonstrates that inland waterway operations introduce additional requirements that are not sufficiently addressed by current maritime route-exchange standards. These include detailed information related to locks, bridges, fairway constraints, traffic management procedures, and other waterway-specific operational conditions. Consequently, extensions to existing standards were required.

A subset of the Mission Exchange Model was successfully demonstrated using an unmanned surface vessel operating in the canal in Trondheim, Norway. The demonstration verified the feasibility of the proposed concept. Although only a part of the model was validated, the results indicate that the proposed approach provides a promising basis for a standardized MEZ.

Future work should focus on extending the model to cover all information required throughout the complete mission lifecycle, including dynamic voyage updates, traffic restrictions, infrastructure status information. Further validation through large-scale operational testing and alignment with emerging international standards will also be necessary before the model can be considered for formal standardization.

7.2 AUTONOMOUS NAVIGATION SYSTEM AND AUTONOMY PACKAGE

The work carried out in Tasks 4.5 and 4.6 has established and prepared an integrated autonomy package for inland waterway vessels. The package combines the Maritime Robotics SeaControl autonomous navigation and vessel control functions, the SeaSight situational awareness system, the Vehicle Control Station, and the Remote Operation Centre concept. Together, these elements provide the functions required to plan, monitor, and execute vessel missions, while allowing a remote operator to intervene or take control when required.

The onboard system architecture has been prepared for installation and demonstration on MS Letitia. The proposed installation integrates the Maritime Robotics onboard system with the vessel's existing Argonics track-keeping system and includes panoramic camera systems, such as dedicated radar, LiDAR, navigation sensors, onboard computing, and communication equipment. The SeaControl On-Board System provides the higher-level guidance and control functions, while low-level manoeuvring and safety functions remain handled through interfaces to existing vessel systems. This approach allows the autonomy package to build on established vessel-control capabilities rather than duplicating them.

The Remote Operation Centre and Vehicle Control Station provide the operator interface for mission planning, supervision, situational awareness, and remote control. The concept is scalable from a single laptop to a dedicated multi-screen shore facility, while retaining the same underlying software and operational functions. This supports different operational configurations and provides flexibility and redundancy in the event that the primary control location becomes unavailable. The integration of the MEZ-extended route files in the Vehicle Control Station further demonstrates how digital mission planning can be connected to the operational control environment.

The results demonstrate that the main building blocks required for an autonomous inland waterway vessel have been defined and brought together within a common system concept. However, the work described in this deliverable primarily covers system development, data collection, integration, and preparation for demonstration.

Full validation of the combined autonomy package on MS Letitia under representative operational conditions remains to be completed. In particular, further work is required to validate the complete sensor-fusion pipeline, assess object-detection performance across a wider range of environmental and traffic conditions, and verify the interaction between the Autonomous Navigation System, the track-keeping system, the Remote Operation Centre, and the vessel operator.

Further work should therefore focus on full-scale operational testing of the integrated system, including autonomous route execution, infrastructure passages, operator intervention, communication loss, and fallback behaviour. The tests should also evaluate the quality and availability of situational awareness information, the effectiveness of operator notifications, and the transfer of control between the Autonomous Navigation System and the remote operator. The results from these activities should be used to refine the system architecture, operational procedures, human-machine interfaces, and safety functions, and to support subsequent validation and certification activities for autonomous inland waterway operations.

REFERENCES

- [1] Marianne Hagaseth, Håvard Nordahl, Lars Andreas Lien Wenersberg, Hans-Christoph Burmeister and Øyvind Pedersen: A Mission Exchange Model (MEZ) for Autonomous Inland Waterway Navigation; 2025 J. Phys.: Conf. Ser. 3123 012012; DOI 10.1088/1742-6596/3123/1/012012
- [2] H. C. Burmeister, Ø. J. Rødseth, and T. Porathe, 'Autonomous Unmanned Merchant Vessel and its Contribution towards the e-Navigation Implementation: The MUNIN Perspective', in International Journal of e-Navigation and Maritime Economy, 2014, pp. 1–13.
- [3] ISO, ISO/TS 23860:2022 Ships and marine technology – Vocabulary related to autonomous ship systems, 2022. Accessed: Jun. 19, 2023. [Online]. Available: <https://www.iso.org/standard/77186.html>
- [4] IMO, 'Amendments to IMO instruments: upcoming and recent entry into force/effective dates'. Accessed: Jun. 20, 2025. [Online]. Available: <https://www.imo.org/en/About/Conventions/Pages/Amendments-to-IMO-instruments.aspx>
- [5] IMO, 'IMO Resolution A.893(21)', A.893(21), Nov. 1999. Accessed: Jun. 20, 2025. [Online]. Available: [https://www.wcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.893\(21\).pdf](https://www.wcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.893(21).pdf)
- [6] Route plan exchange format - RTZ. [Online]. Available: <https://cirm.org/rtz-xml-schemas>
- [7] A. Rydinger, 'MONALISA 2.0 – Activity 1.3 STM Voyage exchange format and architecture', MONALISA 2.0_D1.3.2, Dec. 2015.
- [8] H. C. Burmeister, T. Scheidweiler, M. Reimann, and C. Jahn, 'Assessing Safety Effects of Digitization with the European Maritime Simulator Network EMSN: The Sea Traffic Management Case.', in The International Journal on Marine Navigation and Safety of Sea Transportation, 2020, pp. 91–96. doi: 10.12716/1001.14.01.10.
- [9] IEC 63173-1:2021: Maritime navigation and radiocommunication equipment and systems - Data interfaces - Part 1: S-421 route plan based on S-100. [Online]. Available: <https://webstore.iec.ch/en/publication/32931>
- [10] S-421 Converter. ECC. [Online]. Available: <https://s421creator.ecc.no/>
- [11] H. Dybvik, E. Veitch, and M. Steinert, 'EXPLORING CHALLENGES WITH DESIGNING AND DEVELOPING SHORE CONTROL CENTERS (SCC) FOR AUTONOMOUS SHIPS', Proc. Des. Soc. Des. Conf., vol. 1, pp. 847–856, May 2020, doi: 10.1017/dsd.2020.131.
- [12] J. (Hans) van den Broek, J. R. (Jaco) Griffioen, and M. (Monique) van der Drift, 'Meaningful Human Control in Autonomous Shipping: An Overview', IOP Conf. Ser. Mater. Sci. Eng., vol. 929, no. 1, p. 012008, Nov. 2020, doi: 10.1088/1757-899X/929/1/012008.
- [13] O. A. Alsos et al., 'NTNU Shore Control Lab: Designing shore control centres in the age of autonomous ships', J. Phys. Conf. Ser., vol. 2311, no. 1, p. 012030, Jul. 2022, doi: 10.1088/1742-6596/2311/1/012030.
- [14] E. Veitch, 'Designing for Land-based Control of Autonomous Vessels', Doctoral thesis, NTNU, 2023. Accessed: May 26, 2025. [Online]. Available: <https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/3088574>
- [15] L. P. Perera, V. Ferrari, F. P. Santos, M. A. Hinostroza, and C. Guedes Soares, 'Experimental Evaluations on Ship Autonomous Navigation and Collision Avoidance by Intelligent Guidance', IEEE J. Ocean. Eng., vol. 40, no. 2, pp. 374–387, Apr. 2015, doi: 10.1109/JOE.2014.2304793.

- [16] Y. Gu, J. C. Goez, M. Guajardo, and S. W. Wallace, 'Autonomous vessels: state of the art and potential opportunities in logistics', *Int. Trans. Oper. Res.*, vol. 28, no. 4, pp. 1706–1739, 2021, doi: 10.1111/itor.12785.
- [17] Ü. Öztürk, M. Akdağ, and T. Ayabakan, 'A review of path planning algorithms in maritime autonomous surface ships: Navigation safety perspective', *Ocean Eng.*, vol. 251, p. 111010, May 2022, doi: 10.1016/j.oceaneng.2022.111010.
- [18] Y. Qiao, J. Yin, W. Wang, F. Duarte, J. Yang, and C. Ratti, 'Survey of Deep Learning for Autonomous Surface Vehicles in Marine Environments', *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 4, pp. 3678–3701, Apr. 2023, doi: 10.1109/TITS.2023.3235911.
- [19] T. Stach, Y. Kinkel, M. Constapel, and H.-C. Burmeister, 'Maritime Anomaly Detection for Vessel Traffic Services: A Survey.', in *J. Mar. Sci. Eng.*, 2023. doi: <https://doi.org/10.3390/jmse11061174>.
- [20] K. Wolsing, L. Bauer, and K. Wehrle, 'Anomaly Detection in Maritime AIS Tracks: A Review of Recent Approaches.', in *J. Mar. Sci. Eng.*, 2022. doi: <https://doi.org/10.3390/jmse10010112>.
- [21] A. Atyabi, S. MahmoudZadeh, and S. Nefti-Meziani, 'Current advancements on autonomous mission planning and management systems: An AUV and UAV perspective', *Annu. Rev. Control*, vol. 46, pp. 196–215, Jan. 2018, doi: 10.1016/j.arcontrol.2018.07.002.
- [22] F. Thompson and D. Guihen, 'Review of mission planning for autonomous marine vehicle fleets', *J. Field Robot.*, vol. 36, no. 2, pp. 333–354, 2019, doi: 10.1002/rob.21819.
- [23] F. Thompson and R. Galeazzi, 'Robust mission planning for Autonomous Marine Vehicle fleets', *Robot. Auton. Syst.*, vol. 124, p. 103404, Feb. 2020, doi: 10.1016/j.robot.2019.103404.
- [24] M. A. Hinostroza and A. M. Lekkas, 'A Rudimentary Mission Planning System for Marine Autonomous Surface Ships', *IFAC-Pap.*, vol. 55, no. 31, pp. 196–203, Jan. 2022, doi: 10.1016/j.ifacol.2022.10.431.
- [25] M. A. Hinostroza and A. M. Lekkas, 'Temporal mission planning for autonomous ships: Design and integration with guidance, navigation and control', *Ocean Eng.*, vol. 297, p. 117104, Apr. 2024, doi: 10.1016/j.oceaneng.2024.117104.
- [26] IENC Feature Catalogue, Apr. 21, 2021. [Online]. Available: https://www.cesni.eu/wp-content/uploads/2023/05/Appendices-Part1-IECDIS_BD.pdf
- [27] INLAND ELECTRONIC NAVIGATIONAL CHART PRODUCT SPECIFICATION, Draft IEHG Publication S-401, Annex A Data Classification and Encoding Guide.
- [28] Autoremove systems. Accessed: Jun. 22, 2025. [Online]. Available: <https://www.dnv.com/maritime/autonomous-remotely-operated-ships/autoremove-systems/>
- [29] Explanatory note related to the international definition of levels of automation in inland navigation, 2022.
- [30] 'Explanatory note related to the international definition of levels of automation in inland navigation'. CCNR, 2022.
- [31] CEVNI European Code for Inland Waterways, 2021.
- [32] S-421 Route Exchange. [Online]. Available: <https://cirm.org/s-421>
- [33] 'Encoding Guide for Inland ENC (draft)'. in Inland ENC Harmonization Group.
- [34] IEHG INLAND ELECTRONIC NAVIGATIONAL CHART PRODUCT SPECIFICATION Draft, Sep. 2024.
- [35] Bayplan/stowage plan occupied and empty locations message. [Online]. Available: https://service.unece.org/trade/untdid/d17a/trmd/baplie_c.htm
- [36] IMO Compendium on Facilitation and Electronic Business. [Online]. Available: <https://imocompendium.imo.org/public/IMO-Compendium/Current/index.htm>

- [37]IHO Marine Harbour Infrastructure (MHI) Product Specification, S-131, Mar. 2023. [Online]. Available: https://iho.int/uploads/user/pubs/Drafts/S-131%20Marine%20Harbour%20Infrastructure%201_0_0%20Product%20Specification.pdf
- [38]Maritime Robotics, 'The Otter X', Maritime Robotics. Accessed: Jun. 19, 2025. [Online]. Available: <https://www.maritimerobotics.com/otter-x>