SAFETY AND TRANSPORT
MARITIME

Reeds - Referensdata och algoritmer till stöd för forskning och utveckling av smarta fartyg

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REEDS - Referensdata och algoritmer till stöd för forskning och utveckling av smarta fartyg

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Abstract

Reference data and algorithms for research and development of smart ships

The Swedish Transport Administration Research and Innovation fund for Maritime research funded the project "Reference data and algorithms to support research and development of smart ships". The project goes by the working name, and is communicated as, Reeds. It responds to a synthesis of a number of different needs identified in previous projects and studies. The background to the project is that in recent years the focus has been on developing algorithms to interpret and act on the physical environment around different types of craft. In order to be able to develop and evaluate these algorithms, it has become clear that open datasets and a fair benchmarking platform are required that allow various developers in industries and researchers to evaluate algorithms. In the road vehicle sector, Kitti, as of 2013, is the largest dataset used as a reference dataset. The dataset in this project contains sensor data from several data collection occasions within a maritime context, from high-precision sensors such as cameras, radar, lidar, and IMU. For marine applications, there has been no similar dataset with anywhere near the same amount of data and time synchronisation between sensors. The reference data and reference algorithms were available periodically during the project through an online service where researchers and developers could upload their algorithms to use the dataset.

In addition to the dataset itself, Reeds adds additional strengths compared to other reference datasets:

- New approach to comparing algorithms fairly, where new algorithms are always compared on a centralised hardware in a cloud service and re-evaluated when new data is added, i.e. an unbiased algorithm evaluation service.
- Method that combines NTP and PTP time protocols for synchronisation between the sensors with microsecond accuracy
- More types and more modern sensors that can be used at a higher level of abstraction and can thus be applied in more areas.
- Sensor fusion of both onboard and land-side sensors
- Identify areas of application for navigation and surveillance on land based on the algorithms developed during the project and the use of new sensor types not established in shipping.
-

The project built up a maritime reference data set that enables the creation of a digital description for the ship's surrounding environment and developed reference algorithms to demonstrate new navigation and monitoring methodology in the area of "enhanced navigation".

"Enhanced navigation" is defined under the project as the use of new technology based on developments in digitisation and autonomous functions, where new navigation methods use sensors both on board and ashore to increase maritime safety and robustness. The project has built a web-based user interface referred to in the report as

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"Crowsnest" that handles these new sensors and visualises this data in a familiar interface similar to an overlay in ECDIS that is openly available for the public to build on. Which was used for the evaluation and concept development of new user interfaces based on feedback from pilots and VTS operators.

By providing reference datasets and reference algorithms with demonstrations, researchers and companies now have the opportunity to develop algorithms for the intelligent and autonomous ships of the future.

Key words: autonomous shipping, MASS, sensor fusion, enhanced navigation, reference dataset, algorithm benchmarking, massive data, shore sensors, algorithm benchmarking, shore sensors, beyond application dataset, lidar, IMU, radar, time synchronisation

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List of abbreviations

- AD: Automated Driving
- ADAS: Advanced Driver Assistance Systems
- AIS: Automatic Identification System
- AtoN: Aid to Navigation
- API: Application Programming Interface
- AUV: Autonomous Underwater Vehicle
- COLREGS: International Regulations for Preventing Collisions at Sea
- CPU: Central Processing Unit
- DP: Dynamic Positioning
- DSO: Direct Sparse Odometry
- ECDIS: Electronic Chart Display and Information System
- FMCW: Frequency Modulated Continuous Wave
- FoV: Field of View
- GAN: Generative Adversarial Network
- GDPR: General Data Protection Regulation
- GNSS: Global Navigation Satellite System
- GPU: Graphics Processing Unit
- HMI: Human-Machine Interface
- HTTP: Hypertext Transfer Protocol
- Hz: Hertz (unit of frequency)
- ICP: Iterative Closest Point
- IEEE1588: Institute of Electrical and Electronics Engineers 1588 (Precision Time Protocol)
- IMO: International Maritime Organisation
- IMU: Inertial Measurement Unit

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- IoT: Internet of Things
- J-turn: Maneuver in the shape of the letter "J"
- Kitti: Karlsruhe Institute of Technology and Toyota Technological Institute dataset
- LIDAR: Light Detection and Ranging
- LSB: Lateral Speed Bow
- LSS: Lateral Speed Stern
- LTE: Long-Term Evolution (a type of mobile network technology)
- MASS: Maritime Autonomous Surface Ships
- MOB: Man Overboard
- MSC: Maritime Safety Committee
- MV: Mastervolt
- NICs: Network Interface Cards
- NTP: Network Time Protocol
- NVMe: Non-Volatile Memory Express
- OS1: Ouster lidar model OS1
- OS2: Ouster lidar model OS2
- PDF: Portable Document Format
- POSIX: Portable Operating System Interface
- PPP: Precise Point Positioning
- PTP: Precision Time Protocol
- RPY: Roll, Pitch, Yaw
- RPM: Revolutions Per Minute
- RS-485: Recommended Standard 485
- RTK: Real-Time Kinematic
- RTX: Ray Tracing Technology
- SAR: Search and Rescue
- SDR: Software-Defined Radio
- SSD: Solid State Drive

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- STCW: Standards of Training, Certification, and Watchkeeping for Seafarers
- TCP: Transmission Control Protocol
- ToF: Time of Flight
- UAVs: Unmanned Aerial Vehicles
- UDP: User Datagram Protocol
- USB: Universal Serial Bus
- VHF: Very High Frequency
- VTS: Vessel Traffic Service

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Sammanfattning

Projektet “Referensdata och algoritmer till stöd för forskning och utveckling av smarta fartyg” har finansierats av Trafikverkets Forsknings - och Innovationsportfölj för sjöfart.

Projektet som går under arbetsnamnet och kommuniceras som Reeds svarar mot en syntes av ett antal olika behov som identifierats i tidigare projekt och studier. Bakgrunden till projektet är att de senaste åren har fokus lagts på att ta fram algoritmer för att tolka och agera på den fysiska miljön kring olika typer av farkoster. För att utveckla och utvärdera dessa algoritmer har det blivit tydligt att det krävs öppna dataset och en rättvis benchmarkingplattform som tillåter olika utvecklare inom industrier och forskare att utvärdera algoritmer. Inom vägfordonssektorn är Kitti, från 2013, det största datasetet som används som referensdata set. Datasetet i detta projekt innehåller sensordata från flertalet datainsamlingstillfällen i en maritim kontext, från högprecisionssensorer som kameror, radar, lidar, och IMU. För maritima applikationer har det inte funnits något liknande dataset med tillnärmelsevis lika stor datamängd och med tidssynkronisering mellan sensorer. Referensdata och referensalgoritmerna var tillgängliga periodvis under projektet genom en onlinetjänst där forskare och utvecklare kunde ladda upp sina algoritmer för att använda datasetet.

Utöver själva datasetet tillför Reeds ytterligare styrkor jämfört andra referensdata set:

- Nytt tillvägagångssätt för att jämföra algoritmer rättvist, där nya algoritmer alltid jämförs på en centraliserad hårdvara i en molntjänst och omvärderas när nya data läggs till, dvs en opartisk tjänst för utvärdering av algoritmer.
- Metod som kombinerar NTP och PTP tidsprotokoll för synkronisering mellan sensorerna med mikrosekunds noggrannhet
- Fler typer och modernare sensorer som kan användas på en högre abstraktionsnivå, och kan därmed tillämpas inom fler områden.
- Sensorfusion av både ombord sensorer och av sensorer på landsidan
- Identifiera tillämpningsområden för navigation och övervakning i land baserat på algoritmerna som togs fram under projektet och användning av nya sensortyper som ej är etablerade inom sjöfarten

Projektet har etablerat ett maritimt referensdataset som möjliggör att skapa en digital beskrivning av fartygets omgivande miljö samt utvecklade referensalgoritmer för att demonstrera nya navigations- och övervakningsmetoder inom området.

“Enhanced navigation” definieras inom projektet som användandet av ny teknik för navigation som bygger på utvecklingen inom digitalisering och autonoma funktioner, där nya navigationsmetoder använder sensorer både ombord och iland för att öka sjösäkerheten och robustheten. Projektet har byggt upp ett webbaserat användargränssnitt, “Crowsnest”, som hanterar dessa nya sensorer och visualiserar denna data i ett familjärt gränssnitt, liknande en overlay i ECDIS som finns öppet tillgängligt för allmänheten att bygga vidare på. Detta användes för utvärdering och konceptutveckling av nya användargränssnitt baserat på erfarna lotsar och VTS-operatörers åsikter. Genom att tillhandahålla referensdataset och referensalgoritmer med demonstrationer ges nu forskare och företag möjligheten att utveckla algoritmer för framtidens intelligenta och autonoma fartyg.

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1 Introduction

1.1 Background

The Maritime sector has long been a leading domain of automation development, with a clear example of demands in the engine rooms leading to innovations such as "Periodically Unattended Machinery Space" (Gordon, 1989) that allows the ships engineers to leave the engine control room and only respond to alarms from its systems for up to 24 hours. The automation of deck duties continued, with development of automated systems for cargo handling, and even further to navigation and monitoring of ships movements, where the Automatic Identification System (AIS) has played a major role in enhancing the monitoring of the traffic situation (Harati-Mokhtari et al., 2007).

More modern research and development trends are steering the evolution of automation towards complete autonomous navigation and steering. In the maritime sector, offshore oil and gas are using Dynamic Positioning (DP), with sensors tracking the relative bearing and distance to given objects (Sørensen, 2011). Continuing even further, there is now significant research into Autonomous Underwater Vehicles (AUV) where few or no other traffic is at risk for collision. However, when it comes to navigation on the surface in congested waters, shared with boats, ships and pleasure crafts of various sorts, there is significant lack of development, with a number of challenges to overcome. A future navigation system has to be able to navigate as good as a human, possibly even better, to be a viable solution for the future of shipping along our coasts, fairways and inland waters.

To be able to innovate, test and in the future certify that such automatic navigation systems are capable, and these systems are safety critical, there is a demand for data of high resolution and quality in all these stages. However, a look at contemporary maritime datasets shows that the majority of published and available datasets are simply not viable, due in part to the lack of sensor capability, lack of accurate timestamping, or simply the data being unviable for maritime purposes (Benderius et al., 2021). In order to build a dataset that can be used to solve the above navigation problems, a dataset methodology was built based on the lessons learnt from Chalmers active automotive safety research, which has been used to ensure that the collected data is of high standard and the usability for research and innovations is at the highest level. To achieve this, an abstract approach can be taken to dataset development, where the development process does not focus on a specific domain or use-case, but instead uses a 'beyond application' approach, allowing the datasets to be used for many kinds of training and validation of algorithms in similar domains such as maritime, automotive, and aerospace industries and research.

Conversely, there is also ongoing research within the automation sector on establishing *fair* testing methods for automation systems. Again, looking at contemporary datasets, and the current trend of online leaderboards for tasks such as object detection and navigation, emphasis is on the accuracy of the algorithm, which can be skewed through hardware performance that not all competitors may have access to (Benderius et al., 2021). In conjunction with a beyond-application dataset, there also needs to be a way to

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fairly evaluate the international community's contributions, as well as develop a method of integration that allows the continuous expansion of testing as new use-cases are put forward as the dataset is distributed.

This development of a beyond-application dataset and the automatic integration of testing is entirely novel, and thus significant effort is required to establish a formulaic approach to sensor, platform, and environmental decisions. This report covers the development of *Reeds*, the first beyond application dataset, developed in said maritime environment, the *SeaHorse* and *Landkrabban* platforms, which were used to develop the dataset, and finally, the testing and evaluation of the dataset and automation systems built from these platforms and this dataset. Lastly, this report will cover the use of this dataset within the maritime domain, specifically with the goal of building systems designed for *enhanced navigation*.

1.2 Goals

The goals of this project were as follows:

1. Establish an approach to beyond-application dataset generation,
2. Formulaically decide on sensors and other hardware for this dataset generation,
3. Develop a platform or platforms to capture this data,
4. Evaluate the data, and establish validity,
5. Create a method for international distribution of the dataset,
6. Expand this method to include automatic integration of testing and benchmarking,
7. Apply the dataset to maritime specific use-cases to demonstrate feasibility within the domain, specifically in the case of *enhanced navigation (maritime)*.

1.3 Methodology

To establish these goals, a number of work packages (WP) have been set, in order to set a structure for the project. *Note – For ease of reading, Work Package 3 has been placed before Work Package 2 within this report, as the topics regarding the abstract dataset concepts and dataset generation and validation align.*

- *WP 1: Reference dataset*
- *WP 2: Shore sensors*
- *WP 3: Benchmarking*
- *WP 4: Enhanced navigation*
- *WP 5: Demonstrations and evaluation*

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1. [WP1] → Define the need for a beyond-application dataset,
2. [WP1/2] → Establish the required sensors, platform, and collection procedures.
3. [WP3] → Collect data,
4. [WP2/3] → Validate sensors, synchronisation and storage,
5. [WP3] → Establish methods for post-processing and benchmarking,

Continue dataset collection, continuously repeating 3, 4 and 5.

6. [WP4] → Develop reference algorithms for the maritime domain use cases.
7. [WP5] → Validate development and establish future research goals.

1.4 Scope

The project scope was limited to focus on a smaller vessel operating in the archipelago and inland waterways, including locks, outside the Gothenburg area and Göta channel. The geographical location provides several advantages for data collection, which can be summarised as the following:

- Proximity to the Chalmers Revere research lab facility: The boat is stored inside the lab on a trailer, the project benefits from being close to the data collection area but limited to long distance travel.
- Year-round availability: The water in this area does not freeze entirely, allowing the small craft to be used and data to be collected throughout the year. But the boat's small size limited data collection in severe weather.
- Variety of ships and infrastructure: The area has a diverse range of ships and features with various infrastructure elements such as locks and bridges.
- Prominence of the Port of Gothenburg: Parts of the area belong to the Port of Gothenburg, which is the largest port in Scandinavia. This makes the area well-known within the maritime industry and adds to the project's suitability.

All above is deemed as an appropriate and suitable geographical limitation, due to the fact that the Port of Gothenburg and its immediate surrounding is the largest shipping hub in the entire Scandinavia region. Not just in size but also in the variety of shipped goods that deal in RoRo, LoLo, Passengers and liquid and solid bulk. The area is also trafficked by a large number of leisure crafts, with a variety of navigation marks from the archipelago such as buoys and signals near locks makes for a large variety of data annotations.

The project's results have been communicated to the industry and interested parties through workshops and networks within the industry, all to increase awareness and competence within the segment that United Nations International Maritime Organisation (IMO) has defined as 'Maritime autonomous surface ship' (MASS).

This project does not look into the details and challenges regarding cyber security and data links between ship and shore.

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2 Reference dataset

2.1 "Beyond Application" Datasets

"Beyond application", as mentioned, is the concept of applying an abstract approach to the development of a system. Through the development of Driver Assistance (ADAS), in 2009 and the development of full automated driving (AD) in 2016, there is a noticeable trend where the current research focus defines the development of the datasets being generated at the time (Benderius et al., 2021). This is known as application centric development, and whilst these datasets work well with the systems they are developed for, they are difficult to migrate to other domains, other applications and other research questions. Thus, the reference dataset for Reeds is built on the principles of "Beyond Application" abstract development, whereby the system should be able to move between domains and use cases.

For this, current datasets were evaluated to find commonality, regardless of application. The key components of these datasets were the components of high quality, high volume, and highly kinematic.

2.1.1 High Quality

High quality data refers to a number of different components but can quickly be summarised as sensors with high resolution, high bit-depth, with a formulaic approach to time synchronisation. The sensors should cover multiple areas (light, radio, visual, etc), should be overlapping to provide redundancy, and should be verifiable through a low trust approach. There should also be sensors that are accurate enough to provide a 'ground truth', to continuously validate the other sensors. Finally, the sensors selected should take the approach of a 'start high' method, whereby users can opt to down sample if they find the quality is too much for development, such as in the case of neural network training compute time.

2.1.2 High Volume

High Volume refers to both the sampling rate of the sensors, as well as the total runtime of the data collection. Diversification of environments allows for the development of adaptable systems, so the goal of the dataset should be to capture multiple weather types and domain objects. Whilst the sample rate of the sensors is important, it often comes at the reduction of quality. A camera typically will have a lower bit depth or resolution to provide a higher sample rate. In this case, the quality should remain as high as possible whilst providing a sample rate that is realistic for modern algorithm development. This can be determined by using a priority-based approach, as defined by Hoel, Wolf and Laine (Hoel et al., 2020), in which the author provides a hierarchy of strategic, tactical and operational decision making. In this approach, it is advantageous to have a higher sample rate on the sensors to be used for operational sensors.

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2.1.3 Highly Kinematic

A highly kinematic system is one that is subjected to consistently large acceleration and angular rotation movements. As with the high quality, a 'Start high' approach applies to the kinematic state, as it is much easier to train a static system with kinematically diverse data, than the inverse. To ensure this, three domains were considered for the data collection, being a land-based vehicle, a maritime platform, and an unmanned aerial system. Of the three, the aerial system was considered too expensive for the payload required to ensure high quality and high-volume data. A comparison was then undertaken between the road and the maritime systems, to determine kinematic viability. For this, the absolute change in acceleration was taken from a random two-minute snippet taken from the initial data collection, using a KVH-P1775 Inertial Measurement Unit (IMU).

Test / **Axis**	**X-Axis**	**Y-Axis**	**Z-Axis**
Road (30km/h)	70.35m/s	74.08m/s	89.24m/s
Road (80km/h)	74.63m/s	82.16m/s	131.63m/s
Water (30km/h)	144.36m/s	57.38m/s	142.63m/s

Table 1 comparison of IMU tests on road and water.

The 30 km/h water test, and the 80 km/h road tests are indicative of typical operations of the sensor platform in that domain. The water test was undertaken in a Sea State ranging between 1 and 2 on the World Meteorological Organization scale, with waves not larger than half a metre. The 30 km/h road test provides a comparison between similar speeds. As shown by the absolute change in acceleration, the maritime domain provides significantly higher changes in acceleration in the X and Z axis, which can be attributed to the consistent, regular impacts with the ocean swell. As the vessel accelerates, the vessel's force, located underneath and to the rear, causes the vessel to move around the pitch moment. The IMU in turn changes orientation, with the Z and X axis interchanging as the front and stern of the vessel raise and lower based on this acceleration. It can then be seen that the kinematic state of the vessel is defined by the combined total of all axes and is clearly considerably larger than a land-based system in either test case. This trend continues throughout every single run conducted on the marine system, only increases as the sea scale increases, and is still significant when conducting slow manoeuvres due to the lack of upper roll limit when compared to a land vehicle.

2.2 The Sensor Platform

Several different workboats were used for initial development and tests, before a final platform was developed for the for data collection. SeaHorse is a 4.9 metre active research vessel, as depicted in more detail within the *WP2: Platform Description, Seahorse* section. The basic sensor platform consists of a GNSS system with three antennas and real-time kinematic positioning capabilities, a fibre optic gyro IMU system,

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four single-channel high-performance vision sensors, two three-channel high-performance vision sensors, a 360 degree documentation camera system, three high-performance laser time of flight scanners (lidar), a conventional marine 360 degree spinning radar sensor, a weather and barometric pressure sensor, and an automatic identification system (AIS). The GNSS sensor and the IMU jointly provide ground truth positioning.

The logging equipment consists of two data centre servers (Seahorse1 and Seahorse2), each equipped with: Two AMD EPYC 7352 CPUs (four in total), 128GB memory, four 16TB Seagate Exos SATA disk drives, one 15.6TB Micron 9300 NVMe U.2 SSD, one 2TB Samsung 980 PRO NVMe M.2 SSD, one Nvidia GeForce RTX 2080, and one Nvidia Quadro RTX 4000. All computational nodes run Linux kernel 5.10 with **PREEMPT_RT** activated.

2.2.1 Network Architecture

Each server is connected to the Flir cameras and the lidars via dedicated 10Gigabit Ethernet links. The remaining sensors are connected via Ethernet to the Intel NICs, but the link speed is dependent upon the requirements of the sensor. The IMU is connected via RS-485 through a dedicated computational unit (Seahorse 0). AIS is connected using an RTL-SDR, through USB interface. The entire system is connected to the Internet using a 4G link.

2.2.2 Time Synchronisation

The three computational nodes (Seahorse 0, 1 and 2) are time synchronised through PTP, with Seahorse1 providing a Grandmaster clock to the network. The FLIR cameras and the Lidars also use this PTP for time synchronisation. To provide an accurate PTP Grandmaster clock, Seahorse1 uses hardware clock synchronisation from the ANAVS GNSS. In the case of a GNSS denied environment, there is a second layer of redundancy, where the system can retrieve NTP clock messages from online services. This NTP layer is also required for the axis cameras, so it is also broadcast through the network. The Radar and IMU, which either do not have a time synchronisation method or are not connected via an ethernet layer, are time stamped and managed by their corresponding compute node. The full NTP stratum and PTP hierarchy can be seen in the following figure:

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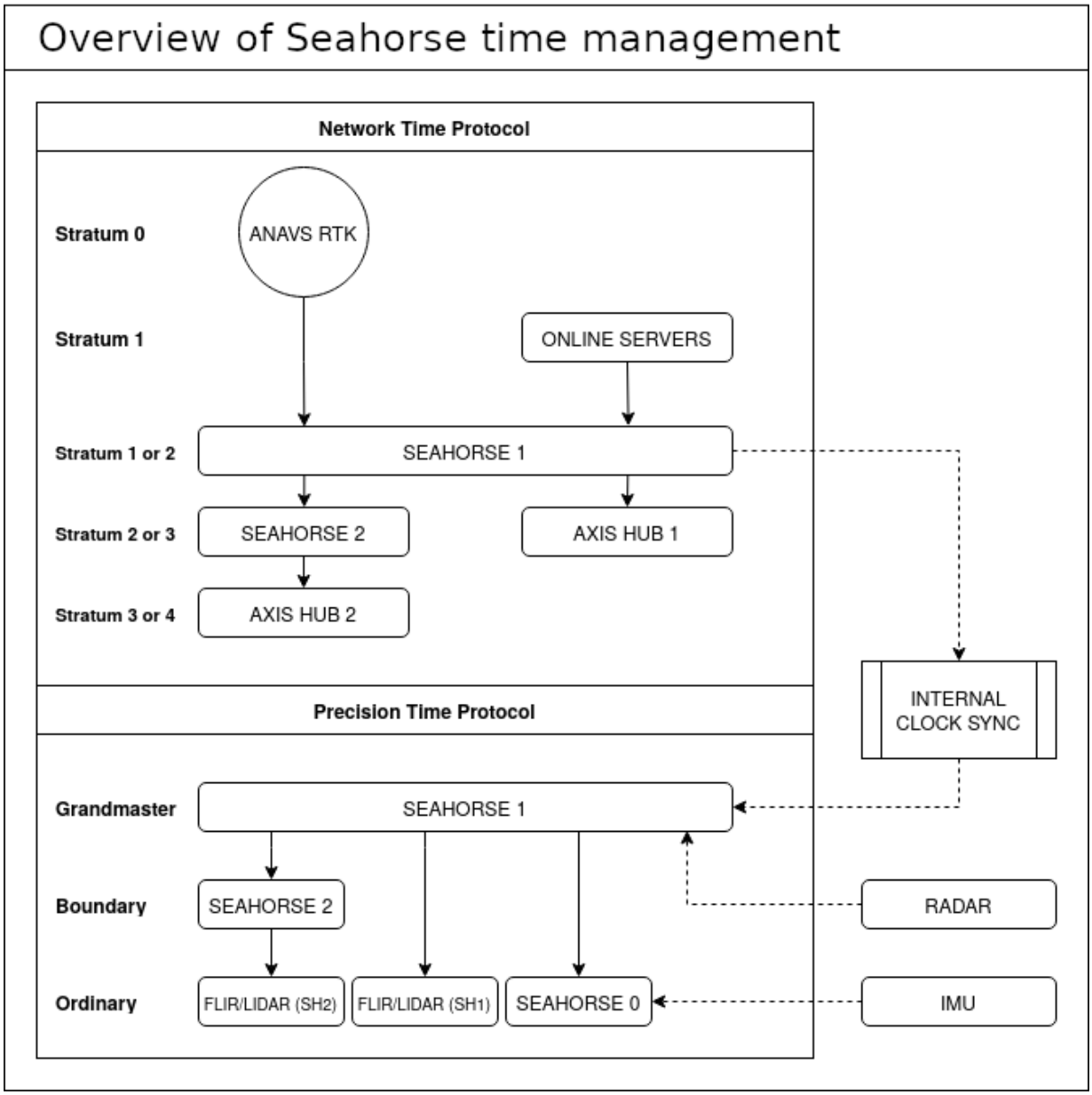

Figure 1: An overview of the time synchronisation architecture within the Seahorse platform

2.3 Data collection

The initial data collections were taken in the littoral waters of Goteborg, Sweden, in varying sea conditions and weather. Each run is between ten minutes and two hours long, depending on the environment, weather, and use case. Scenarios involving extrinsic factors such as river locks are likely to take longer, whereas point to point travel in calmed open waters may be shorter. The goal of this dataset is to provide high volume and highly kinematic data, so whilst the aim for each run is to obtain roughly an hour of data, it was deemed more beneficial to capture varying lengths of data that contained short bursts of differing environmental conditions.

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2.4 Data management and processing

2.4.1 Storage

The data is captured locally into Seahorse using the OpenDLV message architecture. The data is captured and processed into a recording file, which captures all aspects from an individual sensor. As an example, the Ouster Lidars provide Lidar time of flight data, but are self-calibrating with internal inertial measurement units, and this data can also be captured. Each separate message contains time sent, time received, the sample time, and the message data. Thus, a .rec file for the Lidar will contain the following message types, and the rate of population is dependent upon the sample rate of each sensor component:

Time (seconds); Time (microseconds); PointCloudAngularLayeredReading

Time (seconds); Time (microseconds); AccelerationReading

Time (seconds); Time (microseconds); AngularVelocityReading

Whilst this is suitable for the majority of the sensors, the FLIR Oryx cameras provide too high of a data rate to effectively provide this method of storage (See WP 2. Sensors). To overcome this, each camera stores the camera stream as individual .raw image files, with the filename providing the timestamp, as well as the gain, exposure and camera format (I,e monochrome or bayer, as well as bit depth).

After collation, the files are moved firstly to the mechanical storage on board Seahorse, allowing for further data capture runs, before moving to the online cloud storage.

2.4.2 Post-Processing

Within the scope of this project, a number of use cases were presented, which dictated the initial use of the data. For visual based odometry methods, it was found that 1920x1080 at 30Hz was sufficient, thus allowing for a much lower storage overhead, however the conversion to this data still falls into the post-processing methodology. These requirements lead to methods that were developed specifically for each task in turn, which was then folded into automated methods which are to be integrated into the automatic benchmarking process. Each sensor also had unique identifiers for annotation. As an example, an object can be visually detected in a camera image, which in turn can be turned into an x/y bounding box for simple annotations, or an x/y scatter plot for a more thorough detection (as seen in Image 1). The level of labelling also differed between use cases. For COLREG uses, a much more thorough annotation method is required, to distinguish between the different maritime objects. Thus, the level of annotation is left to the user, which is shown in the following section detailing the design of the automated benchmarking system.

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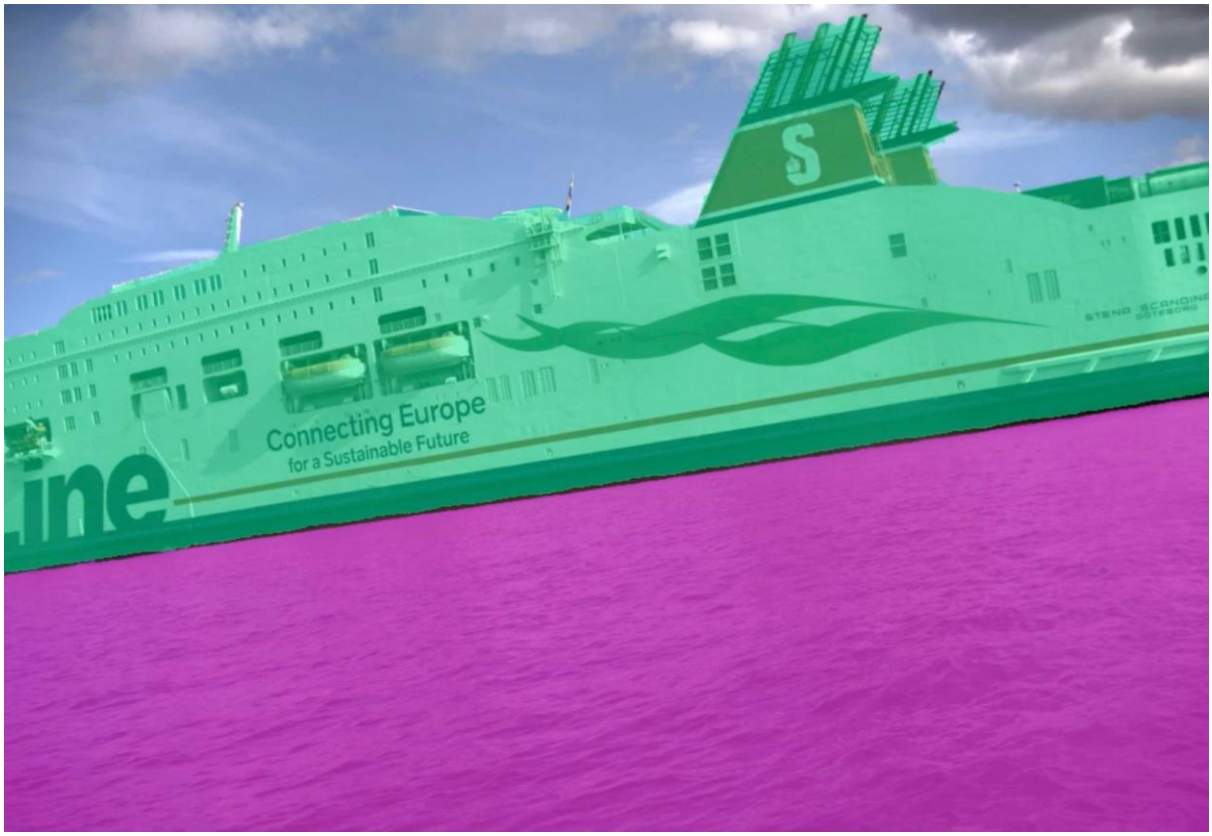

Image 1: A post-processed image from a FLIR ORYX 10GigE 71S7-C, during a Reeds Datarun, after annotation to distinguish a vessel and water elements.

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3 Benchmarking

3.1 Design

A key feature of the Reeds dataset infrastructure is the automated evaluation of algorithms. Having this in place allows fair reproducible benchmarks of previous and future algorithms. Furthermore, it removes the need of downloading vast amounts of data, but rather moves comparatively smaller software executables or source code to follow the design principle of bringing the fishermen to the lake than vice versa. However, by also allowing users to utilise the backend infrastructure for evaluation, even if restricted to the officially approved leaderboard candidates, the computational needs on the evaluation servers are significant. Not only restricted to CPU time, but also GPU and wear on disk drives. Therefore, as the most naive way of evaluating algorithms towards the data does not scale well with an increasing number of algorithms, a well-designed evaluation procedure was employed.

The overall design of the evaluation infrastructure was made within a focus group interview between five different test projects using early snippets of the dataset. Each project was selected for the purpose of having different requirements from the dataset and the evaluation of the resulting algorithms. The test projects included: Motion estimation and 3D-reconstruction using mono and stereo cameras (Nguyen et al., 2022), object detection and classification, rain-drop removal from video feeds, simultaneous localization and mapping (SLAM) using lidar (Engström et al., 2022), and radar-based estimation of motion. Two of these test projects are now published within the International Federation of Automatic Control.

In a first set of meetings, the authors of this paper individually met the principal investigator for each project to discuss their evaluation needs. Then, towards the end of the projects, a joint meeting was organised where the group combined all requirements into a joint proposal that would be able to cater to the needs of each project. Finally, some adjustments to the design were made before concluding the design, as shown in Figure 2.

In the design, a common interface towards the dataset is given. Using this interface, data can be consumed by the algorithm in the Reeds cloud environment. The basic method for data access is through shared memory, on the CPU side implemented as POSIX and on the GPU using the *external memory* feature, using **VK_KHR_external_memory** from Vulkan (a standardised multi-vendor API for GPU access). In order to scale well with an increasing number of algorithms, the data is fed to algorithms in parallel during evaluation. For example, when working with video feeds the involved steps are as follows:

1. All video frames belonging to a time slice are read from disk and decoded using an Nvidia GPU,
2. the resolution of the images and frame rate are stored into shared memory,
3. the resulting images are copied to each GPU in the cluster using Vulkan and a handle to the memory is stored in shared memory,

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4. each algorithm is using the data from the time slice and releases the shared memory when done,
5. the output from each algorithm is compared towards the ground truth data, and
6. when the entire collection run is consumed, the resolution (spatial and temporal) is reduced before starting over at step 2. The accuracy and precision as well as expectation times of the algorithm is then summarised and automatically reported towards the public leaderboards.

For evaluation, the preset resolution and frame rate profiles were based on other existing datasets (Kang et al., 2019). All datasets listed by Kang et al. were reviewed together with common datasets for UAVs to find such presets and relevant settings were extracted. It was found that the two common frame rates used are 30Hz and 10Hz, and resolutions are typically around 1920x1080 (1080p) or 1280x720 (720p). An exception is the Apollo dataset which includes videos in the resolution of 3384x2710 at 30Hz. Furthermore, since the Kitti dataset is still considered very important for evaluations, it was decided to also include the rather unusual resolution of 1382x512 in Reeds as well. In cases where the images could not be scaled with preserved ratio, the overflow was cropped, to avoid any stretching. The cropping is always done relative to the centre of the image.

The benefit of the proposed evaluation procedure is that each set of frames are only fetched from disk and decoded once for all algorithms and all down-scaled resolutions, resulting in n fetch and decode operations where n is the number of frames. With the naive method of evaluation, this step would have been repeated for each frame, algorithm, and down-scaled resolution, resulting in $n * m * p$ where m is the number of algorithms and p is the number of preset resolutions to evaluate. As n corresponds to the fetching and decoding of about 30 terabytes of data, and with $p = 12$ and a reasonable value $m = 100$ (in fact, this could potentially grow to a few hundred over time), the parallel evaluation is expected to save processing worth 36 petabytes (36000 terabytes) of data per data log, by reading the 30 terabytes only once. The drawback of the parallel evaluation is that each algorithm needs to wait for the completion of all other algorithms, per frame.

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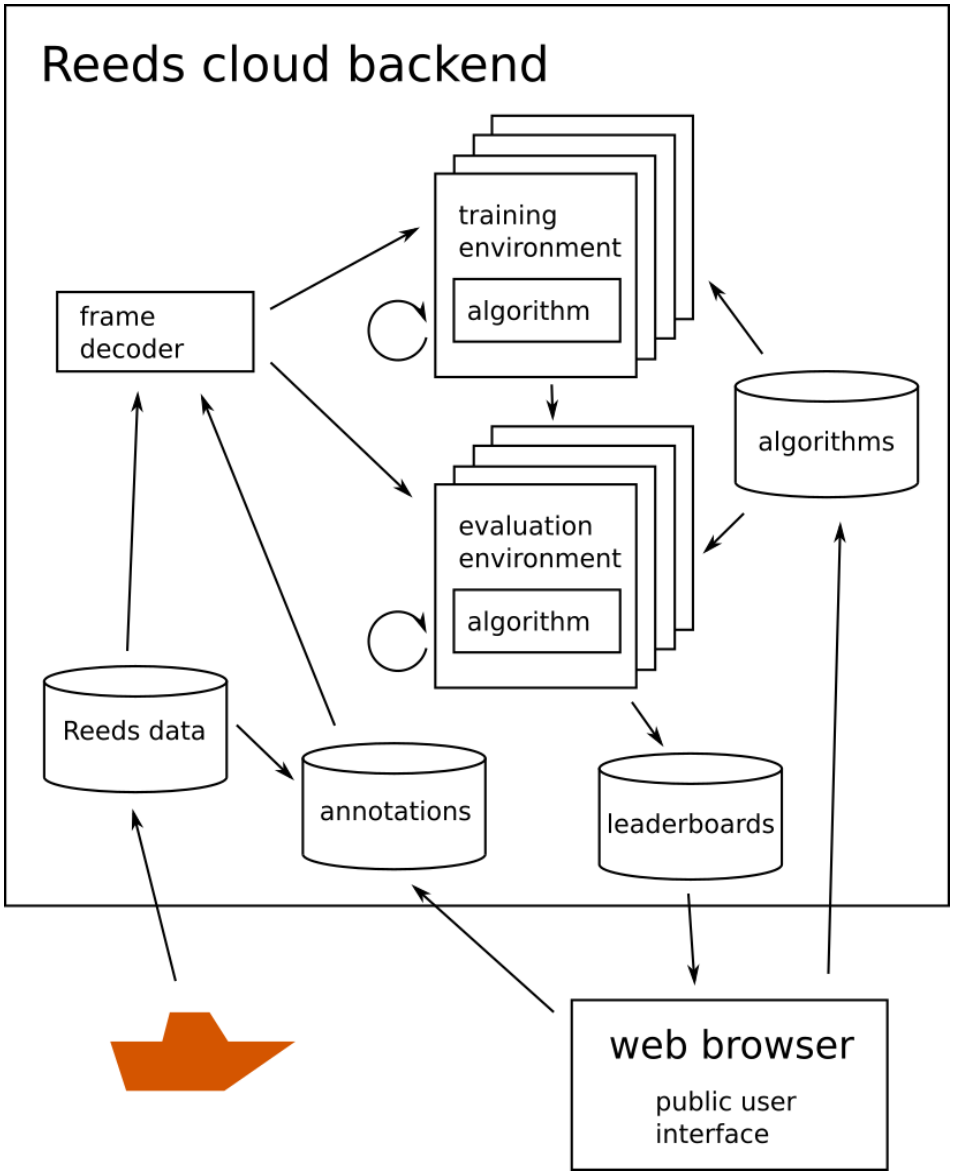

Figure 2: A flow diagram detailing the use of the Reeds dataset for a typical online user for online training, evaluation and benchmarking.

3.2 Implementation and analysis

3.2.1 Odometry

In the aforementioned test cases, the project looking at odometry based on stereo camera vision (Nguyen et al., 2022), and the project looking at developing localisation and mapping with Lidars (Engström et al., 2022) both developed novel algorithms for the maritime use cases. In these cases, they are the first to be developed and tested upon the Reeds dataset, however, both systems performed as described, with comparisons to the ground truth using individual sensors, and sent these results back to the developers in a format that could then be transferred into visual media for presentation. The results can be seen in the following two figures, taken from each respective project, which showcase the final output of the benchmarking system.

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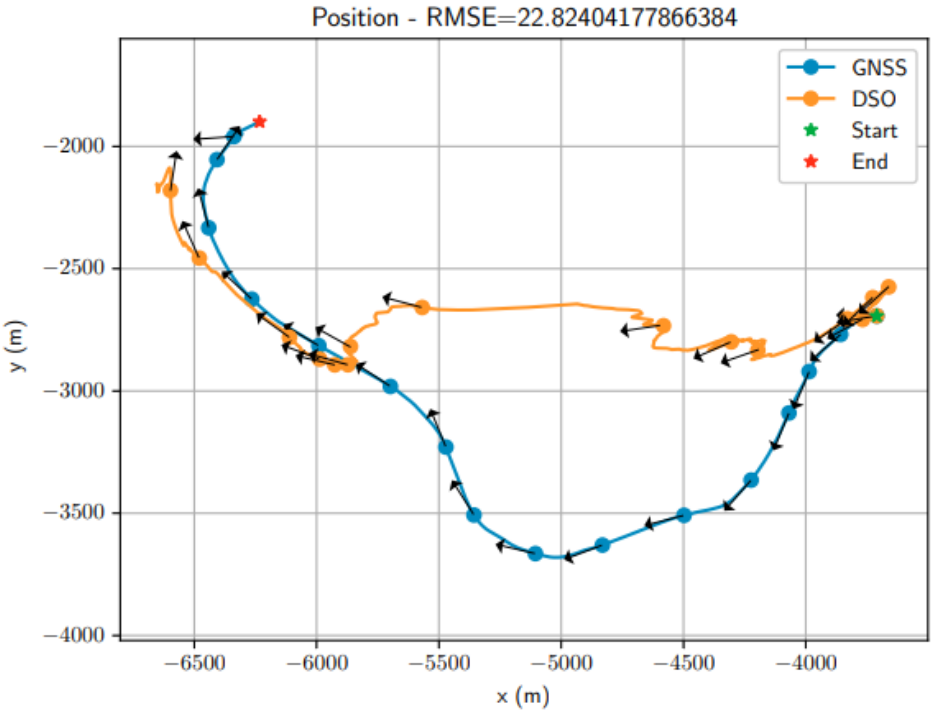

Figure 3: A comparison between ground truth (GNSS) and an automated odometry algorithm (DSO).

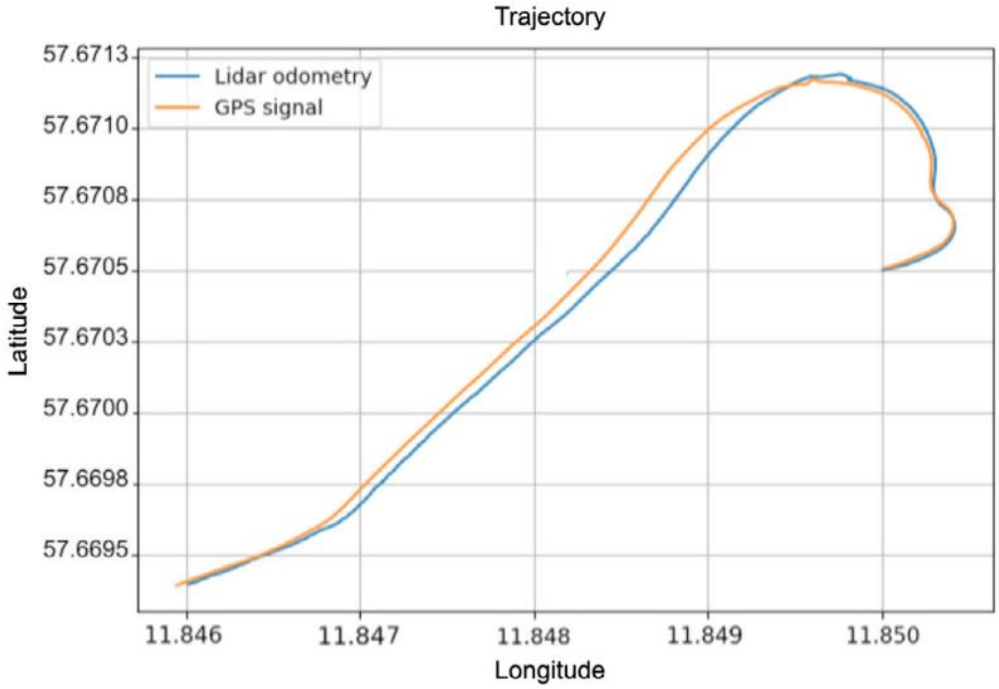

Figure 4: A comparison between ground truth (GNSS) and an automated odometry algorithm (LIDAR SLAM)

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3.2.2 Object Detection

Likewise, a number of projects were undertaken with the goal of object detection. These included projects that used a generative network to detect and remove water droplets from camera lenses, and another that used machine learning approaches to maritime object detection. These systems differ to the Odometry methods, in that they cannot use the Ground Truth sensors to provide initial feedback, and instead use their own annotations or labels for comparison, as shown in Figure 5.

Figure 5: Master Thesis results using a Generative Network to remove water droplets from a FLIR image (Sophonpattanakit, 2022). Results are based on how close the generated image, which is built from a water drop annotated image, matches a non-water drop image of the exact scene.

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4 Shore and Platform Sensors

The chapter starts with highlighting use cases identified under the project that could be solved mainly by the new sensor types not widely used in the sea transport market, Reeds explores the new sensor types during the project. This continues with a comprehensive overview of all sensors and the sensor platforms used in the project, it will explain why we chose this specific sensor setup and configuration. Notably, a significant portion of the chosen project sensors was not originally designed for the marine market/segment. Therefore, we conducted a performance assessment for these non-established marine market sensors. The evaluation aimed to assess their suitability and identify potential benefits these new sensor types could bring to the maritime sector.

4.1 Use cases

Within project discussions with Swedish pilots, Vessel Traffic System (VTS) operators, and other marine experts, specific use cases were identified where sensor perception could significantly enhance sea transport safety and resilience. Today's sensor perception week points were identified by areas where more information is needed to increase the degree of automation, the navigator's situational awareness, or the potential to reduce cost compared with traditional equipment used within the domain.

4.1.1 Ships manoeuvring in port or restricted water

Determining a large ship's relative distance to smaller objects within close range of the vessel can be difficult due to the large distance between the observer and the object of interest. For example, if the observer is located on the navigation bridge. Even the ship´s superstructure can limit the view under close-quarter manoeuvring, as exemplified in Figure 6.

These new sensors offer the potential for precise navigation during manoeuvring, allowing the ship to find the final position alongside when it comes to bollards ashore or hard arms used for loading and discharging liquids. By employing high-accuracy sensors, it becomes possible to monitor the speed of approach and departure from a jetty and track the relative angles. These inputs are needed because an average freighter ship's precision of the GNSS system is insufficient.

Additionally, the sensors can verify the final positioning of a vessel with remarkable accuracy, which is particularly crucial when considering factors such as infrastructure ashore like hard arms, gangways or ramps used for cargo operations. Furthermore, these sensors have the capability to detect protruding objects from the shoreside or ship side, enhancing safety and navigation in maritime operations as well as protecting the port infrastructure.

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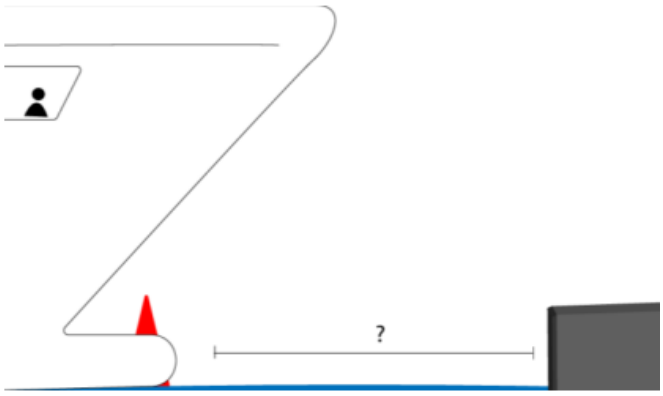

Figure 6: Lookout placement in the bow of the ship has a limited view.

4.1.2 Verification of ship position and AIS outline

Today larger ships are legally mandated to transmit identification information via the Automatic Identification System (AIS). The AIS transponder transmits standardised messages containing essential details such as ship size and position reference point. This enables units to accurately plot the ship's position and size on a chart, providing vital information to Pilots and VTS (Vessel Traffic Services) for assessing the ship's position relative to navigational hazards or aligning the vessel during port manoeuvres which is essential in challenging conditions with limited visibility.

However, it is essential to note that due to a lack of industry standardisation and specific requirements, the details provided by the AIS system can only serve as a guide and cannot be solely relied upon. Pilots have reported instances of low-quality GNSS (Global Navigation Satellite System) or misconfigurations, highlighting the need for caution. These discrepancies become readily apparent when the ship is moored alongside, and the ship sections plotted can be compared to the shoreline, allowing for accurate detection of any inconsistencies. But this method is not available on arrival when a ship approaches from the open sea, and the information is most valuable to take the ship safely alongside.

Having sensors that can scan the ships before arrival and do a position validation and outline verification of the AIS information. This would allow the VTS and pilots to have validated GNSS and metrics on the ship before arrival, enhancing maritime safety.

Having multiple sensors will increase the redundancy regarding positioning and calculation of curved headlines and so on since a lot of these functions rely heavily on the GNSS- system today. Not only would it create a system more resilient against spoofing or just poor reception to different satellites, but it would also increase the accuracy of these systems since these sensors have a higher accuracy overall.

4.1.3 Perceptions sensor in large quantities

The current sensor setup commonly observed in coastal areas, fairways, and ports is characterised by perception sensor systems that are expensive and primarily designed for a single purpose and use by a single operator. However, significant advancements

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have been made in radars targeting the marine pleasure craft market the past 20 years. These advancements have resulted in improvements across multiple areas. The quality and resilience of radar equipment have notably increased. At the same time, the performance on short-range distances below 3 nautical miles has surpassed the requirements for professional use in some areas, which later sections in this rapport cover in more detail. Additionally, these radar systems offer the advantage of low power consumption, which benefits users in remote locations. These enhanced characteristics have opened up new possibilities and use cases within the professional maritime domain.

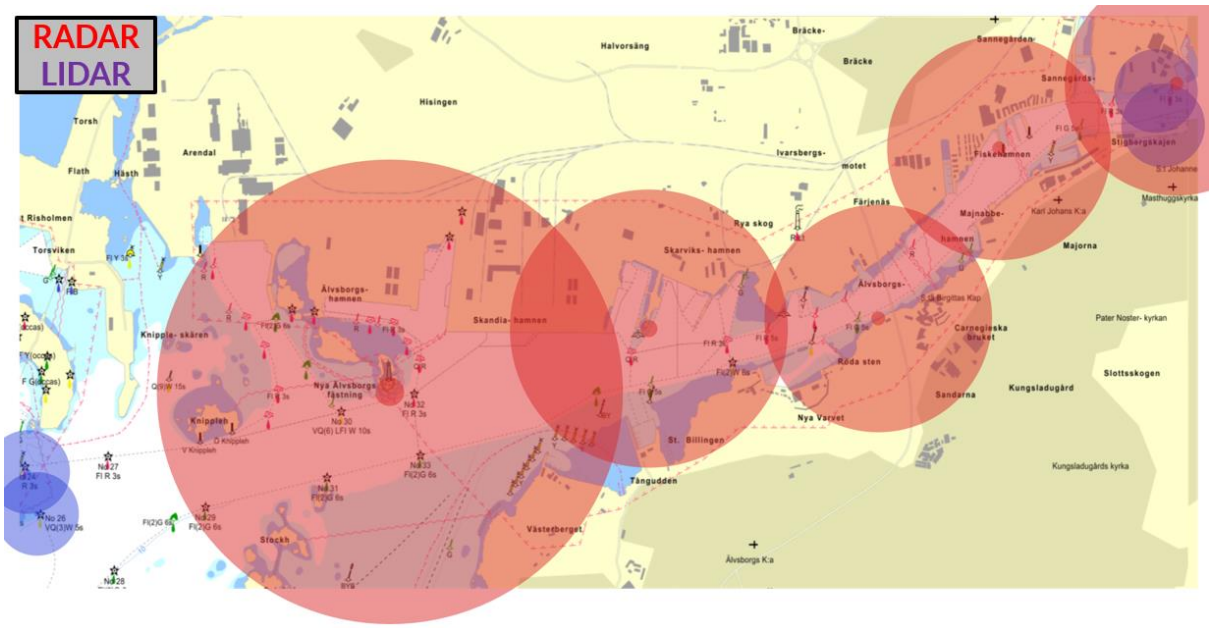

Figure 7: An example of radar and lidar placement along the Göta Älv river that could provide high-resolution traffic awareness.

Coastal radar stations are limited in numbers and cover large areas, often failing to cover smaller areas such as inlets or regions behind islands. However, installing smaller radar units can effectively address these gaps in coverage. Since the unit cost of these smaller radar units is significantly lower than that of coastal radar, it becomes feasible to install a larger number of units to cover costal radars blind spots.

In particular, areas with high traffic, such as the archipelago with numerous pleasure craft boats that may not have AIS (Automatic Identification System) technology, are currently not adequately accounted for in the VTS (Vessel Traffic Service). By expanding the traffic monitoring capabilities through the deployment of additional radar units, a more accurate and comprehensive picture of the maritime traffic can be presented to VTS centres or pilots. This enhanced monitoring capability contributes to improved situational awareness and decision-making in maritime operations.

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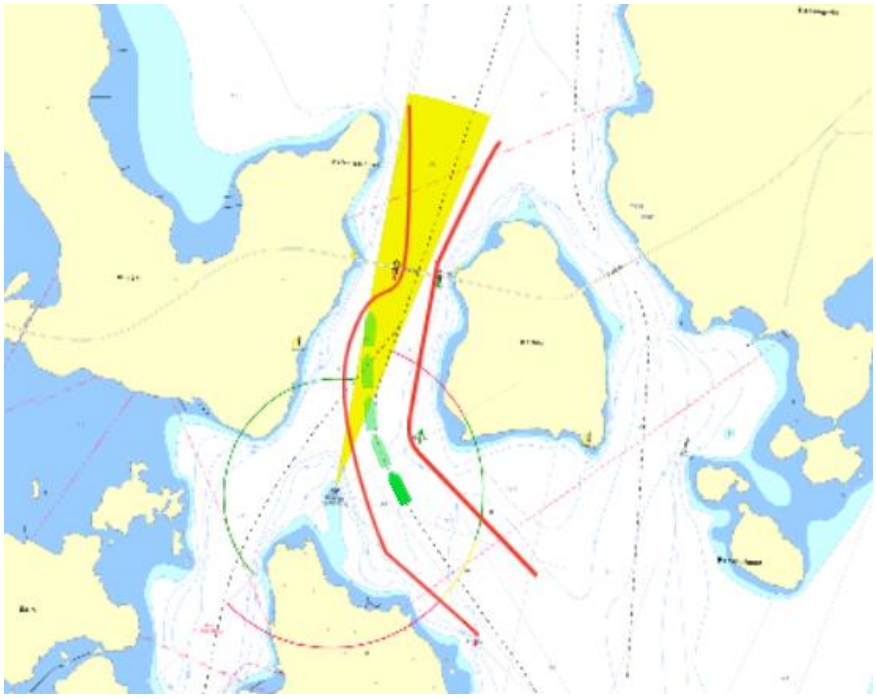

Image 2: Illustrates a challenging location for a traditional marine surveillance system, which faces limitations in providing adequate coverage. The passage depicted is narrow, making it impractical to rely on a single observing point. In such cases, employing multiple short-range sensors is a more appropriate approach to ensure comprehensive coverage of the area.

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4.2 Platform description: Seahorse

The Seahorse data collection platform is a second-hand recreational boat that has been retrofitted with a sensor platform in the bow and stern that are referred to as wings and a waterproof server box located in the centre of the boat. You can view the plans for the boat modification in picture X, which illustrates the aluminium construction work that was carried out by Depå Services in Malmö. The boat was specifically chosen to be handled by two people and light enough to be towed by a car on a trailer, and also have enough capacity to carry a stand-alone 24V power system and sensors while still being seaworthy.

Specifications:

Model:	*Ockelbo B16AL*
Engine:	*45hp outboard petrol engine*
Draft:	*0.40m*
Length overall:	*4.95m*
Total weight:	*650kg*
Material:	*Aluminium*

Image 3: Main data collection platform Seahorse at Fiskebäck 2022.

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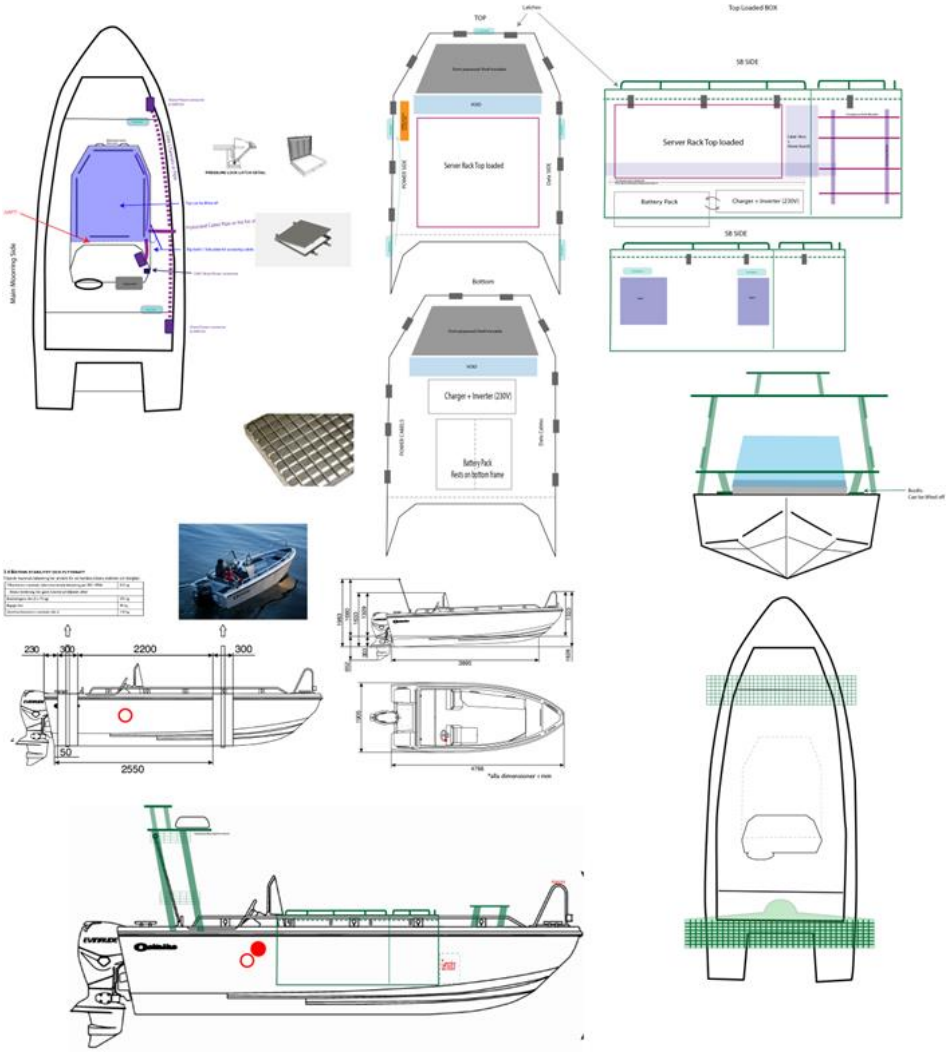

Figure 8: The general arrangement of Seahorse.

The Seahorse vessel modifications and addons transformed the boat into a versatile platform for data collection. Figure 8 provides an overview of the planned general layout of the Seahorse before construction. During the process of equipping the vessel with various mounting platforms, sensors and a standalone 24V battery power system, a primary concern was to manage the total weight and centre of gravity carefully. This was essential to ensure that the boat maintained good stability even with the additional weight from the added-on equipment and power system.

The reconstruction involved the incorporation of several heavy components. The Mastervolt battery pack weighs approximately 65kg, and the servers with the rack weigh around 45kg. Furthermore, the built-in aluminium construction bow and stern wings and a waterproof server box added to the overall weight of the boat.

To ensure the stability and seaworthiness of the boat, a strategic approach was adopted in positioning the heaviest equipment. The decision was made to place the heaviest

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components towards the stern of the boat at a low point. This location was selected due to several reasons. Firstly, the stern is the widest part of the vessel, providing the most counteracting force to counteract heeling and list. Secondly, by distributing the weight towards the stern, the boat is more likely to maintain its bow up and not dive into waves even when facing challenging conditions at sea.

During the initial sea trial, we closely monitored the performance of the reconstructed boat and observed that it exhibited excellent stability. However, we encountered a challenge in achieving planning speed with the 40-horsepower engine as the vessel struggled to reach the desired velocity. Despite this limitation, we were pleasantly surprised to find that we were able to achieve an operating speed of 23 knots, which exceeded our initial expectations. Our original goal for the vessel was to collect data at a speed range of 6 to 8 knots. The second concern under the sea trial was that it required quite a lot of force input on the wheel for steering but ended up being just a lack of lubrication. However, the vessel's performance surpassed our expectations, enabling us to gather data even at higher speeds than initially planned successfully. This outcome opened for collecting data at varying velocities, enhancing the versatility and efficiency of our data collection efforts.

Seahorse had been effectively adapted to serve as a stable and efficient platform for data collection activities.

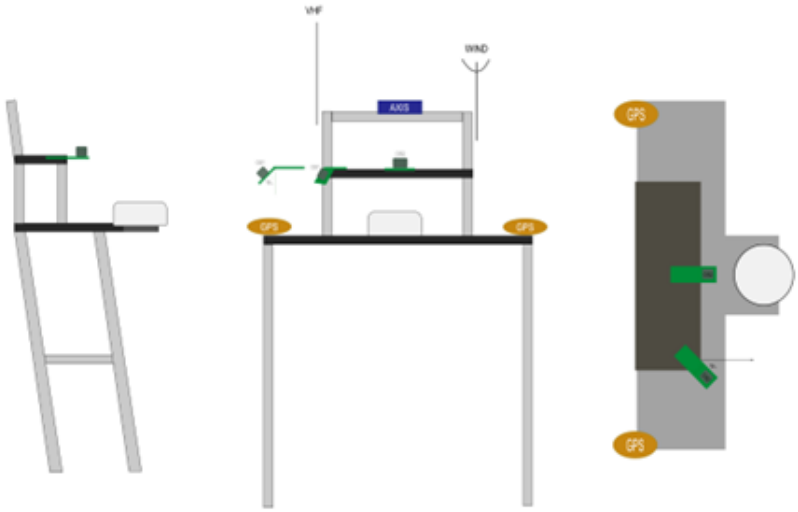

Figure 9: Aft sensor platform general arrangement.

The sensor mounting platforms on the Seahorse vessel are referred to as the rear (aft) wing and the forward (bow) wing. These platforms are constructed using aluminium framing, providing a sturdy and durable structure. To facilitate the installation and adjustment of sensors, the mounting surfaces are made of plastic walkway grating mesh. The use of plastic walkway grating mesh ensures not only secure sensor attachment but also enables convenient adjustments to optimise sensor placement for optimal performance. The bow and aft wing are detachable to allow for easy modification and multi-purpose use.

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The server box located in the centre of Seahorse can be seen in Image 4. The server box's largest part is the server rack installed in its forward section, which is supported by rubber dampening mounted to the box frame. To facilitate easy installation and maintenance, the server rack frame pieces are detachable, enabling the servers to be lifted into the rack with convenience.

In terms of the server rack mounting direction, careful consideration was given to aligning the *longitudinal* direction of the motherboard PCI slots with the primary impact direction force caused by waves. This alignment strategy aims to distribute the stress forces exerted on the PCI slots more evenly, ensuring their durability and optimal performance even in challenging marine conditions. As the PCI slots are fitted with GPU and network cards. By implementing this approach, the server rack is better equipped to withstand the potential impact and vibrations encountered during maritime operations, providing stability and reliability to the server system on the Seahorse.

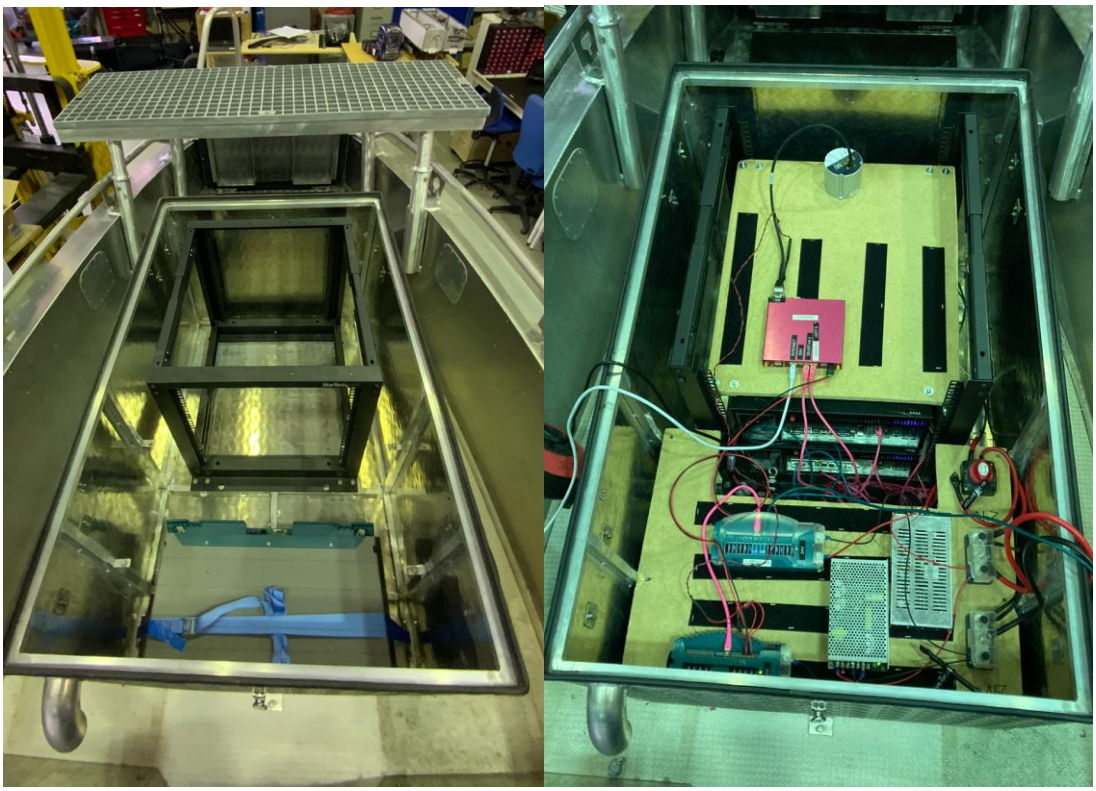

Image 4: The waterproof server box in two stages of installation. Inside the box, the server rack is mounted, and the battery pack is temporarily installed in its final location. In front of the box is the bow wing.

4.2.1 Power system

The power supply for the sensors and servers on the Seahorse is independent of the boat's power system. It utilises a standalone system consisting of a 24V battery pack and charger, which are mounted in the aft section of the server box. The power distribution, including the DC-to-DC converters, is located on the aft top shelf.

The system is designed to be charged only on shore power at 230V. However, to expedite the charging process when available, a fast charger with a 110A supply is installed. This

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allows for rapid charging, provided that the shore-side power source can accommodate such a high-power consumption.

By implementing this dedicated power system, the sensors and servers onboard the Seahorse are supplied with reliable and regulated power, enabling their optimal performance throughout data collection operations.

The main power system components are from Mastervolt (MV):

- *Charger: ChargeMaster Plus 24/110*
- *Battery: Li-ion MLI Ultra 24V, 6000Wh, 230Ah*
- *Digital Switch: MV Masterbus Digital DC*
- *Onboard control unit: Easyview*
- *DC/DC Converters Meanwell*

The operation time on the batteries vary from 4h to 6h depending on the computer load, but we did not let the charge level go below 15% to conserve the battery life.

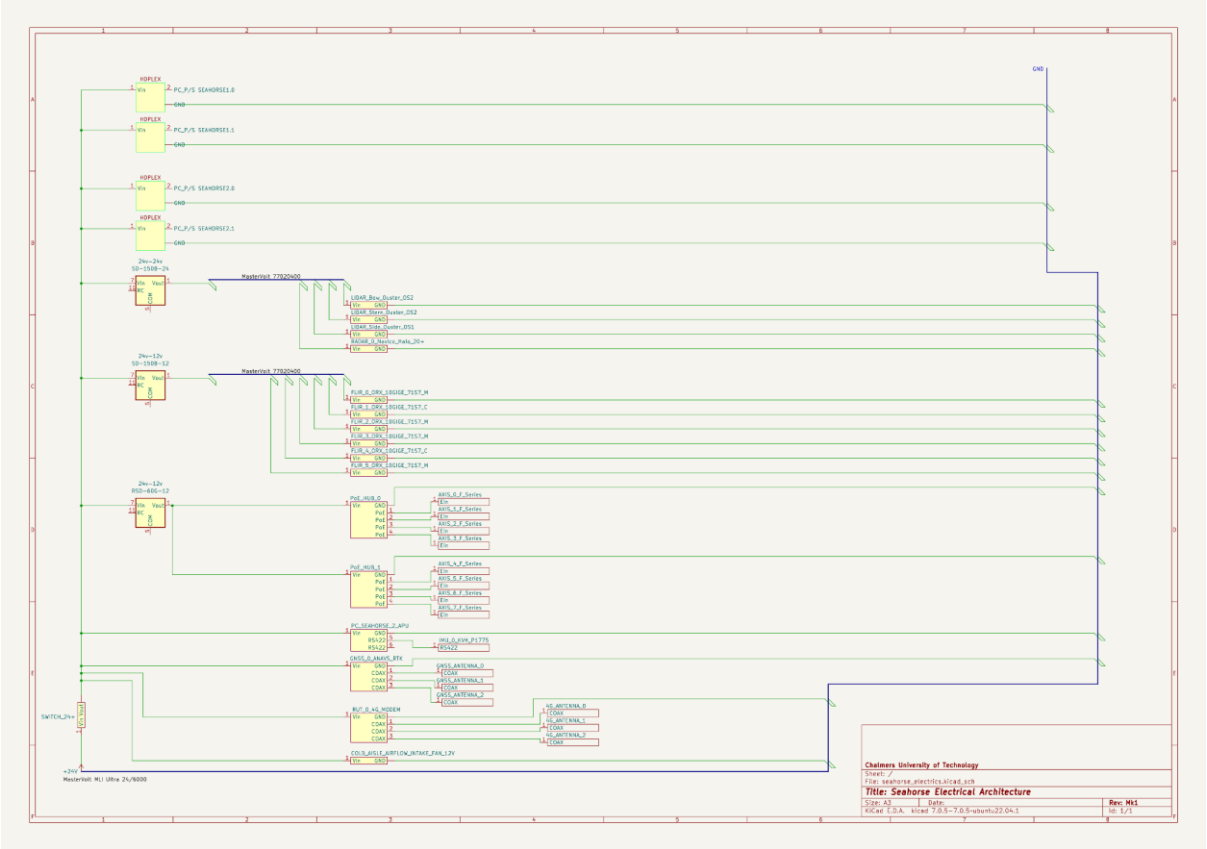

Figure 10: The SeaHorse electrical architecture, including all power routing of the direct current system, starting with the 24v MasterVolt 24/6000 battery system.

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4.2.2 Temperature control

Originally, the plan for the reeds project involved utilising an external water supply to cool the servers. However, that plan was made for a larger boat, and the decision to shift to a smaller boat was made after the purchase of an internal water-cooling system. The provided water-cooling system required airflow to move through the front of the server rack over radiators. Water was circulated through these radiators after transferring heat from the central processing units and graphical processing units. All other components in the system required airflow to achieve cooling.

A hot-cold aisle system, as standard with modern data centres, was built to separate the server box into two, with the forward compartment being designated 'cold' and the rear 'hot'. A 24v engine ventilation fan was installed to push approximately 3 m^3/min of airflow into the high-pressure 'cold' area. Within the server box, the airflow was restricted, so it redirected the airflow through the servers. The flow of air was aided by additional fans inside the servers strategically placed to focus airflow on sensitive system components. By implementing this air-cooling setup, the Seahorse project effectively managed the cooling requirements of the servers. As a bonus, the 'hot' compartment provided thermal heating for the MasterVolt battery, thus increasing the battery capabilities during the colder months.

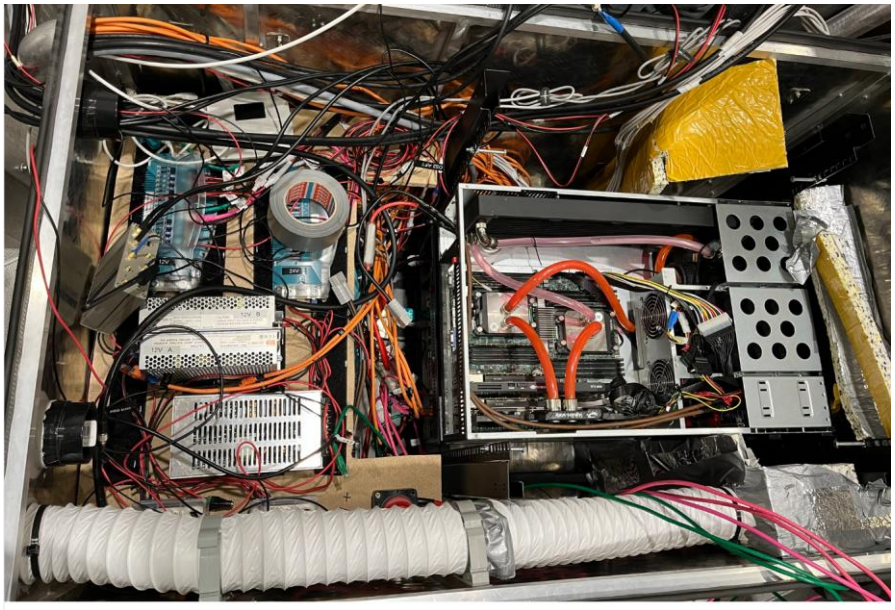

Image 5: The installation in progress of insulation between the hot and cold sides, as well as the installation of an intake vent for the 'cold' aisle.

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4.2.3 4K Cameras

Selection of visual sensors was based on the current industry trends for long-range, high-fidelity optics. The requirements for the vessel were that the visual range had to include the forward 180-degree arc whilst being able to provide the frame rates and resolutions outlined within the Benchmarking: Design section. For this, the camera requirement was that it was to be at least 2160-pixel vertical resolution, which is commonly referred to as 4K, whilst maintaining a frame rate above 60 frames per second. The last requirement was that the cameras be able to significantly distinguish objects in varying light. The FLIR Oryx 10GigE (Model 71S7) cameras met all of these requirements and provided a 12-bit depth image. This bit depth allows for a much higher colour range, giving the ability to distinguish objects in much brighter and darker scenarios. The FLIR cameras use the Bayer camera software layer, with FLIR's own software package acting as a broker. The FLIR cameras were chosen as they met these requirements and also due in part to the fact that the Revere lab had prior experience using and developing logic systems with the FLIR software. To reach the 180-degree arc, Edmund optics, providing a forty-two-degree field of vision, were selected, also due to the prior experience with these lenses at Revere lab. Multiple FLIR cameras with overlapping fields of view than provided the 180-degree arc.

One of the other notable features of these cameras is their compatibility with IEEE1588 clock synchronisation. This synchronisation functionality ensures that each image is precisely time-stamped with high precision. By leveraging this synchronisation capability, accurate timing information is associated with every image, enabling accurate synchronisation with other data sources and precise event coordination.

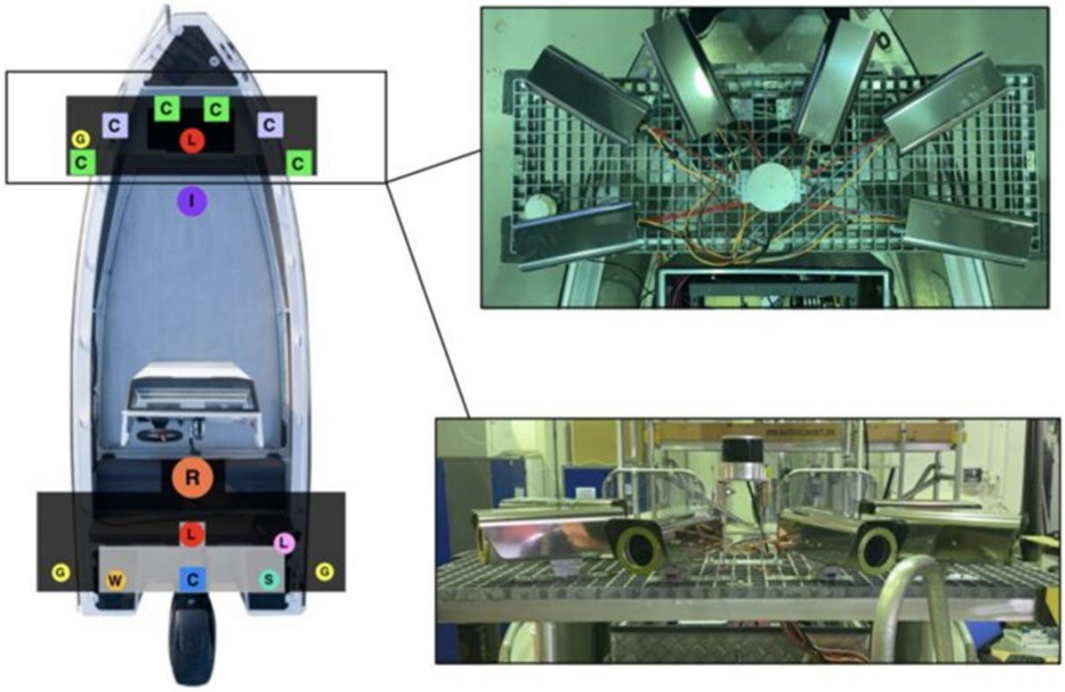

Image 6: 4K FLIR cameras mounted on Seahorse on the forward wing.

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***Specifications**:*

Name:	*FLIR Oryx 10GigE 71S7 Colour*		
Format:	*Bayer 12bit 4K*	*Bayer 12bit 1080p*	*Bayer 10bit 4K*
Frame Rate:	*87 (60*)*	*112*	*112*

Name:	*FLIR Oryx 10GigE 71S7 Monochrome*		
Format:	*Greyscale 12bit 4K*	*Greyscale 12bit 1080p*	*Greyscale 10bit 4K*
Frame Rate:	*87 (60*)*	*112*	*112*

**Frame rate is dependent upon computational load and operating temperatures. Initial datasets taken during colder weather conditions allowed for a continuous 87fps at full resolution and bit depth, however it was noted that during warmer conditions, frame rate stability was inconsistent. This also degraded when multiple cameras were run in parallel. Stability is given at 60fps when used with two cameras per compute node, and 30fps with three cameras per compute node.*

Data recordings statistics:

It was found that at 60 frames per second, at 4K, and at 12-bit depth, each camera generated approximately 3 GB/sec (180GB/min).

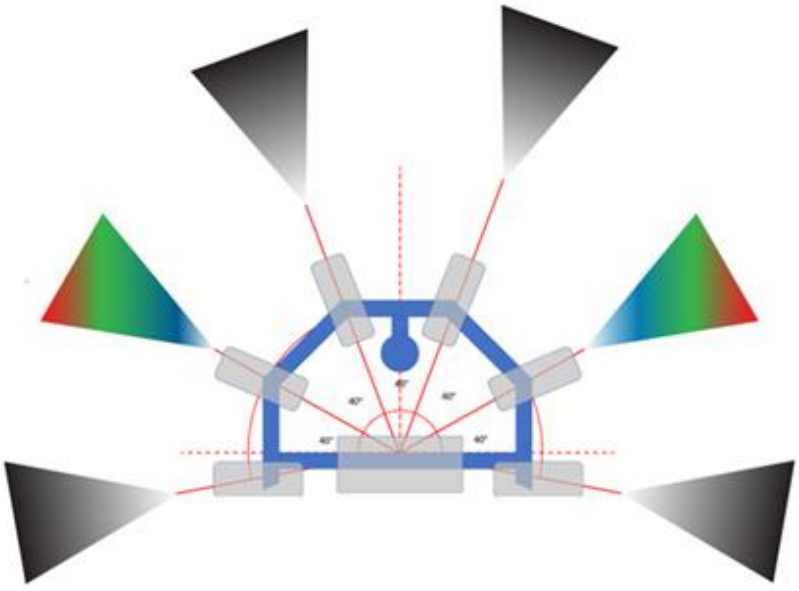

Image 7: FLIR cameras mounting positions with colour cameras covering port and starboard side for COLREG applications.

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The 180-degree camera configuration setup was carefully chosen specifically for the COLREG (Collision Regulations) application algorithms. The most common navigation markers within this schema are the red and green lights indicating left and right, which vary in context based on location. On vessels, they can be used to identify their angle, as well as the direction of travel, and when stationary in the environment, they dictate safe waters to travel through. The ability to accurately identify these lights enables mariners and future algorithms to adhere to proper navigation behaviour and avoid potential collisions.

Additionally, to the red and green lights, future camera systems need to recognize and interpret colour patterns of signal flags, navigational marks, emergency signals as well as other aids to navigation. Signal flags serve as important visual signals in maritime communication, conveying specific messages and indicating various conditions or warnings. By incorporating the capability to recognize these patterns, the camera setup enhances the overall situational awareness and decision-making process for the mariners. These signals are required to be detectable for a general-purpose autonomous system in the case that they should incorporate standards in 2023 and share navigable water space with human sailors.

The careful selection of the camera configuration for the COLREG application algorithm demonstrates a focus on ensuring that the reference data set can be used to develop the detection and recognition algorithms required for critical visual cues detection in the maritime environment. By accurately identifying navigation lights, signal flags, and other aids to navigation, the future algorithms developed would enhance the safety and efficiency of vessel navigation.

4.2.4 Lidars

The decision to select the Ouster lidar OS1 and OS2 was carefully made, taking into account their performance capabilities and pricing. When evaluating other lidar brands, we found that their prices were considerably higher, which would have restricted us to using only a single lidar unit. However, recognizing that lidar technology is relatively new to the maritime sector and that there are numerous unexplored use cases, we opted for a more flexible setup with three lidar units.

The inclusion of three lidar units allows us to leverage their unique strengths and cover a wider range of applications. Specifically, two of the lidar units are dedicated to long-range detection, with the OS2 model set to detect objects at distances up to 200 metres using a 10% threshold, while the OS1 model focuses on short-range detection with a 10% threshold at 90 metres. This configuration enables effective object detection during underway operations using the OS2 units, while the OS1 unit is primarily intended for dock and close-range mapping purposes.

By selecting the Ouster lidar OS1 and OS2 models, a balance between performance, pricing, and flexibility was obtained. This decision allows it to explore various applications within the maritime domain, leveraging the strengths of each lidar unit to address different scenarios and maximise the benefits of lidar technology in the project.

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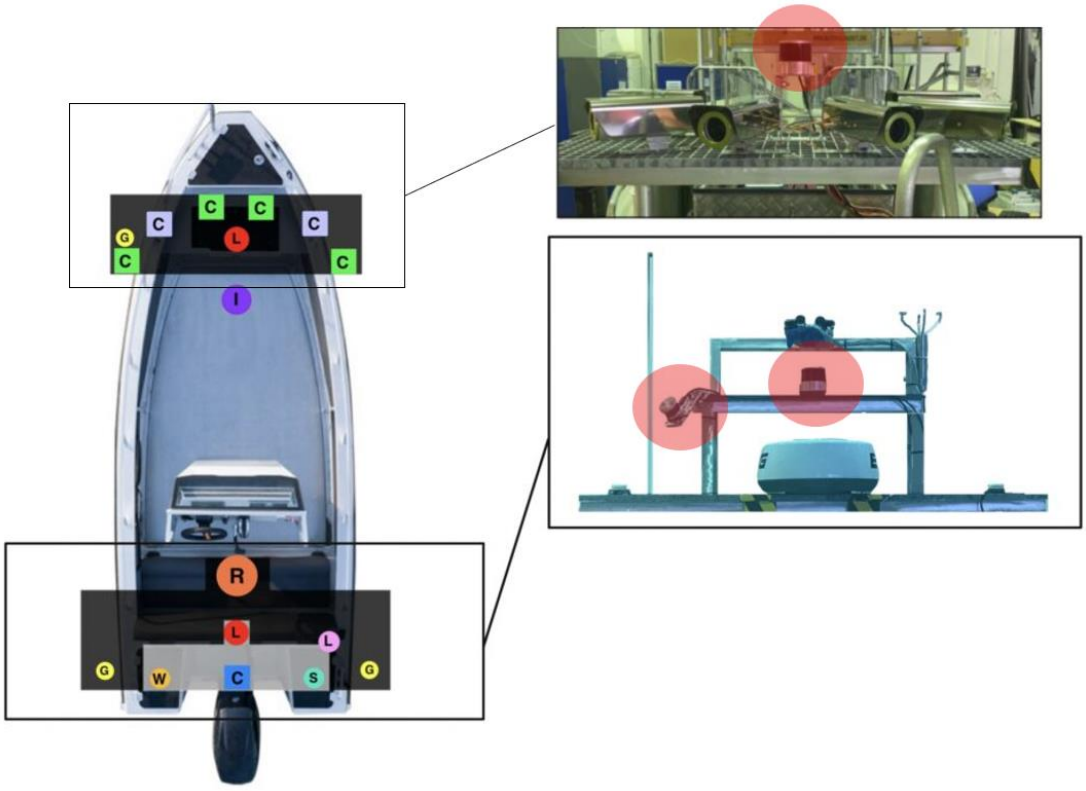

Image 8: The mounting locations of the Ouster OS1 and OS2 Lidars, situated on the forward and rear wings.

Specifications:

Ouster OS1

Location: Rear wing (Purpose mainly mapping at close range: rotated 45° from main travel direction and tilted 45°)

View angels: Horizontal 360° & Vertical 45°

Range: up to 120 metres (10% 90m)

Range accuracy: +/- 0.7-5 cm

Ouster OS2

Location: Front wing, Rear wing. Set for 360 horizon scanning. Oriented upright with no offset.

View angels: Horizontal 360° & Vertical 22.5°

Range: over 200 metres (10% 200m)

Range accuracy: +/- 2.5-8 cm

Vertical beams: 128

Data recordings statistics:

Each lidar captures 2.6M points per second, and with 3 lidars this totals 7.8M points/sec. At full resolution, this produces 14GB/min.

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Range measurement simple validation

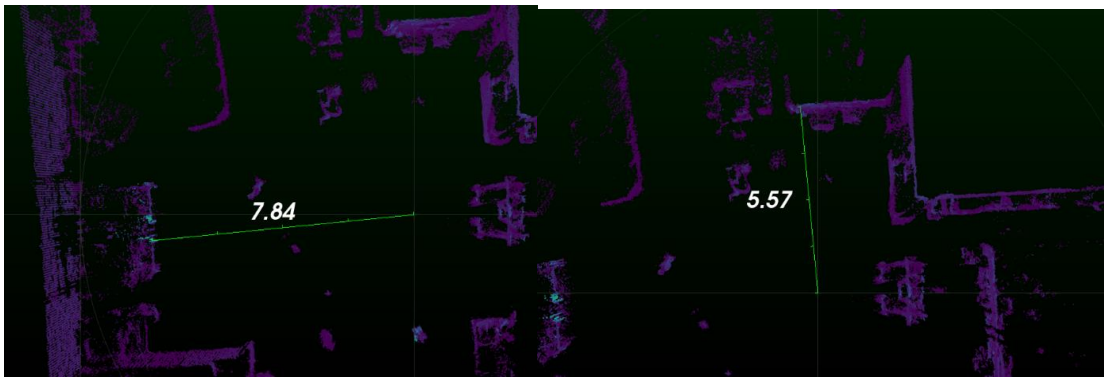

Figure 11: Lidar measure A to the left and lidar measure B to the right.

The measurement results revealed a slight discrepancy of 1 cm between the lidar and laser measurement units. The lidar range measured distance was compared to a laser measurement unit Bosch GLM 50-27C with a laser measurement accuracy +/- 1.5mm (*Bosch*, n.d.). To ensure accuracy, each measurement was repeated three times, and an average value was calculated. The measurements were taken straight ahead and to the side at a perpendicular angle.

By conducting multiple measurements and averaging the results, we aimed to minimise any potential errors or variations in the measurements. The chosen locations for measurement were carefully selected to provide reliable reference points for comparison. This rigorous approach helps to ensure the reliability and validity of the measured data.

Test result:

Measurement A: Bosch GML average 7.83m and OS2 average 7.84m diff 0.01m
Measurement B: Bosch GML average 5.58m and OS2 average 5.57m diff 0.01m

4.2.5 Radar

The 4K cameras and Lidars provide high-resolution, high-volume data at significantly high sample rates, but this data is limited to close-in ranges, and when applied to algorithm development, was tailored towards the operational and tactical decision-making strata. The decision to select a NAVICO Halo radar was based on the lack of long-range strategic decision sensors. Whilst the Halo provided a lower sample rate and lower resolution solution, it had the significant benefits of low costs, low power consumption, and a community-driven open-access API for accessing the raw radar data stream, as well as communicating with the unit to set parameters, whilst being able to provide ranges well above those mentioned above visual and light sensors. The lack of open-access APIs within the maritime radar domain made a feature comparison between other brands difficult, and it was quickly established that the performance and features of the Halo outclassed any other radar that had available software at the time of purchase.

Marine radar is a well-established and reliable technology for long-range object detection and tracking, making it a preferred choice within the maritime domain. It is the only technical equipment recognized by COLREG (International Regulations for Preventing

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Collisions at Sea) to be used for collision avoidance. Therefore, the technology is well established, and radar installations need to comply with radar performance standards and regulations designed explicitly for radar systems onboard SOLAS-classed ships (*MSC*, 2004). While the Seahorse does not fall under the SOLAS classification, it still requires a high-performance radar system suitable for its small size and operational domain.

Furthermore, mariners undergo training that includes the use of the radar, ensuring that the crew onboard has a solid understanding of radar performance capabilities as well as its limitations. This familiarity with radar enhances safety and promotes effective navigation practices.

In summary, marine radar's proven track record, recognition in regulatory frameworks, and the crew's training and familiarity with radar contribute to its widespread adoption and confidence as a crucial tool in maritime operations. In the future development of autonomy in navigation, the radar sensor is essential to include in sensor fusion applications for collision avoidance.

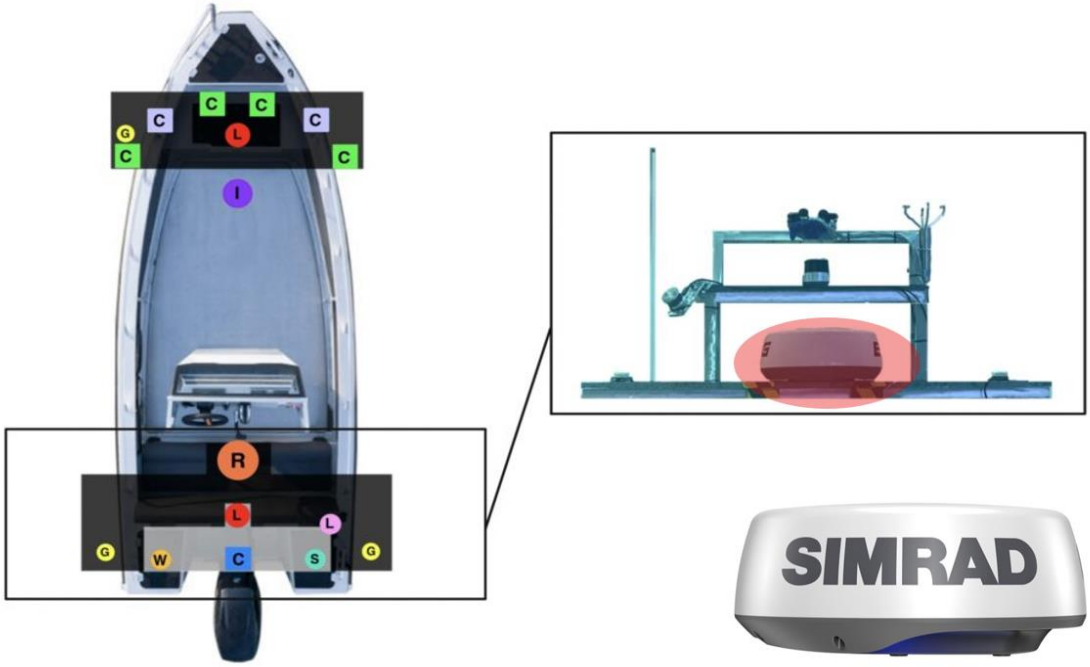

Image 9: The mounting location of the Navico (Simrad) Halo 20+ on the rear wing.

Specifications:

Name:	*Navico Halo 20+ (Branded B&G, Simrad or Lowrance)*
Type:	*Solid State doppler, X-band 9.4-9.5GHz, Dual range*
Angles:	*Horizontal 360° & Vertical 25°*
Range:	*30m - 67000m*
Rotation Speed:	*20 -60 rotations per minute*

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4.2.6 Ground Truth Sensors

To ensure that development of sensor and navigation algorithms are accurate, there needs to be a known measurement that is considered a *truth,* in that every other system must make the assumption that the data provided is accurate and precise enough that it can be measured against. For the Seahorse platform, this is provided by the IMU and GNSS sensors. To ensure these systems are consistently accurate and precise, the manufacturer data sheets must be verified, and systems must be in place to validate the sensor. Due to this level of scrutiny, the selection of the IMU and GNSS was considerably more in-depth.

4.2.6.1 IMU

The inclusion of a high-precision Inertial Measurement Unit (IMU) significantly enhances the accuracy and performance of the Autopilot system and other related equipment. The IMU, due to its swift detection of inertia, can provide more precise inputs for managing the steering gear with greater accuracy. This results in reduced instances of overcompensation by the rudder or pods, especially during manoeuvres such as turns.

The utilisation of high-precision IMU's is already widespread in the offshore industry, where they are used in conjunction with other sensors like wind sensors. The integration of a high-precision IMU allows for an earlier response to external forces, such as gusts of wind, which could potentially alter the vessel's heading or position. By promptly detecting changes in the vessel's orientation, the IMU enables swift adjustments to be made, ensuring optimal course-keeping and mitigating the effects of external factors.

The integration of a high-precision IMU offers several advantages, including improved accuracy of the Autopilot system and potential position keeping by dead reckoning to high accuracy. This is essential for navigation redundancy to GNSS as well as input to SLAM algorithms. Overall, it has already been shown that the adoption of a high-precision IMU contributes to enhanced safety and efficiency in vessel operations.

However, the process of selecting a model of IMU for the Reeds data collection must be done on the basis that not all IMU’s are highly precise or accurate. A number of IMU’s were assessed for accuracy, precision, errors, reliability, time precision, ease of use and stability. These included devices from Panasonic, Anello, OxTS and KVH. Three different technology systems were also evaluated, being Fibre-Optic Gyroscopes (FOG), microelectromechanical systems (MEMS) and mechanical accelerometers. The goal of this evaluation was to determine how much error was developed inside a system during a typical data collection run, in a hostile sea state (highly kinematic). In all of the assessed criteria, the FOG KVH P-1775 either provided significantly higher scores or the results were negligibly close.

The results also showed the expected level of bias, noise and other errors that would generate throughout a typical data collection run (Seen in Figure 12). Referring back to the limits of data storage on the platform, it was determined that the KVH P1775 did not generate measurable drift within the maximum time frame denoted by this limit. The unit also provided component temperatures, which showed that once self-calibration

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was complete, the unit remained at a stationary temperature and that there were no errors induced by temperature flux.

In summary, the KVH P1775 provides a 5000Hz, 9-channel IMU, with 32-bit precision for acceleration and angular rotation per channel and also provides magnetic field detection. It was determined that the unit would retain a level of precision and accuracy beyond the length of a typical data run and would hold reliably in harsh environments. The experimentation showed that the dataset could reliably trust the KVH unit as a *ground truth*.

	Roll	Pitch	Yaw
Panasonic			
N $\sigma \frac{rad/s}{\sqrt{s}}$	8.70E-03	1.03E-02	7.41E-03
K $\sigma rad/s \cdot \sqrt{s}$	2.72E-03	1.63E-06	2.60E-03
B $\sigma rad/s$	1.01E-04	1.02E-04	8.50E-05
Anello			
N	1.08E-04	1.47E-04	6.12E-05
K	4.99E-07	8.66E-07	1.96E-07
B	2.07E-05	2.19E-05	8.52E-06
Anello (FOG)			
N	-	-	1.44E-05
K	-	-	**1.22E-08**
B	-	-	5.91E-06
KVH			
N	*6.52E-06*	*6.24E-06*	*6.51E-06*
K	**1.50E-08**	**9.43E-08**	2.08E-08
B	5.92E-07	7.71E-07	6.49E-07
OxTS			
N	1.09E-04	1.13E-04	1.14E-04
K	5.58E-07	4.28E-07	6.30E-07
B	4.35E-05	3.75E-05	3.67E-05

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	X	Y	Z
Panasonic			
N $\sigma \frac{ms^{-1}}{\sqrt{s}}$	1.39E-03	1.30E-03	1.29E-03
K $\sigma ms^{-1} \cdot \sqrt{s}$	3.25E-05	4.76E-02	6.01E-05
B $\sigma ms^{-1}/s$	2.54E-03	1.46E-03	8.46E-04
Anello			
N	4.80E-04	4.54E-04	4.70E-04
K	8.16E-06	8.37E-06	1.17E-05
B	3.87E-04	3.84E-04	2.83E-04
KVH			
N	3.16E-04	3.17E-04	3.14E-04
K	5.28E-04	2.50E-04	9.27E-06
B	2.09E-03	4.16E-04	4.41E-04
OxTS			
N	*2.95E-04*	*1.54E-04*	*1.79E-04*
K	**2.29E-06**	**5.88E-07**	**2.67E-06**
B	6.88E-05	6.62E-05	6.55E-05

Figure 12: Results showing Velocity and Angle Random Walk (N), Rate Random Walk (K) and Bias (B) of comparable IMU's during Allan variance Testing. Bold, underlined and emphasised text indicates category leader.

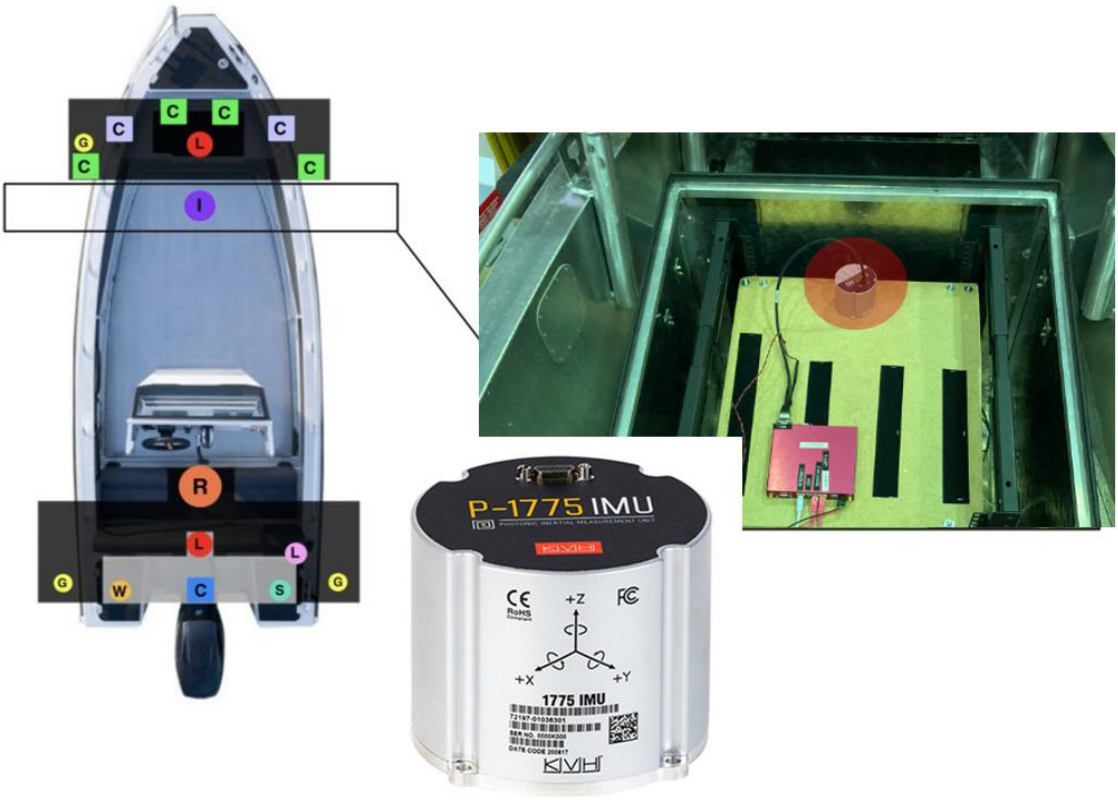

Image 10: Mounting location of the KVH P1175 IMU, located within the server box.

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Specifications:

Name:	*KVH P1775*
Sample Rate	*100-5000Hz*
Drift:	*0.001 rad/hr (angular rotation), 0.0025ms/hr (acceleration)*

4.2.6.2 GNSS

The decision to choose the ANAVS MSRTK was primarily influenced by the positive experience gained from previous projects involving ANAVS technology. The ANAVS MSRTK unit offered several advantages over traditional GNSS systems, making it a preferred choice.

One notable advantage of the ANAVS MSRTK was its high level of accuracy and precision in positioning. The Real-Time Kinematic (RTK) system uses a sensor-fusion approach to provide centimetre-level accuracy, which surpasses the performance of standard GNSS systems. This enhanced accuracy was crucial for the project's requirements to collect high-performance sensor reference data.

Furthermore, the ANAVS MSRTK unit was installed with three GNSS antennas, allowing for the obtaining of both heading and odometry data, including roll, pitch and yaw, as well as altitude. This additional information provided valuable data parameters to complement the reference dataset.

The final decision that cemented the use of this system as ground truth is that it also provides a real-time value for sensor confidence, as well as system redundancies for signal degradation due to jamming or line of sight loss. Whilst the user may not be able to have centimetre precision during these times, they will be informed of the current level of precision and accuracy available. With NTP time synchronisation, the database can be annotated with this information to allow users to develop their algorithms in sections where a certain level of accuracy is required.

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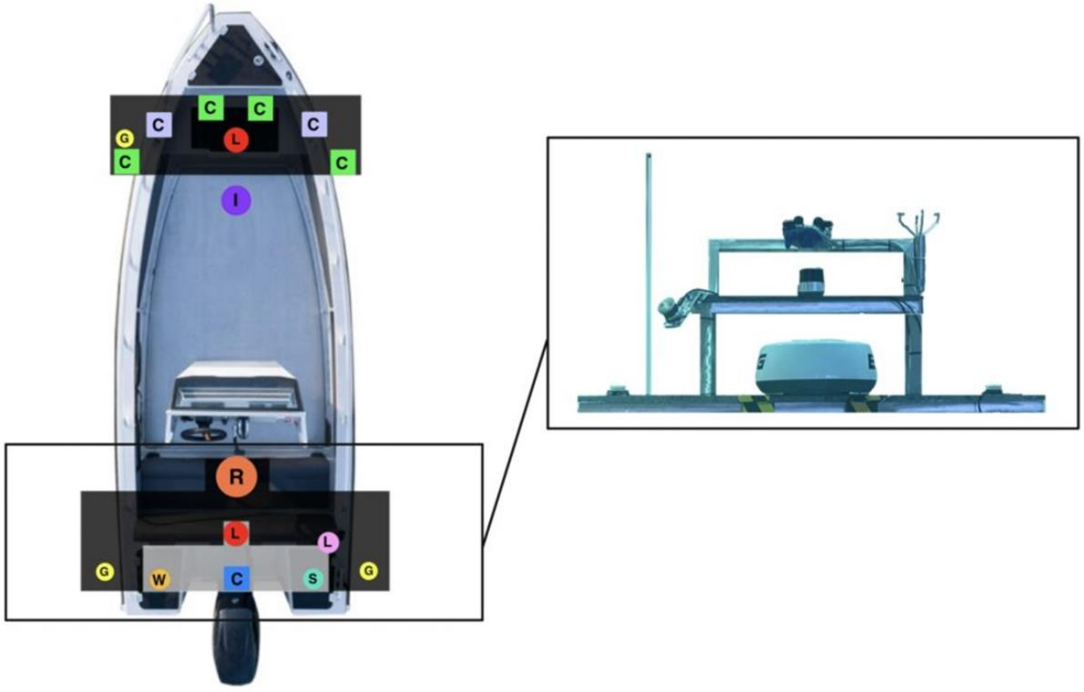

Image 11: Mounting location of the GNSS antennas, denoted with the 'G' symbol. The Ground Truth location is the XYZ coordinate between the rear two antennas and is provided as North, East cartesian, with altitude (in metres), above sea level.

Specifications:

Name:	ANavS® Multi-Sensor (MS-) RTK/PPP
Sample Rate:	100Hz
Accuracy:	RTK: 10mm horizontal, 20mm vertical, PPP: 150mm horizontal, 200mm vertical, RPY (Roll, Pitch, Yaw): 0.004 radians.

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4.2.7 Other sensors

With the established ground truth sensors, as well as the high quality and high-volume sensors, the platform was evaluated for the potential for other sensors based on power and storage requirements, prior work with Revere projects, future collaborations, as well any limitations found with the initial Mk1 SeaHorse setup. Initial findings were that the high volume of the FLIR cameras made real-time playback difficult, as well as data management difficult when objects of interest were found. This created a need for documentation cameras, which provided a manageable video stream and allowed for full 360-degree visuals. Likewise, there was a discussion on including low-trust sensors - namely, the information provided by external datalinks or other shared data spaces. It was found that AIS provided significant benefits to the maritime use cases, and whilst this is a very specific system and thus application-centric, it provides an additional data format for the maritime use cases. It is deemed useful enough to explore developing a system to capture it.

4.2.7.1 Documentation cameras

8 AXIS F Series cameras were strategically installed onboard to serve as documentation cameras, offering a comprehensive 360° view around the boat. These high-definition cameras are an integral part of the reference data set. Their primary function is to provide a situational overview of the surrounding environment near Seahorse.

One of the key purposes of these cameras is to aid in the analysis of sensor data. In cases where such as radar or lidar detects unknown objects, the cameras can be utilised to easily visualise and playback the captured footage. This enables a deeper understanding of the events or objects in question.

By incorporating the AXIS F Series cameras into the system, the project benefits from a reliable documentation solution that offers a wide field of view. This ensures that any potential anomalies or noteworthy observations can be effectively recorded and reviewed, enhancing situational awareness and facilitating a comprehensive analysis of the boat's surroundings.

4.2.7.2 AIS and VHF

The choice to incorporate RTL-SDR (Software-Defined Radio) was driven by the desire to capture AIS (Automatic Identification System) and VHF (Very High Frequency) traffic as part of the comprehensive data collection for COLREG compliance. However, due to privacy regulations such as GDPR and the confidentiality of VHF communications, the recorded data is not stored or saved.

The decision was made to obtain AIS data from the Swedish Maritime Administration Sjöfartverkets AIS data stream. This choice was influenced by the fact that some logging sessions with Seahorse are relatively short and may not capture all the metadata included in the AIS messages. For instance, information such as ship dimensions is sent at a slower update frequency compared to vessel positions. By accessing the Sjöfartverkets AIS data stream, we can ensure a more comprehensive and all lower frequency messages

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are included to allow a complete AIS data situation awareness for the data recordings scenarios.

The VHF RTL-SDR unit deployed in this project serves the purpose of providing real-time monitoring of marine radio frequencies. It allows for the immediate reception of VHF transmissions, which can be utilised for ongoing research and analysis. It is important to note that the system does not retain voice recordings from the VHF channels, ensuring compliance with privacy laws and maintaining the confidentiality of sensitive information.

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4.3 Platforms description: Landkrabban

"Landkrabban" is a Swedish term used to describe individuals who lack experience in seafaring. This term sets the context for the platform named Landkrabban, which serves as a shore-based sensor platform. The Landkrabban platform is designed to facilitate a flexible setup of sensors, and its modular and lightweight construction enables convenient transportation.

The primary objective in utilising the Landkrabban platform was to conduct experiments focused on low-cost and novel sensor types with the aim of assessing their performance and test use cases for shore-mounted sensor applications that observed a port or fairway area. By evaluating various sensors and use cases, it was possible to gather comprehensive insights into each sensor's potential to increase safety or aid future marine systems with a higher degree of autonomy.

The versatility of the Landkrabban platform proved invaluable as it enabled sensors to be mounted quickly at different locations and to explore diverse combinations of sensor setups. This flexibility allowed for the coverage of a wide range of scenarios and to gather data from multiple perspectives.

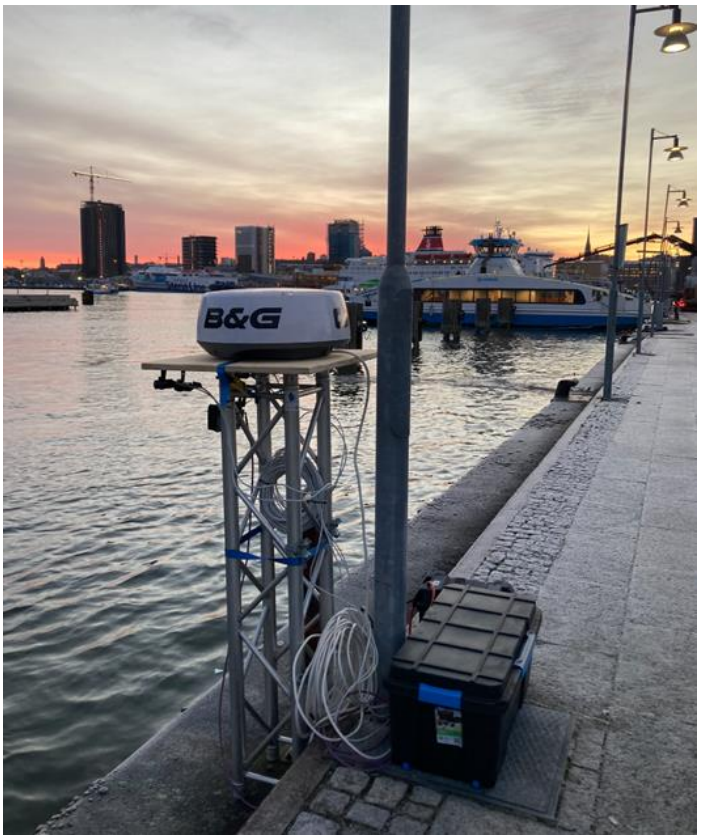

Image 12: Landkrabban installed on Lindholmen for data collection with vehicle radar and complementary sensors for performance comparison.

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4.3.1 System Architecture

The Landkrabban platform consists of several key components, including the Sealog logging computer, a 4G router, and a power supply system. The power supply system can be configured using car batteries, offering options for both 12V and 24V setups, an overview is found in figure 13. Additionally, if a 230V power supply is accessible, a charger can recharge the batteries.

The Sealog logging computer serves as the central unit for data collection and storage on the Landkrabban platform. It is responsible for recording and managing the sensor data obtained from various connected devices. To ensure connectivity and remote access, a reliable 4G router is incorporated into the Landkrabban setup. This allows seamless communication and data transfer between the platform and external systems or users.

The power supply system, which can be powered by car batteries, offers flexibility in terms of voltage options. This allows for compatibility with different sensor and equipment requirements. If a 230V power supply is accessible at the location, a charger can be used to recharge the batteries, ensuring the uninterrupted operation of the Landkrabban platform.

The truss structure is a versatile mounting that provides stability and flexibility, allowing for the positioning and alignment of sensors according to specific requirements. The Landkrabban sensor installation and alignment are preferably done in a laboratory environment and later moved to the actual data recording location. This enables researchers or technicians to conduct controlled experiments before data collection and develop software components in a controlled environment.

Overall, these components form the core infrastructure of the Landkrabban platform, enabling efficient data logging, connectivity, and power management for various sensor applications.

Specifications:

Mounting:	Truss 2m high
Computer (Sealog):	TLSense 10210U (Intel i5, 4GB RAM)
Battery:	2x 12V 75Ah

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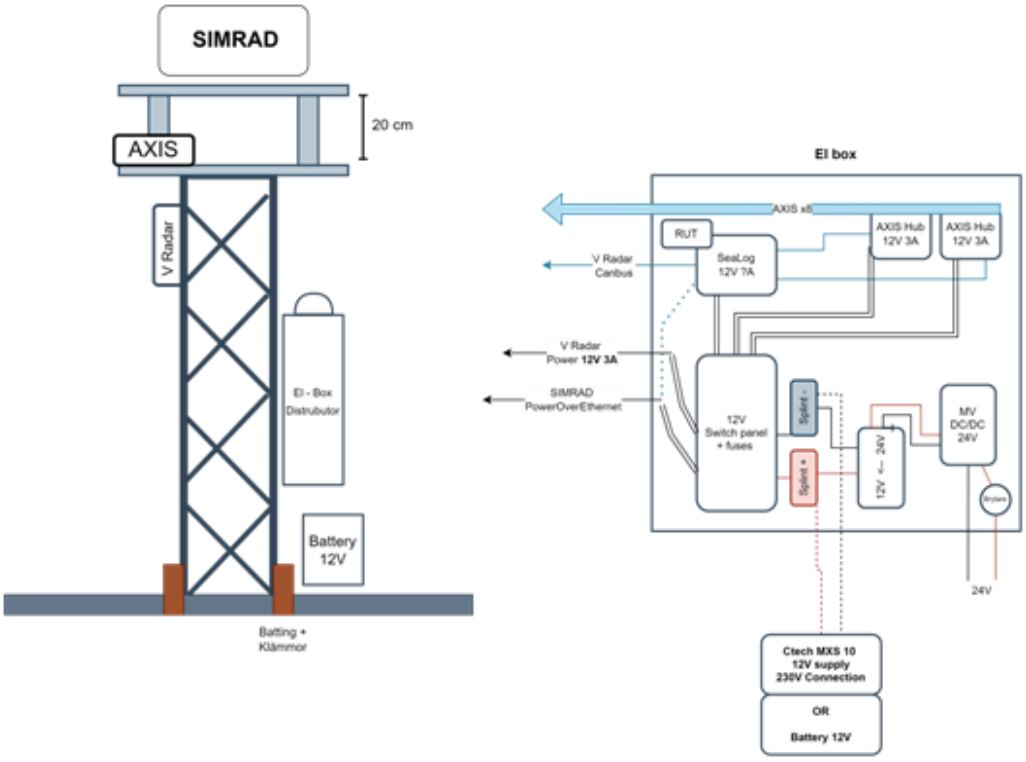

Figure 13: The general arrangement of Landkrabban.

Image 13: Seahorse on a trailer, can also be utilised as a fixed shore sensor platform for a location that provides sufficient manoeuvring space for parking the trailer.

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4.3.2 Software setup

The Landkrabban software for data logging and sensor connections are configured with either Crowsnest or OpenDLV connectors, which are managed within Docker containers. The setup involves utilising Docker Compose files to configure and manage these containers effectively. This approach ensures a streamlined and organised documented environment for the microservice components, facilitating efficient data logging and seamless sensor connections.

The configuration and setup details can be found as open source on GitHub under the organisation MO-RISE.

Direct link to Github: https://github.com/MO-RISE/platform-landkrabba

4.3.3 Crowsnest user interface

The Crowsnest is a research platform accessible through any web browser and built on the react framework for visualisation of real-time data and using a microservice architecture where docker containers are used as connector or processor nodes. The purpose of the platform is to be able to easily design our own interface to connect sensors and process raw sensor data along with modular applying algorithms in whatever way is deemed suitable for the intended purpose.

This means that it has the benefit of being accessible from anywhere as long as there is a connection local or over IP, and one screen can show the user any number of different inputs from sensors.

Direct link to Github: https://github.com/MO-RISE/crowsnest

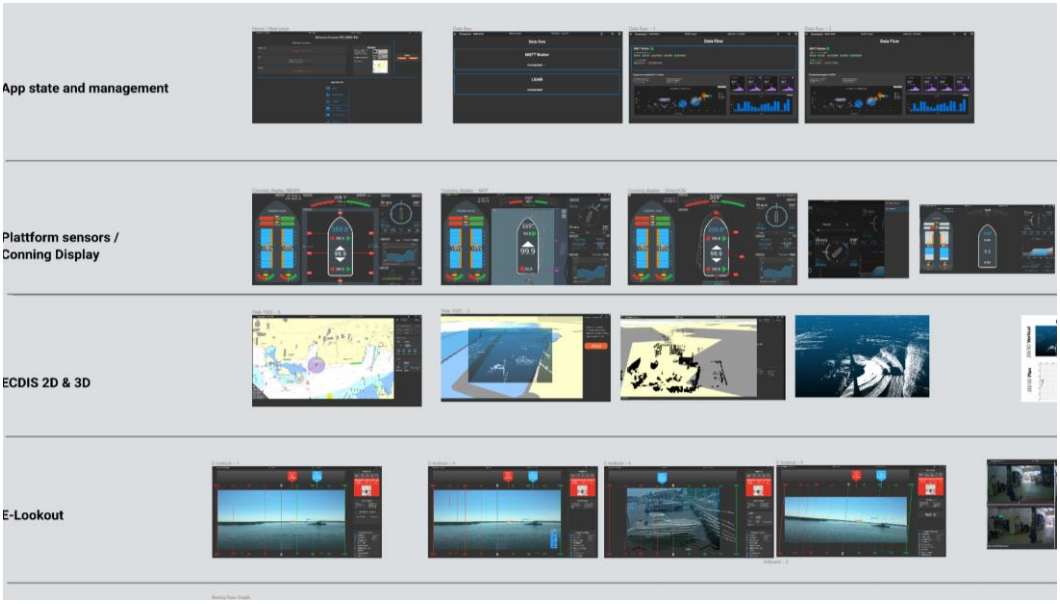

Image 14: A selection of Crowsnest mock-ups under development.

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4.4 Summary of sensor performance

This section provides an overview of the selection criteria for each sensor type, taking into account their suitability in the marine environment. Factors considered include weather conditions, ship motion, and operating ranges. It is important to recognize that no single sensor type is universally suitable for all conditions and operations. Therefore, the integration or fusion of multiple sensors is necessary to accurately capture and create a digital representation of the marine environment above the water surface for autonomous ships or surveillance. By combining the data from different sensors, a more comprehensive and reliable understanding of the marine environment can be achieved. It can be concluded that thought and planning are advisable to mitigate external noise that can be reduced significantly by using mountings and physical structures that can aid the sensors in their operational reliability, which will reduce malfunction and misrepresentation of data.

4.4.1 Comparison table of perception sensors

Based on literal review and own experience using the sensor following comparison table was generated:

- Slight - Influences that cause small errors on special occasions.
- Moderate - Influences that cause perception error up to 30% of the time.
- Serious - Influences that cause perception error more than 30% but lower than 50% of the time.
- Severe - Noise or blockage that cause false detection or detection failure.

System	Operational Range	Frequency/ Wavelength	Heavy Rain >25mm/h	Mist	Snow	Dark	Strong Light
Lidar: Ouster OS1	<120m	Near Infrared 865nm	Moderate	Severe	Severe	No effect	Moderate/serious
Lidar: Ouster OS2	<240	Near Infrared 865nm	Moderate	Severe	Severe	No effect	Moderate/serious
Camera: FLIR	Line of sight	Visible light spectra	Serious	Severe	Moderate	Severe	Severe
Camera Axis	Same as FLIR	Visible light spectra	Same as FLIR	Same as FLIR	Same as FLIR	Same as FLIR	Same as FLIR
Radar: Navico (X-Band)	Line of sight, display down to 0,25NM ~ 463 metres on commercial larger vessels	3cm ~9GHz	Serious	Slight	Serious	No effect	No effect

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Table 2 comparison of sensor perception performance.

In summary, all the sensors used throughout the project can both be utilised on and offshore (except for the IMU which is not useful on stationary equipment). The table above describes the operational ranges and other factors that may limit one sensor, but another might not have the same restrictions. This will be useful when designing the requirements standards to make a system that is reliable with sufficient redundancy. For instance, a lidar, camera and radar setup should be very reliable in different weather situations and object tracking and verification can be accomplished on different sensors simultaneously for verification. Although the radar may be difficult to represent in a 3-Dimensional environment for a human user, the other sensors could accomplish just that and be used when a human is needed to monitor a specific situation.

4.4.2 A start to develop sensor functional requirements for ships manoeuvring in port or restricted water

Discussions and workshops conducted with maritime experts such as pilots and VTS operators and representatives from the maritime industry resulted in the following suggestions as a starting point to develop functional requirements for future perception system for monitoring of ships movement in restricted water or manoeuvring in port.

- Track and monitor smaller bots moving near the ship based on sensor measurement, for example tracking the pilot boat under boarding operation.
- Detection of small objects floating on the surface such as life rings and floating debris, at a distance such vessels can take appropriate action after detection.
- Distance measuring between ship and infrastructure should be available under manoeuvring from sensor measurements.
- Sheared sensor ashore and onboard connected by a data link to assist in areas with an obstructed view should be optional to be displayed and visualized clearly and distinguishable. The data link state and latency need to be clearly communicated to the user.
- For the sensor determined as operational critical a redundancy system should be available to allow continuous operation in case of sensor breakdown.
- Continuous monitoring of sensor state and operational conditions is needed and should be accessible to operators and other systems.
- System capable of operating in weather conditions according to deployment areas 95% weather conditions and severity.

To gain trust in the new system evaluation and testing are needed, but there is a lack of standardised methods for testing perception systems in the maritime context. The report section on benchmarking includes just a few examples of validation odometry and improved camera images for object detection. However, for future assessments of both sensor and algorithm system performance, a clear evaluation method or a comparable approach is required. The project explored just a small set of validation methods to a limited extent for benchmarking. Nevertheless, the availability of raw sensor data in the reference dataset now allows for the possibility of testing additional validation methods more effectively in the future by learning from the algorithm benchmarking.

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4.5 Automotive radar in a maritime environment

This work primarily concentrates on exploring the potentials and challenges of using existing radar technology, originally developed for the automotive sector, in the context of shore-mounted marine support systems. The objective is to utilise a cost-effective, short-range, directional radar system capable of effectively tracking objects within confined water areas. By leveraging radar technology already available, this approach could offer a viable solution for monitoring and tracking purposes in restricted marine environments.

The most common type of radar today for automotive applications is likely some form of chirping type working in the 76-81 GHz frequency band (typically around 77 GHz) (C. Waldschmidt, J. Hasch and W. Menzel, 2021). A typical example of a chirping radar is Frequency Modulated Continuous Wave (FMCW). Even though not all chirping radars are FMCW, they often share the same advantages, and for ease, the radars discussed here will be referred to as such even though it is not strictly true.

Previously radars working at 24 GHz has also been common, but changes in regulation and higher demands on resolution have forced a move away from this band. The smaller form factor is possible, the higher frequency has likely also been an attractive feature for the automotive industry. The Narrow Band (NB) Industrial, Scientific and Medical (ISM) at 24 GHz is still available for applications with lower demand on range resolution (*Advantages of 77 GHz Automotive Radars Over 24 GHz Systems*, 2019).

To piggyback on the advances of the automotive it is thus likely preferable to focus on 77 GHz FMCW radars, but some of the principles should still be valid at other frequency bands as well.

The marine environment is likely to place high demands on the robustness of the sensors and their performance in adverse environmental conditions. Similar demands are likely found for automotive radars where the suppliers assure that they should also work e.g., in areas with wintry conditions using salt on the roads or during great precipitation. From correspondence with a sales representative, this has also been confirmed at least with that supplier, who claims their units to be fully functional after extensive salt spray testing performed in accordance with DIN EN 60068-2-11.

4.5.1 Typical output and performance specifications

Oftentimes automotive radars are separated into long- and short-range. They typically differ in their intended use case. In automotive applications, a range of 200 m is typically considered long-range. In general, the data is processed in the radar unit, and the output of the radar is a list of targets, objects or similar. The FMCW-type radars should be able to separate detections in range bins, velocity bins and angular (azimuth) bins. Some automotive radars also have a limited ability to locate/separate detections by elevation angle. Depending on the underlying algorithms the detections may or may not be grouped into objects and tracked over consecutive frames for further analysis.

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4.5.2 The typical range and field of view of automotive radars

Automotive radars may have different demands on the range and size of the field of view (FoV) depending on their typical use case and the direction they are expected to be looking. Generally, there should be expected to be a trade-off between range and range resolution. This is normally not an issue as it can easily be argued that the importance of good range resolution increases with shorter range and long- and short-range radars can be combined if needed. For angular resolution, the case is reversed as a better angular resolution will be needed to separate targets at a larger distance.

The range and FoV of automotive radars are most likely adapted to their intended use cases. The demand on the range is much higher in the forward-looking direction to be able to predict what is coming. It could likely be assumed that most roads are not wider than 20 m or so (even though there are some extreme examples to be found), and it is probably due to such reasoning that many long-range radars, intended for looking forward, have a quite narrow FoV. In close-range scenarios, such as lane changing, parking, or city scenarios, higher range resolution and a wider FoV are likely prioritised. It is not uncommon to see a suggested combination of several wide FoV, and short-range radars for a full 360 FoV around the ego-vehicle.

As radar technology has progressed it seems both range and FoV has been expanded. Better processors, faster radio chains and sampling rates, and a move from mechanical sweeping to arrays using digital beam forming could all be examples of improvements that could help improve both ranges, FoV, as well as resolution thereof.

The typical range and FoV of older generations of front-looking long-range automotive radars were in the lines of 200 m range and an FoV of <20°. A radar used within this project e.g., has a range of 200 m and FoV of 17 ° (see Figure 14), which could likely be considered sufficient in many automotive use cases. It does however not quite reflect the possible performance of more current systems. As an example, the latest generation radar from the same manufacturer has a standard range of 300 m, which can be extended up to 1500 m for larger targets, and an FoV of 120° (see Figure 15 for comparison). The later generation also has the ability to distinguish the direction of the reflections in the elevation plane, so that it can clearly distinguish a low overpass from a wall. Similar specifications can be found from other manufacturers as well.

4.5.3 Experiments and results

Through a previous project there has been a 77 GHz FMCW type automotive radar available. The radar in question is a Continental ARS308-C for which the CAN database and message list are available, such that it was fairly straightforward to develop a program to connect to the sensor, read out the sensor output, and format the data to fit into a clean message so that it can be collected in the same manner as the other sensors already in the project.

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The main advantage of using this radar is that it was readily available. The latest generation of radars also appears to have been released quite recently, and the price tag is still quite high compared to the older ones. If acquiring a sensor for further development, it could be advantageous to ensure that some insight into the detection and tracking performed by the radar is readily available as the intended use case of the Reeds project differs from the typical use case of the sensor units and thus possibly also their built-in detection and tracking algorithms.

From the sensor used, a list of detections was extracted which each have a position, signal strength and velocity associated with them. The position is expressed in a range from the sensor and azimuth angle relative to the centre of the FoV. Signal strength is expressed as Radar Cross Section (RCS). For velocity, it is only the radial component, relative to the sensor, of the velocity that can be directly extracted at each single measurement instance. Using clustering algorithms and object identification it is likely possible to extract the velocity of an object by tracking it over several measurement frames, but that process is not as straightforward.

The experiment made an overlay of automotive radar detections and a map of the area on Lindholmen in Gothenburg where commuting ferries are docking. Both long and short range was used and the FOV angles can be seen in Figure 15. As the FVO is optimized for road use the section did not cover the entire are of interest. In figure 15 spots and arrows visible indicate radar detections. The colour from yellow to red corresponds to the intensity of the detection. Detections marked by arrows indicate the velocity of that detection point with the size corresponding to the velocity. The red oval marks detections related to a turning vessel where the detections in the front have a clear radial velocity while the detections further towards the rear look to almost be at a standstill. An image of the vessel can be seen in image 14.

An 5th generation automotive radar FOV would cover most of the area if interest as in the performed experiments for easier comparison. For smaller/less reflective objects (e.g., kayaks or stand-up paddle boards) the range is likely heavily reduced towards the edges of the FoV in the azimuth.

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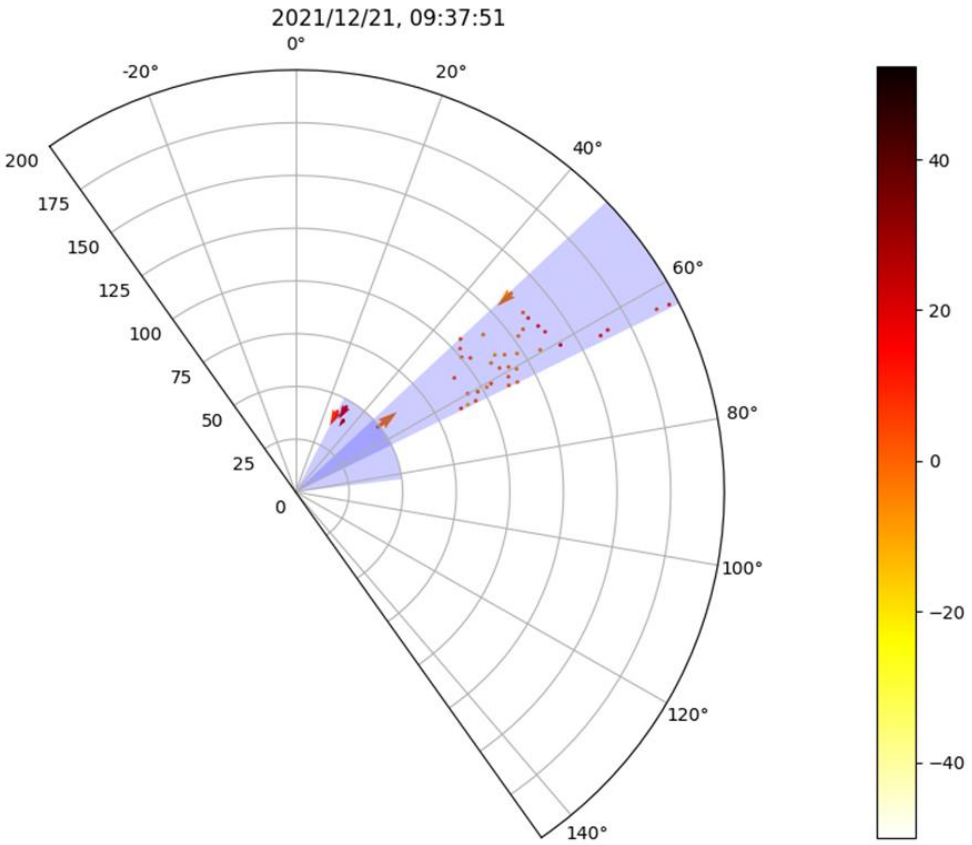

Figure 14: Radar detections without map overlay plotted relative distance in meters and angels in degrees with 0° as northerly direction. The colour bar shows how the colour of the detections relates to the RCS in dBm2. The position of the detections is at the base of the arrows.

Image 14. Image frame of approximate moment corresponding to presented radar frame.

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As we can see in Figure 14, a vessel may produce several different detections. Since the velocity reported by the radar is always only the radial component, relative to the radar, an object covering a large number of azimuth angles may have different velocities reported for different parts of the object. As the object is rigid, and thus there should be some correlation between the movements of its different parts, it could be possible to derive an average velocity of the object as well as an estimate of the rate of turn and the location of the pivot point from these velocities, even without the full velocity information of each of them individually. This exercise has not yet been performed and will be left for future work.

In Figure 15 a sketched example is provided to help understand what the vectors indicate and what is actually measured by the radar.

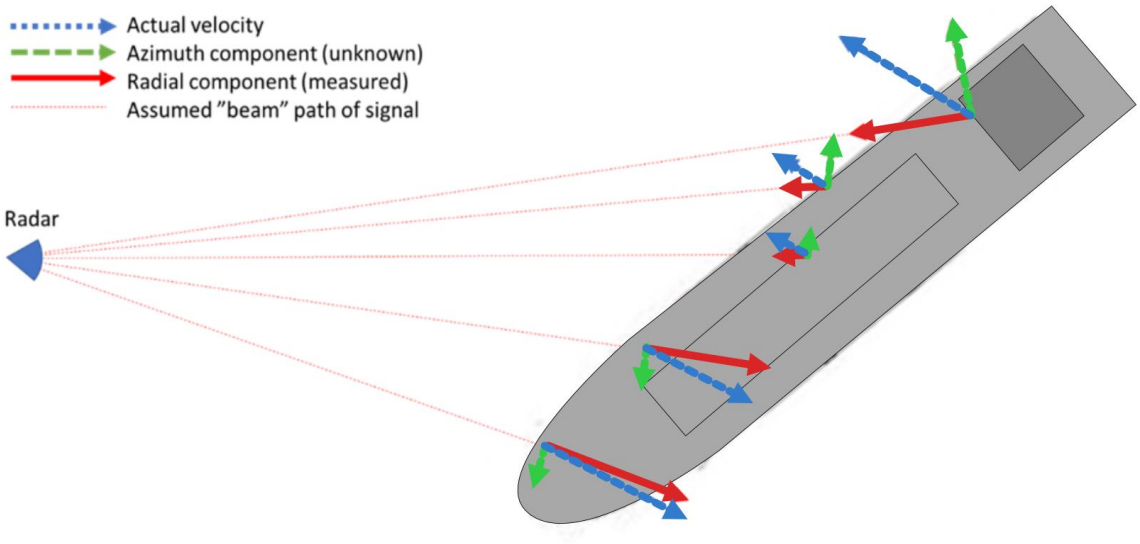

Figure 15: Examples of imagined detections with position and velocity components relative to the radar are indicated. The red arrows indicate the radial component of the velocity, which is the one directly measurable and reported by the radar. The green arrows represent the unknown azimuth component and the blue arrows, the actual resulting relative velocity. To clarify which components are measured the imagined beam path from the radar to the detection points is also included.

4.5.4 Further future Possibilities

When using stationary sensors some prominent features of the surroundings should be expected to recur in the measurements. This could likely be of great advantage to continuously evaluate the performance and reliability of the sensor by inspecting such recurring features at different detection ranges and angles. This would likely be useful for noise reduction and/or predictive maintenance of the system.

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4.6 Automotive lidar in a maritime environment

Lidar technology has gained significant attention across various industries for its exceptional ability to create geometrical representations of the surrounding environment. However, its application within the maritime sector has so far been limited. With the expected mass production of lidars in the automotive industries, the unit price will drop. It was estimated in 2022 from Mercedes' optional high-end safety packet that their lidar unit cost is about 500€ (Rangwala & Danise, 2022). Nevertheless, recent developments indicate that lidar sensors hold great promise in enhancing maritime safety and improving perception in situations where traditional radars are inadequate for the task, particularly at short distances. By leveraging lidar's capabilities, maritime operations can benefit from enhanced situational awareness and improved safety measures.

Lidar, light detection and ranging in analogy with radar, is an active sensor which means it is relatively insensitive to ambient lighting conditions such as shadows, glare and darkness. Time-of-Flight (ToF) sensors are the most common, where the emitted laser light, sent as a short pulse, is reflected at an object and the returning signal is sampled. Most lidar scans the environment in different directions by a sweeping pattern sometimes possible to change by the user at runtime. The beam scanning is periodic and the collected data within a period, often called a frame, returns a point cloud data format. Some sensors return a 2D projection, that is, an image data type including depth. The scanning pattern of the beams determines the two angles in a 3D polar coordinate system and the distance is calculated from the time sampled data knowing the speed of light. The sampling is fast enough (a few ns sampling time) to allow for an accuracy of some centimetres, which is enough for automotive applications, and it should be quite enough for marine applications. Each point in the point cloud usually has at least the following properties: time of hit, returned intensity, and location (in polar or cartesian coordinates).

There are different technologies that generate a beam scanning pattern over the intended field-of-view. The scanning can be achieved for example by mechanically rotating mirrors, which is used by the Ouster OS2. To be more robust, many manufacturers go for "solid state" which means no motion (e.g., optical phase array) or micromechanical systems with small mirrors moving. Another technique is to flash momentarily instead of scanning the emitted light (Li & Ibanez-Guzman, 2020). The number of approaches might be a sign of a pre-industrialization and ongoing development in search of a suitable robust, compact and capable sensor.

The spatial distribution of (possible points in) the point cloud is typically non-uniform. The Ouster OS2 lidar used in this project is mechanically rotating 360 degrees having 128 swept non-uniform distributed layers perpendicular to the rotating axle. As a result, the number of points that hits a non-moving object depends not only on the distance to but also on its orientation and location relative to the sensor. Most lidars do not collect a point cloud momentarily sampled, which means that dynamic objects will move during

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the sampling of a frame. Depending on the application, this distortion needs to be corrected.

The emitted laser beam is divergent, rendering a larger area projected at an object further away. An object of low reflectivity and an object at long distance return less energy back to the sensor and is thus less likely to generate a point in the resulting point cloud. A single laser beam will occasionally hit multiple objects, e.g., an edge in the foreground and then also a hit in the background in the same direction, giving rise to more than one point in the cloud. A laser beam can of course also bounce on a specular surface. Retroreflectors, like reflexes on road signs, might be of concern for some types of devices.

The wavelength of the laser light is often close to visible light (near-infrared), typically 850-950 nm or 1550 nm, where the latter gives a range advantage of admitting higher optical power while keeping eye safety within prescribed limits (*An Introduction to Automotive LIDAR (Rev. A)*, n.d.). The range depends on the reflectivity property of the target. For the Ouster OS2 and for an object that diffusely reflects 80% of incoming light the probability of a detection at 210 m is 90% (*OS2 Long-Range High-Resolution Imaging Lidar*, 2021). This means, for example, that a 150 m long ship at a distance of 300 m, which potentially will be hit by many lidar beams but all returns will not always be detected. The net effect is that the ship appears as glimmering when looking at the object frame by frame, thus calling for additional filtering.

4.6.1 Experiments with tracking based on lidar

The aim with the study presented in this subsection is to show how a land-based lidar sensor can complement GNSS based positioning and prediction. There are three reasons to request this. First, the position of the antenna of the on-board GNSS might not be correctly assigned in the AIS. Second, the accuracy of the satellite position can vary tens of metres compared to ground truth from time to time, which is cumbersome when the vessel is close to a fixed structure in a harbour. And third, redundancy gives a more resilient system. The motion of the vessel(s) should be presented graphically in a user-friendly format. It is straightforward to present the raw data from sensors for example as an overlay to a 2D chart, but the task here is to, based on the raw sensor data, estimate the position, orientation, and velocity. This can be presented graphically on a chart in real-time where it also is possible to measure distances between arbitrarily assigned points.

Depending on actual circumstances involved in the measurement task, a set of assumptions can be made. In this study, it is among other things assumed that the size of the vessel is not restricted within reasonable limits; the dimensions and the orientation are unknown. Further, the position of the sensor relative to the vessel is not chosen to always facilitate the task of estimation motion.

A basic challenge is the absence of a coordinate system of the target. If the dimensions of the vessel are estimated, an origin defined by means of the shape, might change. Another challenge is the non-defined relative position and angle between sensor and target, for example a worst case is found when the vessel is so close only a small part is seen. A third

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challenge is the undefined initial conditions. A fourth challenge, connected to the local coordinate system, is a question of how to determine its orientation in the longitudinal direction.

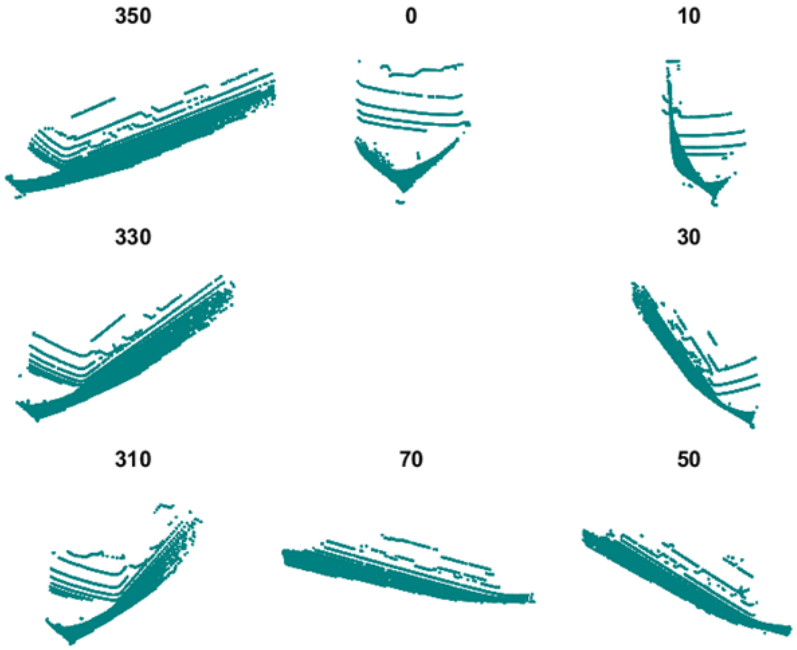

Figure 16: The sensor only sees one projection and is not guaranteed to see over to the far side of the object, thus cannot safely determine the object's extension in that direction. Numbers represent bearing from ship to sensor.

Figure 16 shows an example of the RoPax ferry Stena Jutlandica from different angles when she turns around in Göta älv river prior to mooring. The point clouds look quite different depending on the angle of orientation (or bearing seen from the ship). This makes it more difficult to estimate its orientation, length and width. Typical point cloud registration algorithms, for example Iterative Closest Point method (*Iterative Closest Point*, n.d.), for estimating the rigid transformation matrix between two instances will work worse; consider for example the case of zero degree bearing: the shape of the point cloud changes considerably when the side of the ship suddenly, that is with a bearing angle change of about one degree, appears or disappears.

4.6.2 Pipeline overview

The pipeline has two major steps when a single object to track has been identified. The first is segmentation, isolating the vessel to measure its dimensions and position then removing outliers. The second step is state estimation of motion, finding the corresponding speed components.

As for the first step, two different approaches to segmentation have been tested in the project. The first approach builds on knowing the object beforehand and identifies the

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rigid transformation matrices using ICP (Iterative Closed Point). The advantage is obviously that the object needs to be known or recorded beforehand. Working directly with point clouds however is computationally expensive and makes it more difficult to fuse with image sensors. The second approach has been based on starting the tool chain by segmenting bounding boxes. This is a fast technique taking much of the computation quickly from point clouds to oriented bounding boxes. The registration approach can be a good complement to the bounding box approach by fine tuning dimensions of a vessel and its local origin. No approach based on training has been tested due to lack of training data. Training should be straightforward to set up and could be a good complement for example to identify, using point clouds or camera images, the orientation of the ship by identifying the bow.

As for the second step, in this study linear Kalman filters have been used to estimate translational and rotational speed, as well as dimensions of the object. The linear filter proves the usage, and it can be elaborated further with non-linear or unscented filters combined with integrated multiple models for predicting curvature trajectories.

The following subsections will describe the setup, approach and results.

4.6.3 Multi-object tracking

Looking at the problem of tracking vessels in a harbour, there are some factors that affect the choice of tracking algorithm. First, the density of tracked objects is low which simplifies the segmentation. Second, the distance between objects is typically large compared to the resolution of the sensor accuracy. It can be assumed that there is free water between the vessel and other objects and that the vessel is not partially or temporarily obscured. Third, the sensor update period (frame rate) is short compared to the speed of the tracked vessels. It can be assumed that for two consecutive frames, there is an overlap in position of parts of the vessel. The orientation or speed of the vessel is not needed to distinguish between multiple identified segmentations. The choice of multi-object tracking is to detect before track. To take advantage of the distant measuring lidar sensor, the segmentation is made in the horizontal plane (top-down view); segmentation could also be done in any other plane, which is useful if for example images are used as a complement.

In the study, a multi-object tracking algorithm has been implemented to allow for selecting one or multiple objects of interest. It also solves the problem of single object tracking in a step which positively is only loosely coupled to the motion state estimation of one or multiple single objects.

4.6.4 State estimations of single objects

The estimation of dimensions is separated from the estimation of motion states. The size of the vessel is estimated from sensor data. A problem is to achieve good initial guesses of the size, which in a general case is not possible to guarantee since the vessel can obscure its own size depending on its distance and orientation relative to the single sensor, see Figure 2. Of course, it would be possible to use initial values from the AIS.

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Here it is assumed that the vessel is larger in one dimension and smaller in the other in the horizontal plane. By keeping track of the sides facing the sensor, a more informed estimation of the dimensions can be made.

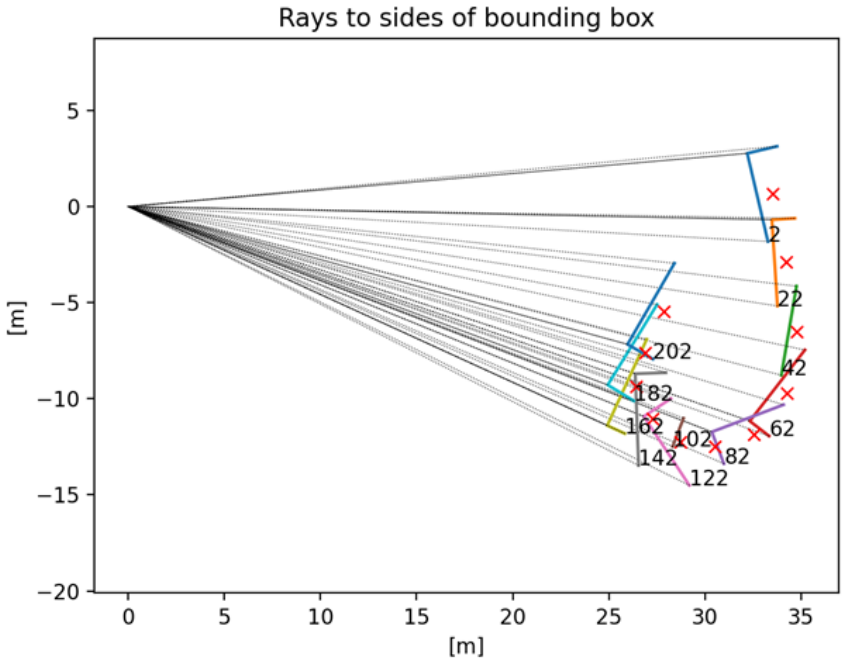

Figure 17: Top view plot of a boat (Seahorse) making a J-turn exposing momentarily one or two sides of its bounding box toward the sensor in the origin. The red cross is the geometrical centre of the bounding box superscribing the (removed from the figure) point cloud of the boat. Numbers refer to frames. In frame 42 only the starboard side is visible to the sensor.

Motion is modelled with translation in the horizontal plane (XY) including rotation around in the normal of the horizontal plan (Z). Other degrees of freedom are not estimated, and probably not of interest for large ships in a harbour. The linear and rotational position of the defined centre together with their first derivatives (unmeasured) are estimated in a global coordinate frame (with the origin in the sensor). Skidding and its momentaneous centre can be derived from this as well as for example a Conning display of longitudinal and lateral stern bow speed and stern speed.

4.6.5 Results from the river

Some results from a measuring campaign at Lindholmen quay autumn 2022 is shown in Figure 18, where the Älvsnabben ferry is marked with a red box. Figure 19 shows the trajectory of Älvsnabben together with predictions every 5th second. Each solid rectangle representing measured position and orientation is accompanied by a dashed rectangle in the same colour, showing the prediction 5 seconds ahead. If prediction was perfect, a predicted boxed from previous time step should be perfectly aligned with the estimate/measurement of the current motion state.

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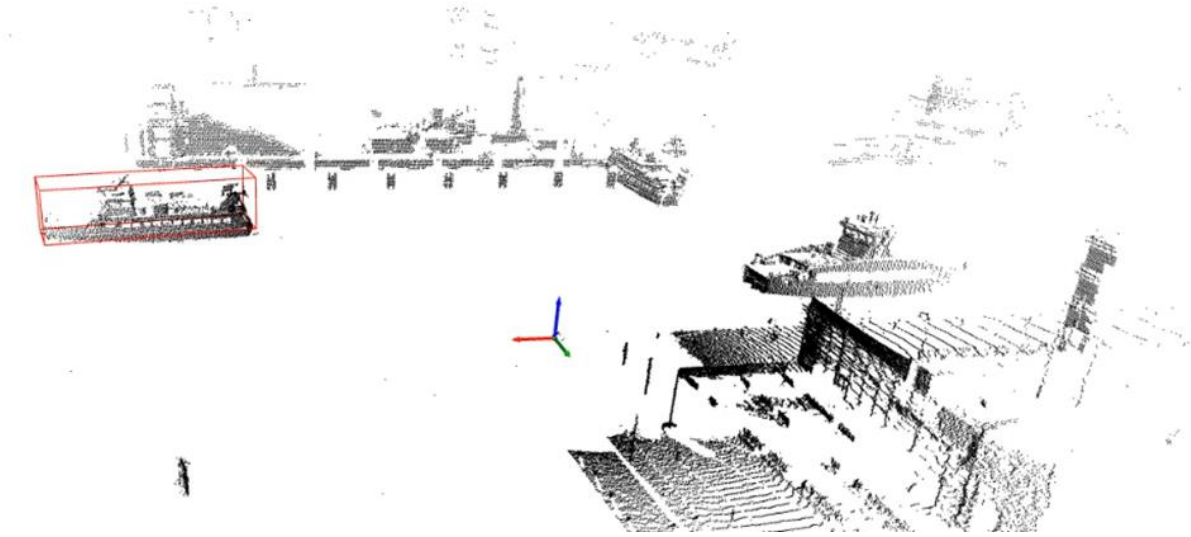

Figure 18: A point cloud view of Lindholmen Göteborg looking west, where the symmetric commuter ferry to the right approaches its landing site behind the Ericsson company's office. The Älvsnabben class of ferry, marked with a red bounding box, heads out in the river in front of the pier with the small house called Örnen. The lidar sensor's location is depicted with the rgb-coloured coordinate system symbol. The water surface typically does not return any signal, except for the wake behind or alongside vessels.

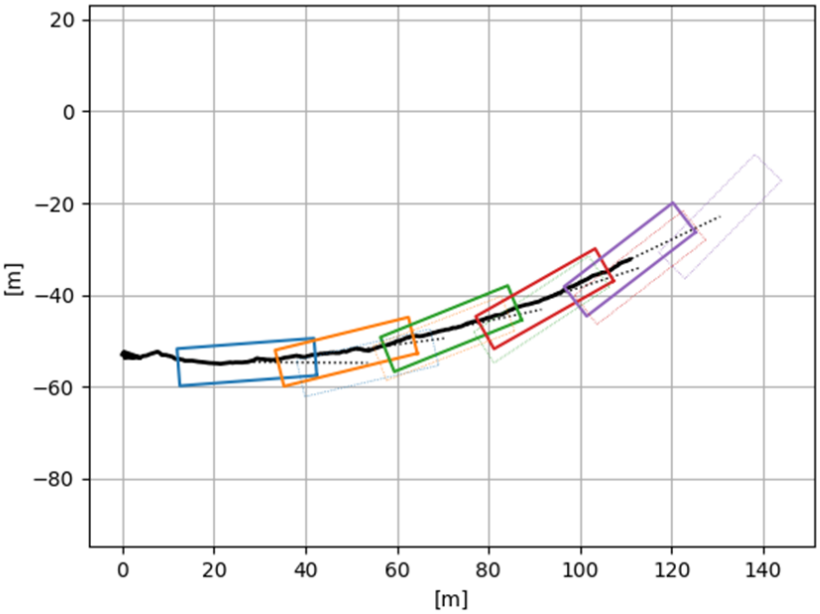

Figure 19 Tracking the current position (solid boxes) of Älvsnabben with predictions 5 seconds ahead (dashed boxes). Dashed black lines are predicted trajectory. The prediction interval is equal to the prediction horizon. Global coordinates.

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From a measuring campaign at the Nya Varvet docks, the Seahorse a snapshot of an animation in Figure 20 shows current position with two predicted positions along the predicted path. Dimension and motion estimations from the J-turn are shown in graphs in Figure 6 and Figure 7. The xy-plot has global coordinates (with the sensor in the origin) and the Conning display shows velocity in the vessel's local reference frame relative to ground (the sensor's reference frame).

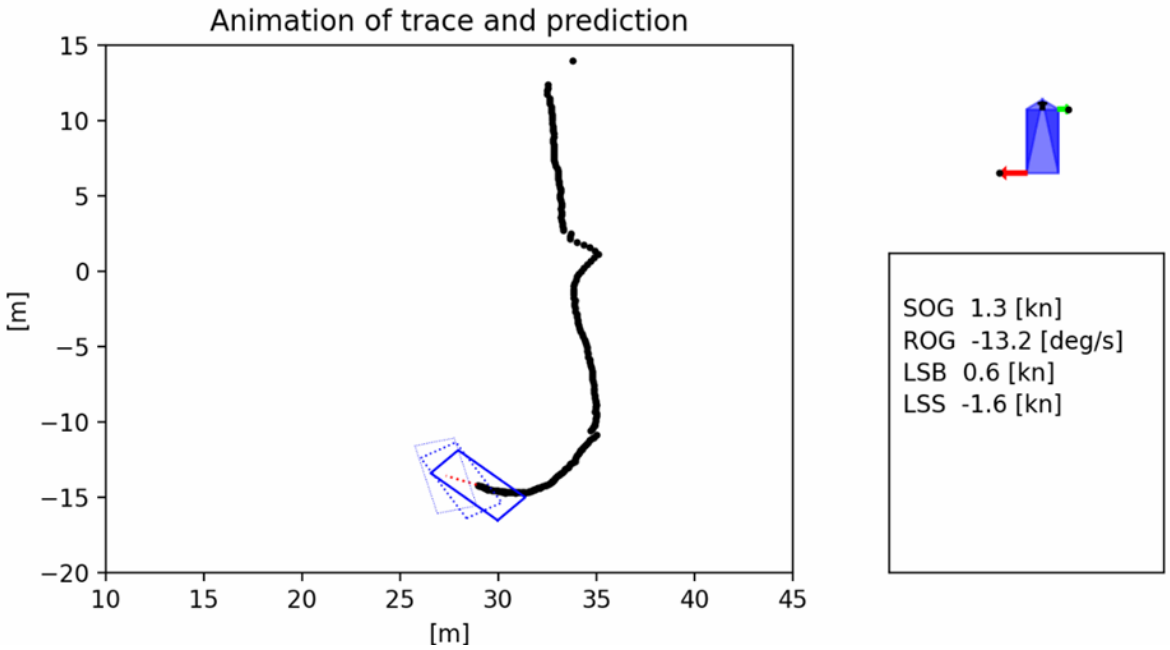

Figure 20: At the end of the J-turn of Seahorse, the speed over ground has dissipated and the stern is skidding clockwise as the rotation over ground is quite large. Solid blue box is current estimation, dashed blue boxes are predictions (1.25 and 2.5 s in the future), red line shows predicted trajectory. Conning diagram to the right with arrows for lateral speeds at stern and bow. SOG speed over ground, ROG rotation over ground (reversed sign), LSB lateral speed bow, LSS lateral speed stern.

An example of size estimation is presented in Figure 21. The hull of Seahorse has a width of 1,96 m and a length of 4,79 m (without the engine). The dimensions are thus probably underestimated by one or two decimetres. The reason the estimation varies is because of initial conditions and that the J-turn effectively exposes or hides the boat's shape.

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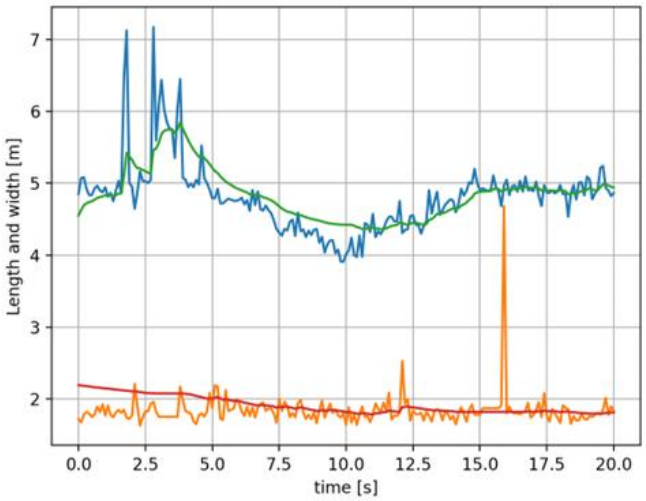

Figure 21: Time series plot when estimating dimensions of the Seahorse. The figure shows unfiltered measurements and filtered estimations with outliers removed.

The estimated position and speed for the J-turn is shown in Figure 22. The measured (and filtered) position and orientation expose smoothed curves which is a good result. The respective speed is not measured, only estimated and thus a bit noisy with the current setup and approach.

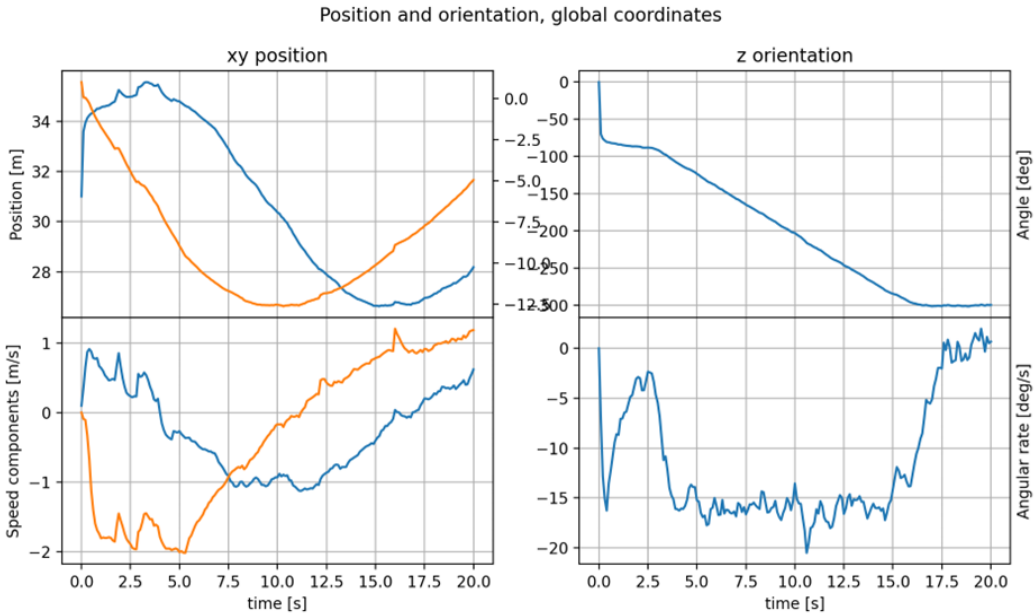

Figure 22: State estimation of Seahorse's J-turn with position (top row) and speed (bottom row) for linear (left column) and rotational motion (right column). Global coordinates.

As a summary of the study with the lidar sensor, the results are promising. It seems possible to estimate a vessel's size within a couple of decimetres and follow its position and speed quite well. There are a number of things to improve regarding the tracking, state estimation and prediction. It would also be valuable to verify the motion by independent and accurate instrumentation.

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5 Enhanced navigation

Enhanced navigation refers to the use of sensor technology to improve situational awareness for navigators and to provide measurements or observations that can be used to create a digital representation of the real world for automation or decision support systems. This technology is intended for use by navigators, pilots, and VTS personnel. While an enhanced sensor array on a ship has numerous potential applications, including search and rescue operations, oil and chemical spill response, fire management, and weather observation, these specific use cases are not included as this project only focuses on navigation.

The International Maritime Organisation, IMO, defines enhanced navigation as "*the harmonised collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment.*" This means that enhanced navigation is not a static concept, but rather as new technology is developed and users have new requirements, the process becomes iterative and continuous development becomes a key factor for the entire concept (*MSC 85*, n.d.).

As a means of testing the feasibility of the contemporary sensors, and to showcase how the Reeds dataset could be moved from beyond-application, into application-centric development, enhanced navigation was selected as a use-case and concepts were designed in parallel with the development of Seahorse and Landkrabban.

The use case of 'Enhanced Navigation' is based on the previous knowledge from the project "Nya sensorer" which identified potential application areas focused on using a new type of marine sensor that is today established in the vehicle automation markets. The "Nya sensorer" project focused on the inland waterway with a distance from the sensor unit up to 2nm. As the Reeds dataset collection finished initial testing, the capabilities of the sensors on Seahorse and Landkrabben were found, and from this, a series of data collection runs were found to be suitable for the development of the enhanced navigation suite.

A wide range of scenarios, locations, and weather conditions were recorded to assess the capabilities and limitations of the sensors. Each demonstration developed was only a proof-of-concept prototype for gaining insight and feedback on the actual value generation to enhance navigation and increase safety and efficacy. The analysis of the sensor data and demonstrations revealed various valuable applications that often required near-real-time processing and the transmission of data over wireless networks, presenting additional challenges in the maritime environment. These findings contribute to the understanding of how sensors from Reeds reference data can be effectively utilised to improve maritime operations.

An overview of the chosen route to conduct data sampling collection is shown in the picture below. This includes navigating through the archipelago, channels, and urban areas near the city centre and ports. Our chosen route is from Vinga to Vänern, which encompasses all the necessary elements. A previous study on urban water transport identified this route as a potentially suitable candidate for autonomous inland waterway

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transport. Highlighting the importance of having a reference dataset from such an area, so technical challenges can be identified to allow research aims to reflect industry needs.

When ships are navigating in narrow waters, it's crucial to monitor objects that are within 200 metres of the vessel. Up until now, human perception has been relied upon in this short-range perception, but to increase automation and decision support, it's necessary to obtain an accurate digital representation of the area under 200m. A regular marine radar is not suitable for such short ranges as its intended operating range is long-distance target detection and tracking. Therefore, the Reeds sensor setup has a wide variety of sensors allowing for explorative studies to find suitable sensors for the marine environment.

5.1 Scenarios and evaluation

Inside the 'Enhanced Navigation' there are a number of scenarios identified by marine experts from Sjöfartverket. Throughout the project, HMI mock-ups and prototypes have been evaluated to assess their effectiveness and guide their development. To ensure a broad exploration of application possibilities, the focus has been on the human interpretation of sensor data through overlays and multiple views that visualise the raw sensor performance. This approach allows for a quick comparison of sensor performance across the different types in the marine environment. Additionally, algorithms developed by Chalmers University have been explored, with a particular emphasis on leveraging raw data analysis to enhance automated sensor interpretation to assist in creating a digital representation of the ship's surrounding environment and condition. The reference algorithms have demonstrated opportunities to simplify and aggregate raw sensor data into concise views for operators, although due to time limitations, some of these cases have only been implemented as mock-ups.

The methods used for evaluation of the scenarios are based on feedback gathered under group discussions with experts from Sjöfartverket. The group consisted of pilots and VTS operators and training instructors.

5.1.1 Docking ship, position and state reference

According to Sjöfartsverket there is a need to be able to monitor vessels docking/mooring procedures with regard to mainly what velocity and angle of attack when the vessel is making contact with fenders. The primary objective is to provide accurate feedback to the navigator responsible for manoeuvring the ship, ensuring optimal situational awareness and reliable information. By monitoring these parameters, the goal is to enhance the navigator's ability to make informed decisions, promoting resilience and trust in the docking/mooring process.

Additionally, the port or infrastructure owner can benefit from the ability to monitor vessel docking/mooring procedures, specifically to track the velocity and angle of attack when the vessel makes contact with the fenders. Moreover, the recorded data can be valuable for the port or infrastructure owner in terms of obtaining statistical information on incidents that may have caused damage to the jetty. This information can be used in insurance claims disputes that may arise from accidents.

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The primary purpose is to provide accurate feedback to the navigator manoeuvring the ship by an additional second source of not only relying on the shipboard system, ensuring the highest level of situational awareness and reliable information.

Another approach we have seen in this application area has involved using laser beams, typically two, positioned at fixed points along the jetty. As the vessel passes through these beams, the system measures the distance between the hull and a reference point (usually the fender). This distance data enables the calculation of velocity and angle. However, precise calculations can only be made once the hull is within range of the second laser. But has the benefit of a very low-cost sensor.

The additional information that could be extracted from the enhanced sensors could be:

- Determining the ship's position in relation to its intended location along the jetty (vertical, longitudinal and angle of attack)
- Shore-based validation of ship position and state.
- Ensuring that the water area is clear of obstacles such as floating debris or maintenance craft.
- Detect the ship's hull or superstructure shape extrusions that could lead to overhang on the jetty.
- Checking the side of the ship for fender position alignment.
- Supervising shore connection such as ramps and gangways.
- Monitoring ship movement during cargo handling operations.

These sensors enhance the monitoring capabilities and provide valuable data for ensuring safe and efficient ship mooring operations and increase redundancy by not just relying on the ship's own system.

The precise measurements provided by the lidar sensor can be utilised to verify the accuracy of the ship's AIS (Automatic Identification System) outline, which describes the ship's dimensions and position reference. By comparing the lidar measurements with the AIS outline, any discrepancies in the transmitted information can be easily detected by a human observer or automated with a shape detection type algorithm based on machine learning.

This capability enhances the situational awareness for a pilot while assisting a vessel, particularly during mooring operations involving unfamiliar ships or when manoeuvring in close proximity to other vessels. The lidar's data allows for a more comprehensive understanding of the own ship's and target ship's actual dimensions and position, dependent on the lidar perspective being mounted on its own ship or shore-based installation. Providing valuable information to assist the pilot in making informed decisions and ensuring safe and efficient manoeuvres.

During our exploration of this use case, we encountered visual examples that are easily understandable for both mariners and non-mariners. One such example is depicted in image 15, where we have overlaid lidar data onto a satellite image and AIS. In this particular scenario, we focused on a ship that frequently travels along a specific route and has extended periods of port stay, allowing us to compare AIS, satellite imagery to

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our lidar measurement as we could measure the ship's outline using lidar at different times.

Upon observing the image, it becomes apparent that the ship's outline, as captured by the lidar measurements, does align with the outline depicted in the satellite image. This similarity is also observed in the AIS outline (Green polygon), which represents the ship's shape as a polygon.

This visual example highlights the potential for verification between different sources of ship outlines, emphasising the importance of cross-referencing and validating the information. By comparing lidar measurements and AIS data, we can gain a more comprehensive understanding of the ship's actual position and shape. This integration of multiple data sources enhances the accuracy and reliability of the information available to mariners and aid in the decision-making processes.

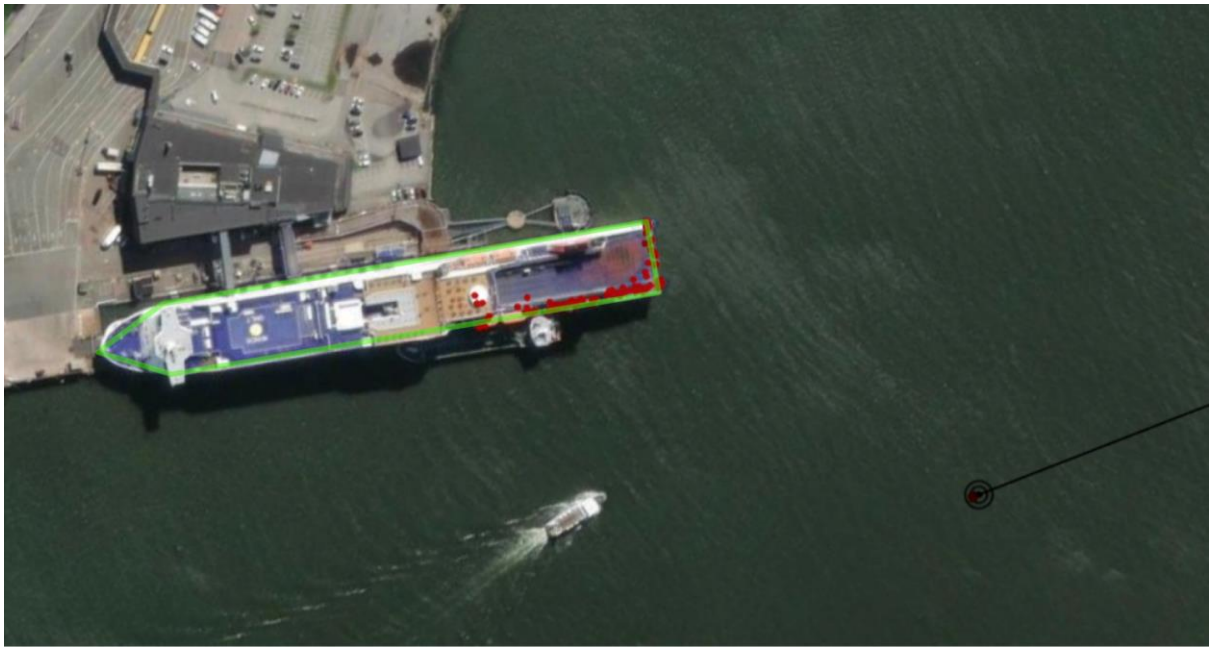

Image 15: The ship outline aligning between lidar (red dots), satellite image and AIS (green polygon). This picture was processed in real-time onboard the seahorse Crowsnest instance (Google maps overlay).

By employing a validated algorithm that compares the outline derived from AIS targets with the recorded lidar data, the resulting output can be effectively communicated to the operator through a commonly used conning display as supplementary information. However, further testing is required to determine an appropriate approach for incorporating additional information into the conning display without overwhelming the operator or creating a cluttered interface.

The aim is to find a suitable alternative that presents relevant data in a clear and concise manner, ensuring that the operator can easily interpret and understand the information without feeling overwhelmed. The conning display serves as a vital tool for presenting essential navigation information, and incorporating the output from the AIS-lidar algorithm that can enhance situational awareness and decision-making capabilities.

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Through careful design and iterative testing, the project aims to strike a balance between providing valuable insights from the algorithm and maintaining a user-friendly interface. This iterative process will help refine the presentation of information, ensuring that the operator receives relevant and actionable data without compromising the usability and effectiveness of the conning display.

Image 16: Crowsnest conning display mock-up.

5.1.2 E-Lookout

The lookout duty onboard plays a crucial role in ensuring the safe navigation of the ship by providing vital information about objects and events in the ship's operating environment. This information is gathered through visual observation, auditory cues, and any other means available. It is essential to have a dedicated lookout at all times while the ship is underway.

The primary responsibility of the lookout is to maintain a vigilant watch and should not be assigned other tasks that may distract from this duty. The lookout's role is to carefully survey the surrounding environment, including other ships and potential hazards, as situations on the open sea can evolve slowly over time. The nature of long working hours and watchkeeping can make it challenging to sustain a consistently high level of attention, and the task can become monotonous.

To ensure the effectiveness of the lookout and assist in higher automation of navigational tasks. Perception sensors or combined sensor types are needed to perform at the same level as a human lookout or better. The navigational aids are developed to be interpreted by human eyes and can recognise a large set of shapes, lights and objects both in daylight and low light conditions.

A test was carried out by Tervo & Lehtovaara, to validate an optical camera's ability compared to the human lookout. It was performed according to maritime standards and

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the recommendations that a human lookout should detect the boat used for the test at a distance of 5,8km. The same test with a full HD camera using a 30x optical zoom could detect the boat at a distance of 6,8km, showing that even with today's technical standards, this technology can surpass the human lookout under prevailing conditions.

The Reed´s setup consisted of 4k cameras capable of recording in 12-bit depth, enabling the capture of high-resolution images with high contrast. This high resolution provides the advantage of digital zoom functionality, eliminating the need for physical moving parts and increasing the system's resilience to impacts. During the demonstration, Seahorse, a lightweight small boat prone to being tossed by waves, was utilised. In the recording session, acceleration in excess of 85 m/s^2 was measured, underscoring the necessity for durable hardware that can withstand such demanding conditions.

The high contrast capability of the camera system enables shape recognition even in challenging lighting conditions. Dealing with circumstances such as the sun's reflection on the sea and low light environments presents difficulties for camera systems. However, significant advancements have been made in digital imagery to enhance camera performance, particularly in the realm of mobile cameras. These advancements include advanced post-processing techniques for combining multiple images to enhance a single image. This holds the potential for improving marine perception systems. Although the project did not specifically focus on exploring image enhancement, it is an integral aspect that will play a crucial role in future automated lookout systems.

Image 17: An image object recognition algorithm being used to detect ships in the vicinity of Seahorse on one of the FLIR 4k cameras.

Image 17 showcases the implementation of an object detection algorithm with the capability to detect vessels. This trial demonstrates the potential of recognising and tracking ships solely based on camera images. However, the current algorithms used for object detection and identification rely on black-box machine learning models. These models pose challenges when it comes to validating their real-world operational performance, particularly in the context of general navigation, which needs to be equivalent to or better than the capabilities of a human lookout for a system aimed to replace the lookout.

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The validation approach for object detection algorithms involves providing the algorithm with new, annotated images that it has not encountered before. The algorithm's detection performance can then be statistically compared against the annotations. However, applying the same approach to validate an e-lookout system would be exceptionally difficult. The validation process would need to consider all the system components, including but not limited to camera hardware (lenses and image sensors), geographical areas, weather conditions, ship motion, and navigation markers such as emergency signals to be detected reliably. This challenge can be overcome with large and validated datasets that the Reeds project contributes towards.

With the ability to detect and recognise objects in images and extract ship velocity data, we envision that camera systems have the potential to surpass the performance of a human lookout in the future. Building on the algorithm tested in this project, several beneficial applications were identified in the project:

- Fuse and validate radar and AIS target information with images of the object to confirm the object type, identity, and navigational state. This integration allows for enhanced object recognition and provides additional validation and information about the detected objects, such as their navigation lights, signal flags, or whether they are engaged in special operations. By combining multiple sources of data, a more comprehensive understanding of the targets can be achieved.

- Shore-based navigation marks can be detected and identified using image data, which radar is unable to detect as it cannot distinguish it from other objects on the shoreline. Navigation buoys and other aids to navigation (AtoN), which can be compared to sea chart information. The system can perform cross-checks between the detected navigation marks and the corresponding information on the sea chart, ensuring accuracy and reliability. If any deficiencies or discrepancies are detected in the AtoN, the system could automatically generate reports and notify the responsible agency for fairway maintenance and alert nearby ships. This enables proactive measures to be taken for ensuring safe navigation and maintaining the integrity of the navigational aids.

- Visual emergency signals, such as flares or day signals, can be automatically detected and located using object detection techniques. The camera system could be capable of identifying the distinct patterns and characteristics of these signals, enabling quick and accurate recognition. By automatically detecting and localising emergency signals, the system can provide crucial information to aid in search and rescue operations or to alert operators, nearby vessels and authorities about potential distress situations. This enhances safety and enables swift response in critical situations.

- Camera systems have the capability to go beyond human visible light and utilise thermal and infrared cameras for enhanced perception. These technologies have already proven their effectiveness in various applications, particularly in search

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and rescue operations, where they have significantly improved response time and overall effectiveness. While thermal and infrared cameras have been traditionally expensive, their prices have been gradually decreasing, making them more accessible for integration into camera systems. By leveraging these advanced technologies, the camera systems can provide enhanced vision in challenging conditions, such as low light, fog, or smoke, enabling improved situational awareness and detection capabilities.

- One crucial aspect of ship navigation is the ability to determine the prevailing weather conditions in the vessel's vicinity. This includes assessing the sea state, ice conditions, squalls, and other weather or environmental events that may impact the ship's course. In particularly severe weather conditions, it becomes important to accurately determine the direction of waves in order to stabilise the ship. By aligning the bow of the vessel towards the incoming waves, the ship's stability can be enhanced, minimising the potential impact of rough seas on its navigation.

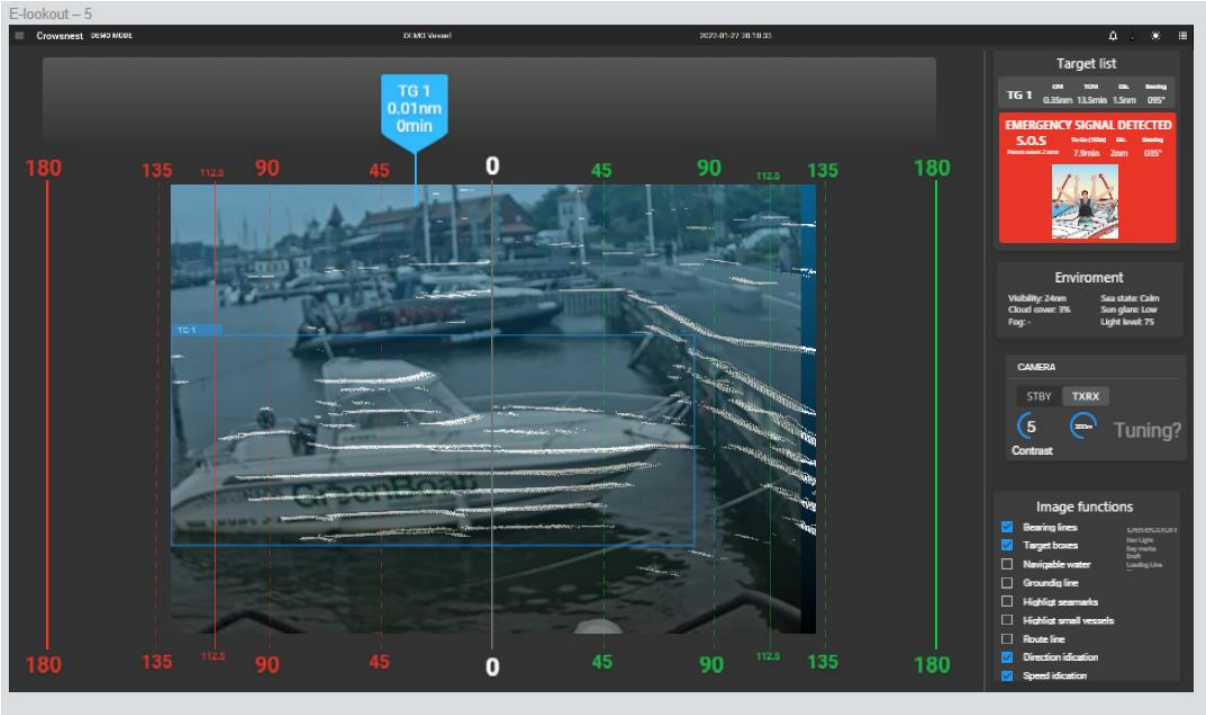

Image 18: A mock-up image created for identifying potential features that could assist an operator's decision-making from the ship's perspective. The mock-up was used for brainstorming sessions with pilots and VTS operators.

The e-lookout camera system, with the aid of machine learning, demonstrates the potential to detect and identify critical information in a manner comparable to or even superior to a human lookout. Validating such performance for a commercial system may present challenges, but it is likely feasible to conduct parallel testing with a human lookout during the development stage. By leveraging advanced computer vision algorithms and incorporating real-world validation scenarios, the e-lookout system can

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enhance situational awareness, improve detection capabilities, and potentially augment or complement the human lookout function in maritime operations.

The marine environment poses significant challenges for camera systems, including vibrations, ship motion, and extreme weather conditions. One common issue encountered is the build-up of water droplets on camera lenses, which can degrade image quality. In response to this challenge, the project master student Sophonpattanakit, J developed a GAN-based solution for water droplet removal, improving camera image quality without the need for physically removing the droplets from the lens. Which is highlighting the promising potential of this emerging technique ensuring clearer and more reliable imagery in adverse marine conditions.

Image 19: GAN-based water droplets removal. Sophonpattanakit, J. (2022).

While the digital approach for removing droplets from camera lenses shows great potential, we acknowledge the importance of incorporating physical means to effectively remove obstructions and protect the camera view from adverse weather conditions. Several physical systems are on the market, including the use of an air curtain (high-pressure airflow in front of the lens), centrifugal or spinning lenses, window wipers, heating elements, and liquid sprays. These physical mechanisms aim to prevent the accumulation of water droplets or other debris on the lens surface, ensuring a clear and unobstructed view for the camera system. By combining digital techniques with appropriate physical measures, the optimal performance and reliability in challenging marine environments for long term use without human maintenance should be a possibility.

An additional significant challenge in the development of an e-lookout system is the accurate identification and recognition of Aid to Navigation (AtoN) light characters, especially in low light conditions. Due to the longer exposure time required by cameras to capture more light in such conditions, a fast-blinking light could be perceived as a fixed light by the camera. This presents a challenge that needs to be carefully addressed during the design of a versatile e-lookout system. Future standardisation efforts may be necessary to establish a reliable interface between the onboard camera system and AtoN, ensuring the accurate detection and interpretation of blinking frequencies. This would contribute to the overall reliability and effectiveness of the e-lookout system in marine environments.

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The placement of camera sensors onboard must be carefully considered to avoid interference from other onboard sensors. In the provided Image 20, the placement of a lidar sensor within Seahorse is shown, which captures the camera's view. Although the lidar light is not visible to humans, it can be detected by the camera. The flickering pattern of the lidar light could potentially confuse the object detection algorithm when combined with other light sources.

Image 20: The lower right corner of the camera view displays the presence of a lidar light that becomes visible under low light conditions.

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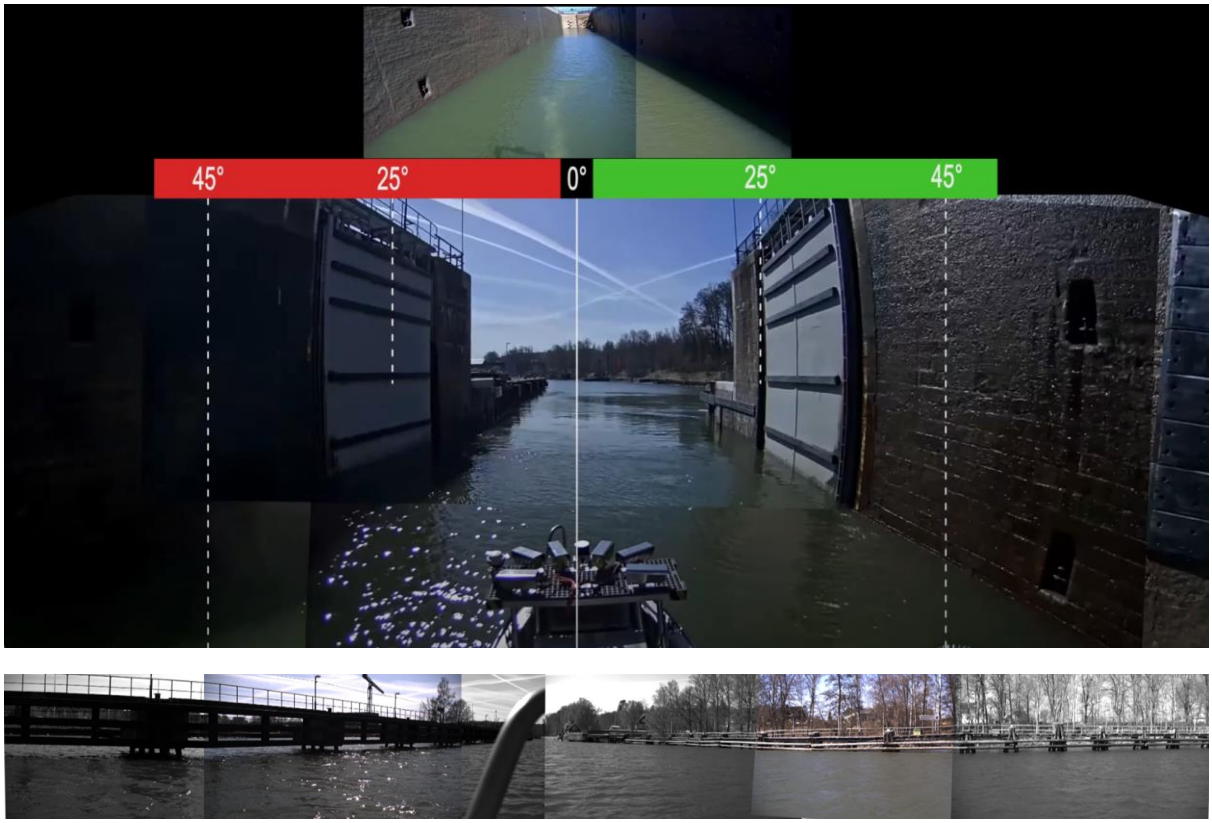

Image 21: A simple merging of multiple camera views with image overlay.

In Image 21, we present a basic example of merging multiple camera views with an image overlay. This simple merging technique allows for a combined view of different camera perspectives. It is important to note that more advanced image merge algorithms, as well as virtual 360° rotatable views, exist but were not explored extensively in this particular project.

While the depicted image merging approach provides a fundamental understanding of combining camera views, further research and development could explore more sophisticated algorithms. These advanced techniques can offer enhanced image-merging capabilities, resulting in a seamless and comprehensive view of the surroundings.

Additionally, virtual 360° rotatable views provide an immersive experience, allowing users to navigate and explore the environment from different angles. Although not within the scope of this project, these advanced features hold potential for future investigations and could further enhance the overall system functionality.

Challenges are many for E-Lookout, for example, calibrating images in order to accurately calculate distance and bearing based only on image data after the object is detected. This calibration or correction must make adjustments for errors in the optics, camera alignment and ship motion, such as pitch, roll, heave, and yaw. The corrections can be done by software or physically but more likely with a combination, for example, a camera housing mounted on a gyroscopic gimbal compensation ship roll.

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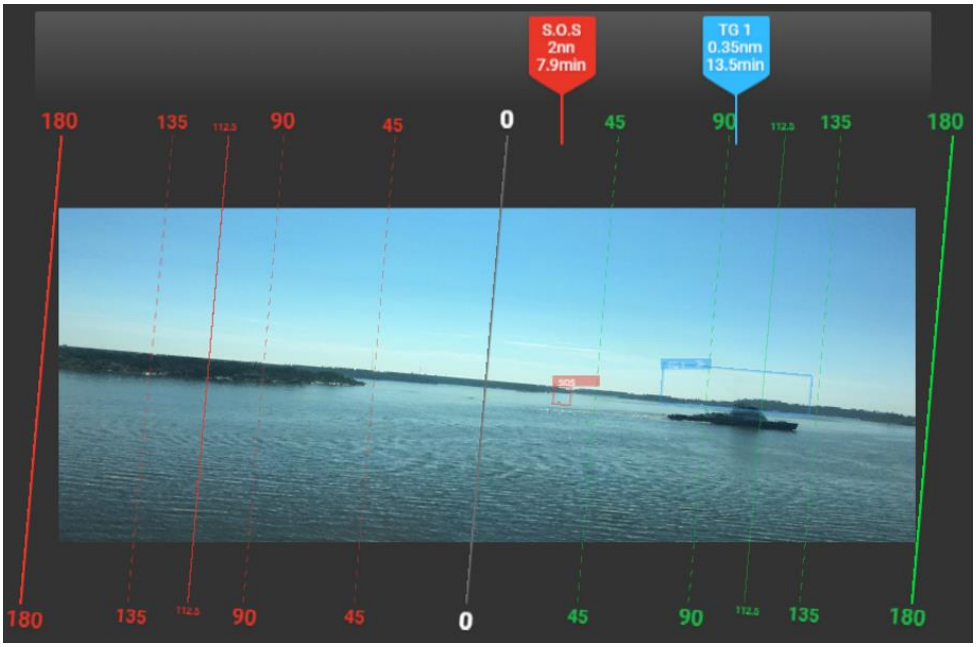

Image 22: A mock-up scenario where a ship is experiencing a list due to a turn to starboard. However, the camera's observation angle in the scenario does not align with the actual bearing to targets and needs to be corrected. For example, the visualization is tilting the bearing lines to accurately represent the ship's orientation.

By continuing to explore and incorporate these advanced image-merging techniques and virtual views, we can improve the accuracy, comprehensiveness, and usability of the system, leading to a more immersive and effective user experience.

To address this issue, it is important to have a well-defined system setup onboard where potential problems can be easily mitigated. This can be achieved by adjusting the placement of sensors or disregarding the portion of the image where the lidar is visible. By carefully considering sensor placement and managing potential interference, the camera system's performance and accuracy can be optimised in the marine environment.

Discussions with experts in the automotive industry regarding perception system development have emphasised the importance of integrating self-testing and validation mechanisms into an e-lookout system. These mechanisms serve two key purposes: establishing the accuracy and reliability of the perception algorithms and ensuring that proper alignment of the camera systems is kept at all times. By implementing self-testing and validation features, the e-lookout system can continuously assess its performance, identify potential issues, and make necessary adjustments or alert the operator to maintain optimal system state awareness. This proactive approach enhances the overall effectiveness and trustworthiness of the system, providing reliable and consistent information for decision-making in the maritime environment.

The e-lookout system plays a critical role in fully autonomous ships, but most likely, the first step is to show the capabilities of replacement for a human lookout. If such a system would be installed on ships operating on global sea trade with the aim of replacing or automating lookout functions onboard, it is crucial for the system to demonstrate performance equal to or better than that of a human lookout. Currently, there are no specific regulations in place for the performance requirements of e-lookout systems, as

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radar systems have. The e-lookout system is not recognized by COLREG, and navigators are not trained to utilise camera systems for navigation purposes. To enable the e-lookout system to be considered a viable option in commercial trade, there may be a need to update or supplement existing regulations and requirements. This would involve addressing the recognition and integration of e-lookout systems and establishing appropriate performance standards to ensure they are safe and effective to use in maritime operations. IMO is now working on developing a MASS code where this question might be raised.

5.1.3 Ship/shore combined sensor infrastructure

Ship navigation involves relatively slower speeds compared to driving a car, resulting in a longer event time horizon ahead. This longer time frame allows navigators on ships to analyse a larger set of data and make informed decisions. However, the abundance of available information can pose a challenge. Navigators must carefully manage and prioritise the data to avoid being overwhelmed. Too much information can lead to cognitive overload and hinder decision-making abilities. Therefore, it is crucial for navigators to develop effective strategies for filtering and interpreting the relevant information while disregarding unnecessary or less critical data. The digital system developed should support in filtering the information and will be a critical part when adding new sources of information from additional perception sensors.

By striking a balance between thorough analysis and avoiding information overload, ship navigators can make well-informed decisions that prioritise safety and efficiency in their maritime operations.

During the project, time and effort was dedicated to developing the Human-Machine Interface (HMI). The objective was to create a user-friendly interface that would facilitate effective communication and interaction between humans and the machine system.

Within the designated time frame, it was possible to achieve this goal by developing an open-source visual interface. This interface is designed to be highly compatible and can be accessed seamlessly through most web browsers. By adopting this approach, the requirement for a specific operating system was eliminated, making the HMI easily accessible to a wider range of users.

The open-source nature of the interface allows for broader distribution and fosters a collaborative environment for further improvements and customization. It also encourages the involvement of developers and users in contributing to the enhancement of the interface's functionality and usability.

During the project, the primary focus was to integrate sensor views to create a unified visual interface that could be easily interpreted by humans. The goal was to combine data from various sensor types, both onboard and ashore, into a single display view. However, the project encountered challenges when it came to synchronising data input and processing, particularly with the integration of sensor feeds from shore sensors.

One of the main challenges encountered during the project was establishing effective communication between physical locations using common mobile LTE network connections. In order to address this issue, it was decided to opt to utilise a 4G unlimited

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subscription provided by a prominent telecom company in Sweden. However, it became apparent that the regular unlimited 4G plan initially relied on had a limited upload bandwidth and there was a need to transmit video and raw high-resolution radar and lidar data. This limitation posed a challenge in ensuring smooth and efficient data transfer between locations and forced a shift to focus more on optimising the data flow.

During efforts to optimise data transfer, another challenge involving the logging computer utilised on Landkrabban became obvious. This computer was not specifically designed for real-time analysis and data transformations involving lidar, radar, and video sensors. Consequently, the unoptimized algorithms running on the computer had a negative impact on the overall performance of the system. In order to address this issue, we had to prioritise the optimization of scaling and pre-processing of the transmitted data. This optimization process required dedicated time and attention, which was taken away from the development of the Human-Machine Interface (HMI) to ensure smoother and more efficient operations.

Overall, the challenges encountered emphasised the significance of meticulously evaluating the network infrastructure and its payload to align with the processing capabilities when integrating sensor data from diverse sources and handling raw sensor data. Moving forward, it will be crucial for future projects to thoroughly address these aspects in order to achieve seamless data synchronisation and ensure real-time performance. Additionally, further research is needed to explore methods for prioritising operational data and determining the necessary update frequency to maintain situational awareness effectively.

Despite the challenges faced, near real-time performance was achieved, as depicted in Image 23. One of the key factors in achieving this was down sampling the data rate and resolution. This adjustment had a significant impact on enabling the simultaneous presentation of data from multiple sensors on the chart interface in near real-time. The success of this approach underscores the importance of conducting further exploration and validation of sensor fusion techniques. Additionally, it highlights the necessity of studying the effects of scaling down sensor resolution in low bandwidth situations and determining the appropriate resolution for different operations to maintain situational awareness effectively.

When managing sensors for navigation purposes, it is important to consider the tuning requirements for different sensor types. In the project, it was observed that the marine radar required more manual tuning compared to the lidar sensor. The lidar sensor, being less effected by disturbances from the surrounding environment in clear weather conditions, mainly required adjustments to the point measurement frequency.

On the other hand, the radar system had a combination of auto-tuning capabilities and the need for manual adjustments. However, throughout the tests, it was found that manual tuning for the specific location and scenario resulted in better performance than relying solely on auto-tuning capabilities. It is worth noting that this manual tuning process of multiple sensors could increase the workload for a navigator during the setup stage and monitoring of the performance.

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To improve perception performance from sensors and ensure optimal tuning based on the situation and environmental conditions, further research is required. Automating the process of maintaining a good perception performance and dynamically adjusting sensor parameters would be beneficial. This would reduce the burden on navigators and ensure consistent and reliable sensor performance throughout different scenarios where sensor fusion is used.

During the development of the interface for multiple users, a decision was made to incorporate the primary/secondary approach for sensor settings. This approach involves assigning a single person as the primary user who has exclusive control over tuning, powering on or off the sensors.

Allowing all users to change sensor settings would not be a practical solution, as conflicts may arise when multiple users attempt to modify the settings simultaneously. To maintain simplicity in the system design within the scope of the project, the ability to tune and apply settings to each sensor was restricted to only the administrator. Other users were limited to observing the sensor data without the ability to apply changes to sensor settings, only settings affecting their own view.

By implementing this approach, we ensured a more organised and controlled environment for sensor settings, reducing the chances of conflicts and maintaining a streamlined user experience.

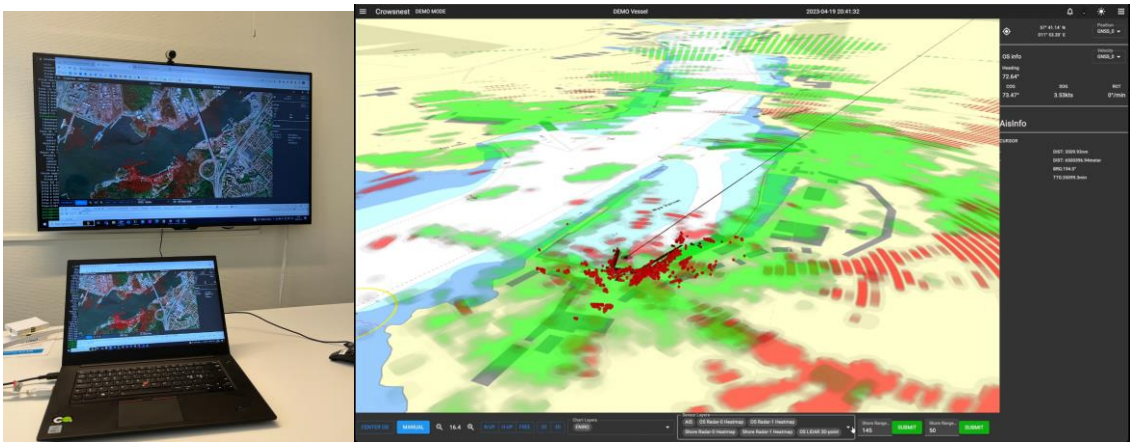

Image 23: On the left side, a simplified shore centre setup in a meeting room, featuring a near real-time view from Landkrabban. On the right side, the viewpoint from Seahorse is shown, displaying the visualised data from onboard radars with two ranges, shore radar with two ranges and 1 lidar in a port area.

The development of the interface drew inspiration from the OpenBridge design system, which serves as a comprehensive framework for creating intuitive and user-friendly interfaces in the maritime industry. While aspiring to fully implement the OpenBridge design system within the chosen interface, time constraints during the development process hindered this endeavour to be fully implemented (*OpenBridge*, n.d.).

Due to these limitations, the project was unable to incorporate the complete range of features and design principles offered by the OpenBridge system. However, its concepts and guidelines were used to ensure that the interface adhered to industry best practices and provided a seamless user experience.

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Moving forward, there is potential for further integration of the OpenBridge design system into the interface, as time and resources allow. This would enable the user to fully leverage its benefits and deliver an even more cohesive and intuitive user experience.

To further aid the navigation onboard and also to further the situational awareness from a shore perspective the use of sensor fusion of different sensors from different areas can be used(as demonstrated via Crowsnest using Landkrabba and Seahorse). Transmitting and receiving data from sensors located at different geographical locations gives the user an enhanced situational awareness and can show objects that might be obstructed from one single viewpoint.

The developed HMI are intended for navigators onboard as well as shore personnel at VTS or future remote pilotage application. The project tested and demonstrated the HMI at fairway, channel and port scenarios with experts from Sjöfartsverket.

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5.2 Risk & safety

The evaluation of the enhanced navigation by additional sensor system based onboard and ashore highlighted areas of both increased safety and new emerging risks. One of the challenges identified was the clutter caused by overlapping areas of different sensors. This issue can hinder the accurate interpretation of the sensor data and pose potential risks to navigation.

Many of the algorithms proposed for analysing and deriving functionality from the sensor data rely on machine learning, neural networks, and other black box systems. These approaches present a challenge when it comes to validation and understanding their inner workings.

The use of machine learning algorithms introduces complexity and opacity to the system. While these algorithms can provide powerful insights and predictions, their inner workings are often difficult to interpret and validate. They are considered black box systems because the decision-making process is not easily explainable or transparent.

The lack of transparency in black box systems raises concerns regarding the reliability and robustness of the results. Validating the performance and accuracy of these algorithms becomes more challenging compared to traditional rule-based systems. It requires specific methodologies and techniques to evaluate their performance and ensure they are functioning as intended.

Efforts should be made to develop validation frameworks and techniques that can provide insights into the functioning and performance of black box algorithms. This can involve methods such as sensitivity analysis, model explanations, and data quality assessments. By addressing these challenges, we can improve the trustworthiness and reliability of the algorithms used in the e-lookout system.

On the positive side, the enhanced navigation system shows potential in providing improved visualisation capabilities, allowing for better situational awareness. However, there is a risk of overconfidence in the technology's performance. It is important to remember that the system should be seen as an aid to human decision-making rather than a replacement for human judgement and expertise until more validation and development is undertaken.

Another aspect that became evident during the evaluation was the need for training and education on the new sensor types for navigators and operators. Requirements of knowledge and proficiency in effectively utilising prescription systems and interpreting the sensor data should be considered potentially as additional STCW requirements. Proper training programs should be developed to ensure the safe and effective integration of these new sensor technologies when tested and validated onboard ships.

By addressing these aspects, such as managing clutter, understanding the limitations of the technology, and providing comprehensive training, the enhanced navigation perception system can offer enhanced safety benefits while mitigating potential risks associated with its use.

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6 Conclusions

6.1 Beyond-Application Dataset

With the creation of an abstract approach to dataset generation, it was found with the initial test run data of Reeds, that the beyond-application approach was suitable for a number of varying algorithm challenges. Two papers, published through the International Federation of Automatic Control, showed that odometry could be established without assuming which domain the data was taken from. The highly kinematic state of the data created a challenge for the algorithms, and the results were model-independent, and simply defined the movement in 3-dimensional space. Transferring these algorithms back into the maritime domain also proved achievable, with the LIDAR SLAM paper, once converted to a maritime model, showing shortfalls with defining vertical movements, which is common with current maritime systems.

6.2 Sensor performance requirements

The Seahorse platform shows, quite soundly, that as the quality of sensor technology grows, so too does the level of effort required to manage and interpret this data stream. Human operators are not able to easily distinguish a change of pixel values in high bit depth imagery, nor are they able to easily filter what is necessary for safe operation of the vehicle. However, these sensors do provide the margins required for significant improvements in automated system developments. Thus, it can be said that as development in these areas continues, it can be expected that there will be a shift towards operator reliance on sensor interpretability. In that case, evaluation of the sensors, and the systems performing logic on those sensors will have to ensure a level of trust with the operator, especially in safety critical systems, such as navigation. In much the same way that there are established methods for calibration of compasses, gyroscopes, and IMU's, this project provides methods for establishing ground truths using contemporary, high-fidelity sensors, which will become the norm as performance standards are established on the international level.

6.3 Seahorse & Landkrabban

With the sensor parameters selected, two platforms were developed in parallel for the data collection. Landkrabban, a standalone shorebased sensor platform , allowed for the development of like sensors in data linking configurations, as shown with the linking of LIDAR and RADAR elements between both shore and surface vessels. Whilst having initial difficulties on a maritime platform, it was eventually resolved with the procurement of a trailable research vessel, that allowed for ease of installation in a secure lab environment, as well as a permanent onboard storage solution which solved the need for moving large amounts of data across a mobile network. The research vessel, now named Seahorse, allowed for the collection of a number of data runs during the limited time since procurement, which led to the establishment of the initial Reeds dataset, and

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the subsequent developments of benchmarking, reference algorithms, and enhanced navigation packages.

6.4 Benchmarking

The initial data collection using Seahorse, was integrated into an automated process for the development of several projects. These included object identification and navigation systems. In all projects a method was developed for validation, typically using a sensor for the logic, and then one of the ground truths for verification of that logic. This comparison showed accuracy between the logic and the ground truth, and showed how effective the algorithm was at the goal. The method of comparison was folded into the automated processes onboard Seahorse and allows for future developments of similar systems to be compared against these initial automation systems. Whilst not yet at the level of international testing, the initial framework of this benchmarking system is complete, and in the following section, it is shown that work is now being done on building the international relations to help test this benchmarking platform.

6.5 International Dissemination & Outreach

Besides the regular synchronisation activities such with the relevant academic and industrial stakeholders to the project, one of the main intentions was also to initiate and establish a larger community. This would not only include the dataset, the application execution and evaluation environment ("leaderboard"), but also a vibrant academic/industrial community around our activities.

As a first step, the project announced the dataset to raise awareness. As a consequence, a seminar series with the Laboratory of Underwater Systems and Technologies (LABUST) at University of Zagreb was initiated. The team at LABUST is focusing on virtual components (for instance, simulators or digital twins) to support the research and engineering of maritime solutions. They are interested in validating assumptions as well as concepts and ideas (like sensor models as an example) with insights from data collected from real maritime environments. This ongoing seminar series resulted in a joint workshop and tutorial proposal (driven by University of Gothenburg and Chalmers) at the 40th IEEE International Conference on Robotics and Automation (ICRA) taking place in London, United Kingdom, from May 29 – June 2, 2023. ICRA is considered to be the premium conference covering advances in robotics and ranked very high to highest (*Top Publication Robotics*, n.d.) in various conference ranking portals. Especially this edition attracted more than 6,000 attendees and hence, setting an all time high (*ICRA*, n.d.).

We set up the tutorial: *TEAM - Technology Enablers for Autonomous Maritime Robotics: Digital Twins with Simulations and Cloud-enabled Massive Scale Datasets for Experimentation and Validation* to address digital twins support for various aspects during the development of software-intensive system functions such as:

- Retrospective system analysis using collected data.

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- System experimentation using simulators with high-fidelity system models.
- Prediction of system properties based on a combination of data and simulations.

During the tutorial, two essential aspects for Digital Twins were presented and demonstrated live: (A) open-loop and (B) closed-loop verification & validation (V&V) instruments.

For (A), the high-quality and high-resolution dataset for maritime vehicles research as established by this project was introduced to address present challenges in existing datasets such as low situational variability or limited annotations. Next to the dataset, the high-fidelity simulator MARUS (*MARUSimulator*, n.d.) was introduced to address (B) that offers advanced capabilities of generating realistic maritime environments allowing for closer-to-reality validation & verification of applications developed for maritime vehicles. The simulator offers synthetic dataset generation with perfect annotations for various sensors such as cameras, lidar, sonar, and radar, and allows for interaction with the environment for closed loop simulation.

The final part of the tutorial was dedicated to host a panel where we could welcome Professor Dr. Fredrik Heintz from Linköping University, Sweden and Dr. Enrica Zereik from Institute of Marine Engineering, Italy as panellists. The panel covered various aspects as presented and discussed during the tutorial and also touched upon the most recent developments in the field of generative AI, AI Ethics, and regulation initiatives for AI.

Our tutorial attracted around 50 participants on-site, which indicated the relevance and high interest in the activities initiated and covered by Reeds.

6.6 Enhanced Navigation

The project defines "Enhanced navigation" as the application of new technology that leverages advancements in digitization and autonomous functions for the purpose of assisting in navigation. This approach combines onboard and onshore sensors to enhance maritime safety and reliability. To facilitate this, the project has developed a web-based user interface called "Crowsnest," which is described in the report. Crowsnest integrates the data from these new sensors and presents it in a user-friendly interface that resembles overlays in Electronic Chart Display and Information Systems (ECDIS). The interfaces developed are openly accessible to the public, encouraging further development and innovation. The concept of sensor data visualisation was evaluated by gathering feedback from pilots and Vessel Traffic Service (VTS) operators as well as feedback from workshops held throughout the course of the project. Given more time and resources the OpenBridge design system can be properly integrated and deployed within the “Crowsnest” interface furthering the use as a decision support tool for the operator.

The project also demonstrates the capabilities of another layer of validation by utilising another sensor such as the lidar to cross reference the GNSS signal in real time. This

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feature is similar to the use of radar overlay already commonly used but never on this small scale that close quarter manoeuvring entails.

E-Lookout showcasing the implementation of an object detection algorithm with the capability to detect vessels has also been demonstrated throughout the course of the project although much more research is needed within this field regarding categorisation and annotation for electronic lookout. The potential within this field of image analysis is very broad in its application and can be a huge aid to navigation in the future. The usage of all of these functionalities has to be adopted into the STCW in order to educate mariners in the limitations and usage of these new technologies to ensure the maximum output as a risk-mitigating and decision support tool.

6.7 Concluding Remarks

This project is the beginning of a research strategy that paves way for Swedish industry to advance on many technology fronts, with software and hardware development, as well as a springboard for Swedish shipbuilders, as many of the automatic and autonomous systems will be of a size that Sweden's yards are well suited for. The Reeds dataset, and the complex set of components required to build this dataset, including research and data platforms, sensor validation, network and time management, storage complexities, as well as algorithmic developments, both for the user as an enhanced navigation aide, as well as pure autonomous systems, shows that this dataset, and the methods developed alongside it, are vital for the continuing development of autonomous systems, not only in the maritime environment, but within all domains

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7 Suggestions for future research

Suggested areas for future research based on the enhanced navigation study and reference dataset work packages in the project:

Identification and Alerting of Squalls and Rain Clouds: Explore methods to identify squalls and rain clouds, along with heavy winds, using camera systems. Investigate how to develop an alerting system for the bridge watch while docked, aiming to prevent accidents caused by rapid changes in strong winds that leads to vessel mooring breakage and drifting in ports, posing risks to life and causing damages.

Tracking and Assistance in MOB/SAR Events: Focus on developing techniques to track and handle Man Overboard (MOB) and Search and Rescue (SAR) situations. Investigate technologies and strategies to improve the efficiency and effectiveness of SAR operations and provide assistance during MOB incidents.

Hybrid (Autonomous and manned ships) traffic Situations and COLREGS: Study the interaction between autonomous vessels and conventionally operated vessels in hybrid traffic scenarios. Examine how the maritime industry can adapt to the emergence of autonomous vessels and ensure compliance with Collision Regulations (COLREGS) while maintaining safe and efficient navigation.

Identification and Classification of Aids to Navigation (AtoN): Research methods to accurately identify and classify Aids to Navigation, including ships' navigation lights, shapes, and sound signals. Explore techniques to improve the recognition and interpretation of AtoN for enhanced navigation safety. Investigate methods to categorise collected data based on recommendations from organisations such as the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) for effective annotation and analysis.

Monitoring Vessel Movement Near Infrastructure: Investigate the development of shore-based monitoring systems for real-time validation and redundancy in tracking vessel movements near jetties and other infrastructure. Explore how such systems can contribute to ensuring the safety and security of vessel operations.

Radio Shadow and GNSS Outage Mitigation: Study the impact of radio shadow and long-term Global Navigation Satellite System (GNSS) outages and develop mitigation strategies. Explore the fusion of signal of opportunity and sensor data, such as radar, lidar, and cameras, for fast corrections and reliable navigation when GNSS signals are obstructed.

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Secure Datalinks and Quality of Service (QoS) in ship to shore: Research secure datalink solutions for maritime communication systems. Examine the impact of spotty connections in hybrid setups where ship and shore-based sensors are combined. Investigate methods to ensure reliable data transmission and maintain desired Quality of Service (QoS) standards under varying connectivity conditions.

Synthetic Data Generation: Explore the use of synthetic data for generating use cases that may not be feasible or suitable to mimic in reality. Investigate techniques to create synthetic datasets that can enhance training and testing of navigation systems.

Development of Marine-specific Sensor Hardware: Focus on the development of sensor hardware specifically designed for marine conditions. Investigate the challenges and requirements for sensors that can withstand and perform optimally in harsh marine environments.

Harmonisation of Sensor Visualisation: Investigate methods to achieve harmonisation and consistency in the visualisation of data from multiple sensors in maritime environments. Explore techniques to integrate and present sensor data from different sources, such as radar, lidar, cameras, and other sensor technologies, in a unified and intuitive manner. Focus on developing visualisation frameworks or standards that allow operators and autonomous systems to effectively interpret and make informed decisions based on the combined sensor information. Consider factors such as data fusion, display formats, symbology, colour schemes, and user interfaces to ensure seamless integration and maximise the usability and situational awareness of sensor data for navigation and maritime operations. By addressing the challenge of harmonising sensor visualisation, this research can contribute to safer and more efficient maritime practices, especially in scenarios involving autonomous vessels and advanced navigation systems.

By addressing these research topics, the maritime industry can advance navigation practices, improve safety measures, and enhance the efficiency and effectiveness of vessel operations.

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