milliAmpere: An Autonomous Ferry Prototype

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Abstract. In this paper, we summarize the experiences with the autonomous passenger ferry development prototype milliAmpere, which has been used as a test platform in several research projects at the Norwegian University of Science and Technology (NTNU) since 2017. New algorithms for motion planning, motion control, collision avoidance, docking, multi-target tracking and localization have been developed and verified in full-scale experiments with milliAmpere. The infrastructure surrounding milliAmpere includes several sensor rigs supporting research on multi-sensor fusion and situational awareness, and a shore control lab which can be used to study the interaction between human operators and the autonomous ferry. Building upon the experiences with milliAmpere, the full-scale autonomous ferry milliAmpere2 was recently launched.

1. Introduction

Among the many potential use cases of autonomy on the sea surface, autonomous ferries represent both a unique opportunity and a unique challenge. Typically, a ferry will only be operating in a limited area, so that the tasks that the autonomy must handle can be more restricted than for a vessel designed operate in more diverse environments. For example, there exists several cable ferries, which could be replaced with autonomous ferries doing exactly the same tasks but without the cable. However, autonomous ferries will often have to operate in environments characterized by heavy and unpredictable maritime traffic. Since they will be used for passenger transport, safety requirements must be high. Therefore, systems for sensor fusion, collision avoidance, navigation and docking must be reliable and of high precision. This also makes autonomous ferries an ideal test case for the development of autonomous surface vehicle (ASV) technology.

Autonomous ferries have received increasing attention during the last 5 years [19], [24]. In 2018, the car ferry Falco performed a fully autonomous transit between Parainen and Nauvo in Finland, using technology by Rolls Royce Commercial Marine, since 2019 a part of Kongsberg Maritime. Since then, a handful of Norwegian ferries operated by Torghatten and Fjord1 have started using auto-crossing functionality in regular operations. The Roboat project [37] aims at developing a fleet of autonomous vessels for transportation and constructing dynamic floating infrastructure such as bridges in the city of

Amsterdam. A prototype was demonstrated in October 2021. Also in the Netherlands, an autonomous water taxi called the Greycraft was demonstrated during 2021 [8].

At the Norwegian University for Science and Technology (NTNU), the autonomous passenger ferry milliAmpere was constructed in 2017, as a half-scale prototype ferry. Subsequently, the full-scale ferry milliAmpere2 was constructed in 2020. The milliAmpere, henceforth known as milliAmpere1, has gradually been equipped with increasingly advanced elements of autonomy, and it has been used extensively in research on marine autonomy by MSc and PhD students at NTNU.

The purpose of the present paper is to give an overview of milliAmpere1, its autonomy systems and research results that have involved milliAmpere1. In Section 2, we describe the background and motivation of milliAmpere1. Section 3 gives a technical description of the ferry. Sections 4 and 5 summarize research results in motion control and automated situational awareness. The Shore Control Lab is described in Section 6, followed by milliAmpere2 in Section 7. A brief conclusion follows in Section 8.

2. Background and motivation

Trondheim, where the largest campuses of NTNU are situated, is one of many cities in the world that is located at a river outlet. The river runs around the city centre, making it a peninsula. Furthermore, the city centre is divided into a southern part ("Midtbyen") and a northern part ("Brattøra") by a canal connected to the river, known as "Kanalen". Municipal plans to build an additional bridge between Brattøra and Midtbyen near the historical fish market "Ravnkloa" were announced in 2016. Such a bridge will become an obstacle for boat traffic in Kanalen. As a response to this, researchers at NTNU began to explore the concept of making an autonomous passenger ferry as a potentially more cost-effective alternative with a smaller environmental footprint. The milliAmpere1 was conceived as a prototype for the future autonomous ferry intended to operate between Ravnkloa and Brattøra. A picture of milliAmpere1, in front of historical buildings along Kanalen, is displayed in Figure 1.

Figure 1. The operational environment of milliAmpere1 (left) and a picture of the ferry (right).

3. The ferry

The milliAmpere1 ferry is built as a mono-hull vessel using aluminium as construction material. The 5 meter long and 2.8 meter wide ferry is capable of carrying 6 persons, although it is not certified for commercial passenger transportation. Instead, the ferry has been built to serve as a platform for developing and testing system components such as motion control system, autonomy system, and various sensor configurations. Figure 2 shows an illustration of milliAmpere1 with the sensors located on the roof. Table 1 contains the major technical data for the ferry. Key components of the system architecture of milliAmpere1 are visualized in Figure 3.

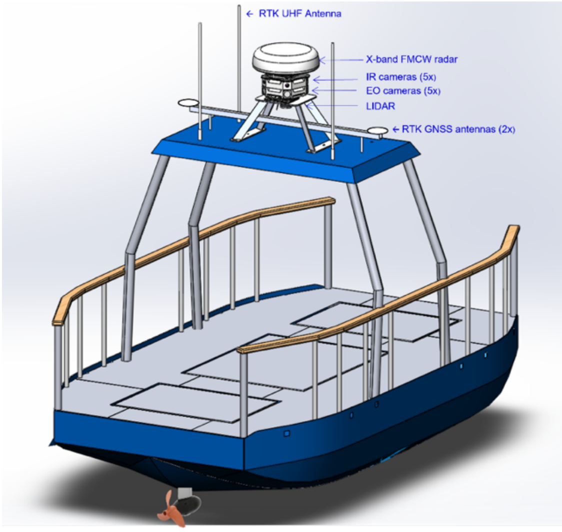

Figure 2. The milliAmpere1 hull with sensor rig mounted on top of the roof. Batteries, chargers, thruster drives, and azimuth servos are located below the deck. Computers, sensors and other electronics are located below the roof.

Table 1. Technical specifications for milliAmpere1.

milliAmpere1	**Technical specifications**
Length (LOA)	5.0 m
Beam	2.8 m
Draught	0.2 m
Air draught	3.3 m
Light weight	1.8 tons
Max passengers	6
Propulsion	2 azimuth thrusters (2kW each)
Operation speed	3 knots
Max speed	5 knots
Energy	Electric, 24V DC system
Batteries	Lead-Acid VRL, 24 kWh
Navigation sensors	RTK GNSS-compass, IMU
SITAW sensors	IR/EO cameras, X-band radar, lidar

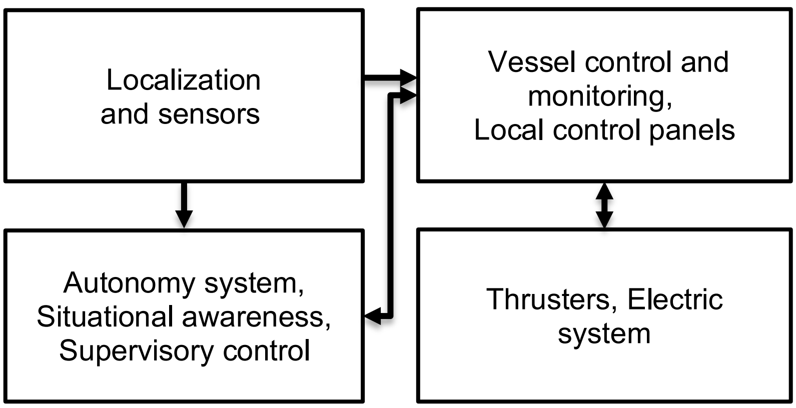

Figure 3: System architecture of milliAmpere1.

The propulsion is provided by two electrical azimuth thrusters located at each end of the hull. This allows the ferry to be highly maneuverable either by using joystick steering from a remote control unit or by the autonomy system. A 24V Lead-Acid (VRL) battery bank with 24 kWh capacity provides electrical power for the propulsion and the on board computers allowing the ferry to operate 6 hours without charging.

We categorize the sensors of milliAmpere1 as proprioceptive and exteroceptive. The former are used to provide information about the vessel itself. These include a Real Time Kinematic (RTK) Global Navigation Satellite System (GNSS) receiver consisting of two antennas together with an internal gyro stabilizer, and a separate Inertial Measurement Unit (IMU), which has integrated GNSS-receiver, magnetometer and barometer. The exteroceptive sensors are used to provide information about the environment around the vessel. All the exteroceptive sensors on milliAmpere1 are placed above the roof, midway between aft and fore, and port and starboard. These include a marine Frequency-Modulated Continuous-Wave (FMCW) X-band radar, a Velodyne VLP16 lidar, and a custom-made sensor rig containing 5 optical Point Grey Blackfly cameras and 5 infrared FLIR Boson cameras.

4. Motion planning and control

Motion planning is an integral part of an autonomous ferry, where the objective of the motion planning is to ensure collision free maneuvering from dock to dock in compliance with the relevant regulations, while ensuring safety, efficiency and passenger comfort. Furthermore, the motion planning relies on a precise vessel motion control system to realize its intentions.

4.1. Motion control system

Some common motion control functionality has been implemented on millliAmpere1 to enable rapid testing of high-level functionality. The motion control system is implemented using the Robot Operating System (ROS), where components are divided into atomic nodes which are connected using publish/subscribe communication. A functional overview of the main components in the motion control system is given in Figure 4. Actuator control nodes provide functionality for automatic control of thruster speed and azimuth angle. The thruster drives are given speed setpoints from the motion control computer, while the azimuth servos are operated in closed-loop with an angle encoder providing azimuth angle feedback and a proportional-derivative (PD) controller driving the servo motor speed. The mapping from desired control forces to thruster speeds and angles are achieved by the thrust allocation node. A novel thrust allocation algorithm has been developed for double-ended ferries which is able to provide a quick solution to the nonlinear control allocation problem [32].

The dynamic positioning (DP) node takes as input the desired and actual pose of the ferry, and issues control force commands to the thrust allocation node in order to track the desired pose reference signal. The DP controller is implemented using a nonlinear proportional-integral-derivative (PID) controller with reference feedforward [23], and a model of milliAmpere1 that was obtained through optimization-based system identification [18]. This controller is capable of tracking a desired trajectory, in addition to traditional stationkeeping. The ferry also supports manual control through a handheld RC controller which controls thrust forces via two joysticks. The milliAmpere1 has a flat keel, which gives the ferry a high degree of maneuverability, but also presents challenges from a tracking control viewpoint [31].

The navigation system estimates the pose of the ferry. This is achieved by an RTK-GNSS receiver with two antennas providing high-precision position and heading. In addition, the ferry is equipped with an IMU providing linear acceleration and angular velocity measurements. The navigation system combines these measurements in an alpha-beta filter to produce smooth and accurate six degree of freedom pose estimates [4].

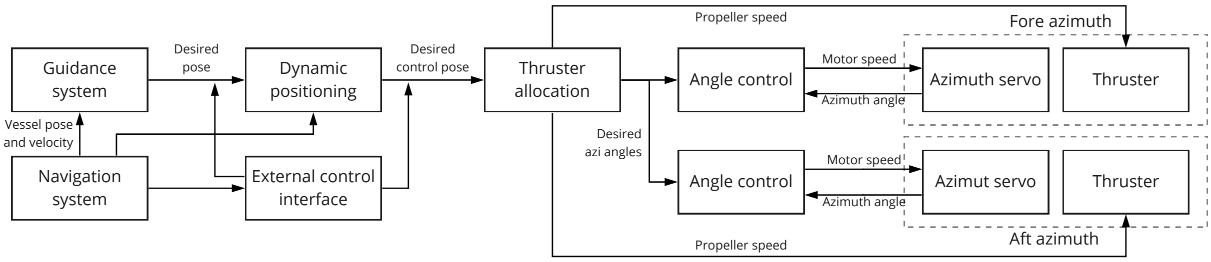

Figure 4: The milliAmpere1 motion control system.

The guidance system takes as input a setpoint for position and heading and produces smooth reference signals for pose, velocity and acceleration. This is achieved by a third-order reference filter with velocity and acceleration saturation. The motion control system is also interfaced through an external control interface which supports both direct force control, and specification of desired pose, velocity and acceleration for the dynamic positioning node.

In [16], a hybrid approach combining reinforcement learning and model predictive control was developed and tested on the milliAmpere1 while performing the four-corner test. The method also demonstrated fault-tolerant capabilities, when an unplanned azimuth thruster failure occurred during testing.

4.2. Planning and collision avoidance

Several motion planning and collision avoidance methods have been developed for autonomous ferry operation and tested on milliAmpere1. In this section, we present three of these methods.

One of the earliest approaches to collision avoidance specifically designed for milliAmpere1 and autonomous ferries is the Single Path Velocity Planner (SP-VP) algorithm [27][28]. The SP-VP algorithm is based on path-time decomposition. In this concept, the ferry is constrained to be located somewhere on a fixed nominal path. Given this nominal path, obstacles parameterized as moving polygons in the Euclidean space can be transformed into the path-time space. A search tree spanning the path-time space, with the current ferry position as the root node and the end of the nominal path as the goal node is then constructed. Collision avoidance is ensured by requiring the edges in the search tree to not intersect with obstacles. Furthermore, a cost dependent on the speed and the closeness to obstacles is associated with each edge, making it possible to find the optimal path-time trajectory using Dijkstra's algorithm. Finally, the optimal path-time trajectory is transformed to a time-expanded Euclidean space as time-parameterized waypoints that the ferry can track.

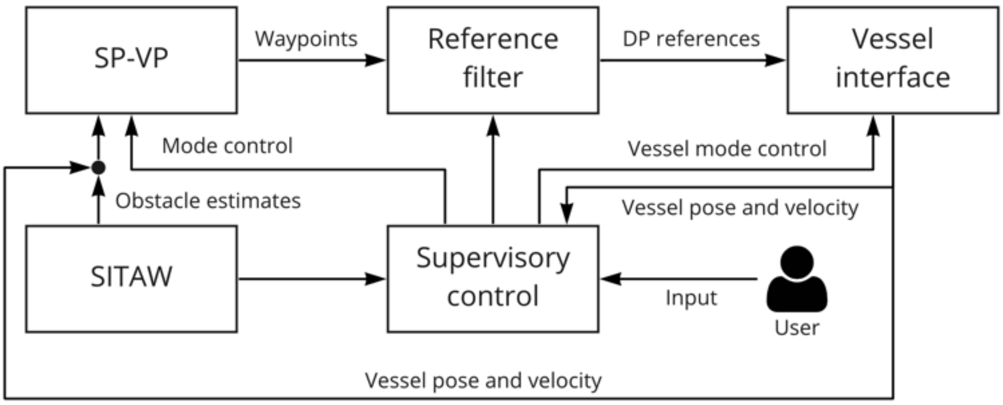

Figure 5: Autonomy system using SP-VP as the core collision avoidance algorithm.

The SP-VP algorithm has been used as part of the basic milliAmpere1 autonomy system (video: www.youtube.com/watch?v=Ry3-yxVaDuE). In this system, the SP-VP algorithm was used together with a tailor-made reference filter to produce continuous pose, velocity and acceleration references for the motion control system. Furthermore, a supervisory control system implemented as a Finite State Machine (FSM) controls the system as a whole to enable autonomous crossing, including docking and undocking. The supervisory control system also implements risk management and several Minimum Risk Conditions (MRCs) serving as fallback solutions in case of unexpected errors. The system can be configured to both run automatically, continuously crossing the canal back and forth, and operate on demand using a button panel to start the ferry crossing.

While the SP-VP is an effective method for collision-free transit across narrow canal-like areas, it does not scale well to a general ferry transit use case. All autonomous vessels must adhere to the maneuvering principles of the International Regulations for Preventing Collision at Sea (COLREGs) when in sight of another vessel, hereafter denoted target ships. This set of rules holds course change maneuvers over speed change maneuvers as the preferred action to avoid collision, and therefore, the fixed path of the SP-VP method makes adherence to these rules problematic. To improve upon this, a more reactive method was developed. The concept was first described in [29], where it was showed that control barrier functions (CBFs) along with encounter-type-specific target-ship domains allowed for maneuvering compliant with COLREGs rules 13-15 and 17. The method ensures collision avoidance with target ships as follows:

1. Classify each vessel-to-vessel encounter with respect to the COLREGs.
2. Assign rule-specific domains to each target-ship. The domains are designed so that if the ferry maneuvers such that it does not violate the target-ship domain, it is also maneuvering in compliance with the relevant COLREGs rule.
3. Formulate CBFs as a function of the distance to and velocity towards each target-ship domain.
4. Apply the CBFs as inequality constraints in a quadratic program that aims to find a generalized force close to the generalized force dictated by the DP controller.
5. Realize the optimal generalized force through the thrust allocation to ensure collision-free maneuvering.

The method also considers static obstacles in a similar way, by formulating CBFs as a function of the distance to and velocity towards each obstacle. The method was verified through experiments in Kanalen with milliAmpere1 and a leisure vessel as target-ship (Figure 6). In the experiments, the target-ship was tracked by lidar and radar, while static obstacles were considered by a combination of electronic nautical charts and lidar.

Works on motion planning among static obstacles include [7], where a two-stage energy-optimised trajectory planning method under polygonal constraints was developed and tested using milliAmpere1. The first stage involved a hybrid A* search, which resulted in a piecewise-linear and collision-free path that was used to warm-start the optimal control solver for further path refinement under dynamic, kinematic and actuator constraints.

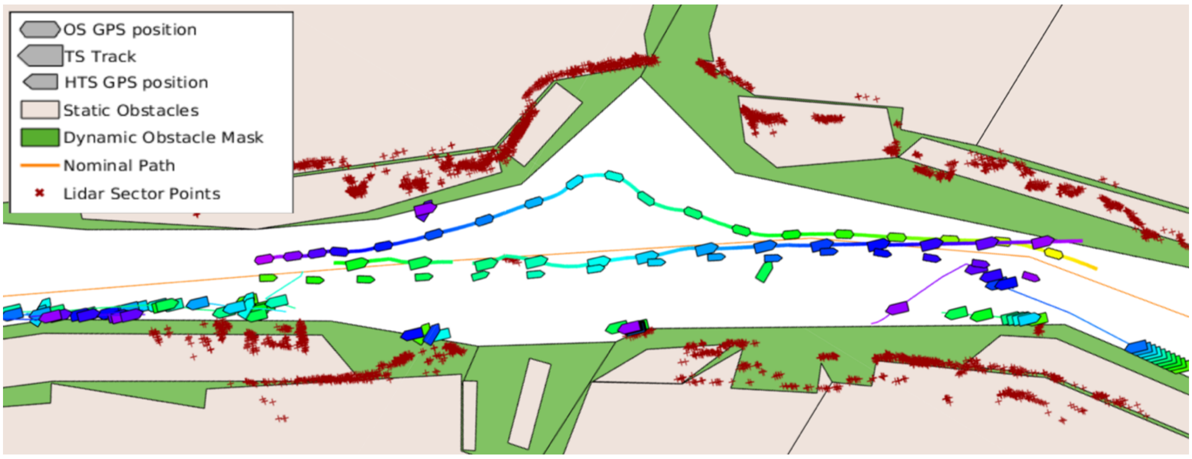

Figure 6: A head-on encounter. The milliAmpere1 tracks a path at the center of the canal and avoids collision by making a starboard maneuver in compliance with COLREGs rule 14. The target ship's tracked position and GNSS position are given by the large and small vessel shapes respectively. The color scale from green to purple represents time. The red crosses give a subset of the lidar points.

4.3. Automated docking

Contrary to motion control scenarios involving path following, trajectory tracking and collision avoidance during the transit phase, automated docking has received less attention in the ASV literature until recently. This is especially the case for works involving field trials and may be attributed to the fact that docking involves intricate maneuvering at low speeds, potentially resulting in high sideslip angles, under the influence of environmental forces. In such conditions, controlling an ASV accurately so as to bring it close to the jetty while avoiding collisions with port infrastructure can be a challenging task even for experienced captains. Moreover, the shape of the ASV has to be considered explicitly to be able to account for collisions between its hull and the infrastructure.

In [14], the finding of docking trajectories was formulated as an optimal control problem (OCP) that incorporates the vessel dynamics and kinematics via a mathematical model, and the harbor and vessel hull layout via appropriate constraints. The OCP trajectory planner was constrained to finding solutions within a static convex set that includes both the ASV in its initial position and the final docking pose.

In [6], this framework was implemented onboard milliAmpere1, with GNSS positioning as the only feedback when maneuvering milliAmpere1 toward the quay from an initial distance of approximately 30m. The previously mentioned PID controller of milliAmpere1 was used to track the trajectories. This docking approach has also been used for undocking in [5]. Then both phases were connected to a transit phase in order to implement a more complete mission.

In [15], the docking algorithm from [6] was further extended to include exteroceptive sensors in the form of lidar and ultrasonic distance sensors. In this way, it was possible to account for unmapped obstacles such as other vessels in the docking area, as well as GNSS positions errors and inaccuracies in the harbor map. An additional contribution was that the convex set, within which the OCP planner computes its solutions, is updated online. Results from the experiments in the Trondheim harbor can be seen in Figure 7, and a video is available at www.youtube.com/watch?v=AyaWlJvI6K8.

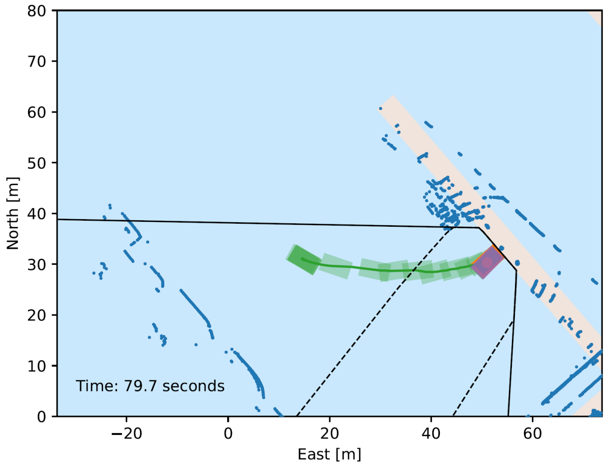

Figure 7: Docking experiments from [15]. The optimization problem plans trajectories within a dynamically-updated convex set. The lidar data (blue cloud) help detect unmapped objects.

5. Situational awareness

Key functionalities for automated situational awareness include detection and tracking of moving obstacles, and localization relative to the surroundings. The latter can be addressed by several approaches, including GNSS-based localization combined with maps, by localization relative to known markers, and by means of Simultaneous Localization And Mapping (SLAM). In this section we summarize the main developments on target tracking and SLAM systems for milliAmpere1.

5.1. Core target tracking system

The basic autonomy system on milliAmpere1 uses RTK-GNSS for navigation, and a combination of radar and lidar for obstacle detection and tracking. Radars have been used in the maritime industry to provide decision support to human navigators long before autonomy, and are especially useful to detect objects far away, at night and in adverse weather conditions such as fog. For these reasons, it is also useful on autonomous vessels. The radar is complemented by a lidar, which is particularly useful for detecting smaller objects that do not have the electromagnetic reflectivity required by a radar. This includes kayaks and small fiberglass/wooden boats, which frequently pass by in urban environments.

The raw sensor data are processed in several steps to extract the information that is used for tracking. In the operational environment of the ferry, most of the data from the sensors are from land-based objects such as buildings and floating piers. In order to remove the reflections from these, the data is transformed to a local Cartesian reference frame. Maps from the Norwegian mapping authority (Kartverket) is used, and only the data from objects on the water is processed further by the detector. This step is highly dependent on the accuracy of the RTK-GNSS. However, in cases with loss of the RTK functionality, the land filtering is still useful to remove most of the detections from land, which reduces the data processing of the subsequent steps. The next step is to cluster point detections from the same target. Points are clustered together via a single linkage clustering algorithm, such that points that are within a defined maximum distance is assumed to originate from the same target. The convex hull of all points in the same cluster is calculated, and this polygon along with its centroid is passed on to the tracker.

Up until this stage, the output of each perception sensor has been processed individually. The tracker fuses measurements from all the available sensors and is based on the integrated probabilistic data association filter (IPDA) [17], which associates the cluster centroids to either existing targets, or creates new targets. It also calculates the existence probability of the target. If the existence probability is sufficiently high, the target is confirmed and used in the motion planning. Tracks with a low existence probability are terminated.

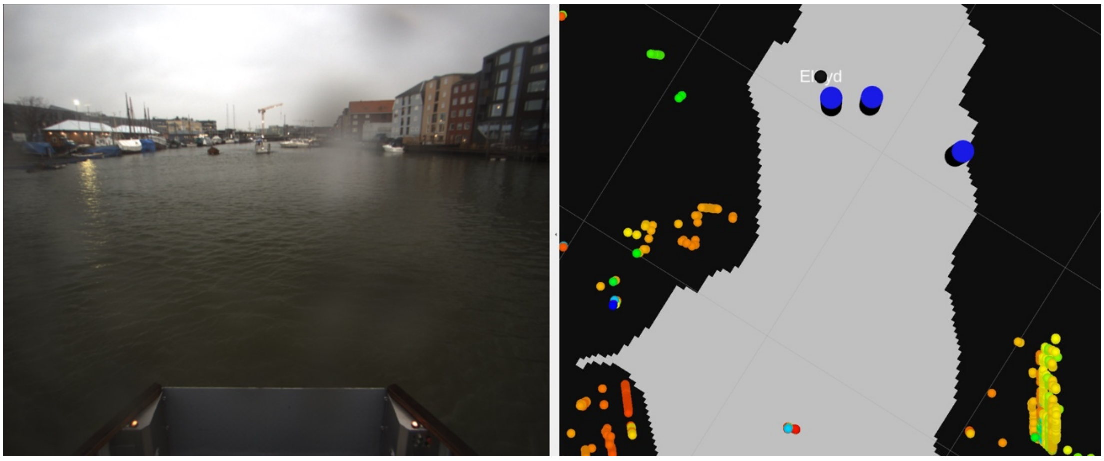

Figure 8: The blue dots are position estimates by means of georeferencing of the ship detections from the image. From the data investigated in [12].

5.2. Active-passive multi-sensor fusion

Research on multi-sensor fusion for milliAmpere1 has focused on measurement-level fusion, where detections from several sensors are fused by a tracking method, as opposed to track-to-track fusion, where separate tracking methods are used for different sensors and then fused. Furthermore, the focus has been on multi-sensor multi-target tracking using variations of the joint IPDA framework. This work is to a large extent based on [10][12], where both radar, lidar, optical cameras and infrared cameras were combined and compared in different fusion configurations (e.g., camera+radar+lidar, pure radar, camera+radar, etc.).

In contrast to the radar and lidar point clouds, the cameras do not supply sensor data in an easily processed format. State-of-the-art techniques for detection and classification in camera images utilize deep learning methods such as convolutional neural networks (CNNs). In the optical camera pipeline used for multi-sensor tracking with milliAmpere1, raw Bayer format images are transmitted via gigabit Ethernet link, converted to color, undistorted to correct for lens distortion (utilizing the camera calibration parameters of each individual camera), and then processed by a CNN such as Yolo v4 to obtain detections (i.e. bounding boxes) as well as class information (e.g. motorboat, kayak, sail boat, etc.). Infrared images are processed in black and white, and otherwise following the same pipeline. The detectors have been trained on images from various littoral environments in Norway.

The passive nature of the imaging sensors only allows detections from images to explicitly encode the direction of the target relative to the camera. This lack of range information can pose a challenge in harbour environments such as milliAmpere1's operational domain because boats moored along the marinas (see top of Figure 8) may flood the system with detections. A solution to this is to use georeferencing, where range is estimated from triangulation by means of the cameras' height above the water [11]. Then, the same land filtering techniques as were used for radar and lidar can also be used to exlude the moored boats. See bottom part of Figure 8.

Notwithstanding these issues, the detection performance of the optical cameras is on level with lidar (above 0.75) and their maximum detection range is also greater. In datasets recorded outside Brattøra in the Trondheimsfjord, an area without moored boats, fusing lidar with optical bearing measurements yielded several performance benefits such as increased tracking accuracy and reduced periods of time when a target was untracked.

Another custom-made sensor rig has also been made for research on stereo vision for milliAmpere1. This rig has two point grey cameras with a baseline distance of 1.75m, enabling reliable distance estimation for vessels up to about 80m away from the ferry [3] [25].

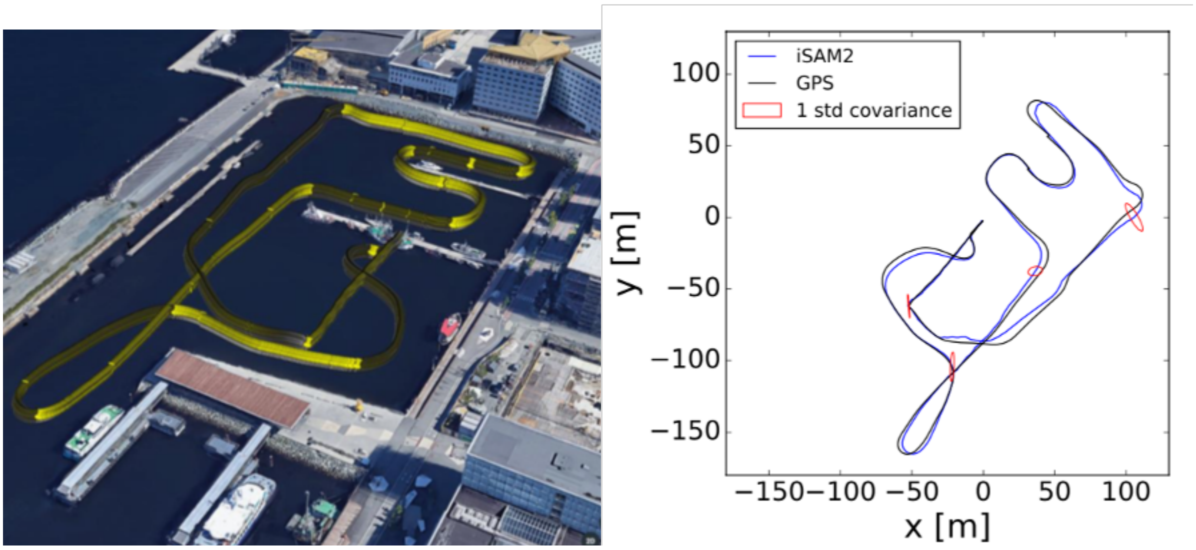

Figure 9: Trajectory of milliAmpere1 during SLAM experiments in Brattørabassenget (left), together with experimental results (right) [22].

5.3. Lidar-based SLAM

Research on SLAM for milliAmpere1 has focused on the lidar. A main advantage of the lidar compared to other sensors is that it both provides high resolution (in common with cameras) and range information (in common with radar) without any need for intrinsic calibration (in contrast to stereo vision). The most mature results so far on SLAM for milliAmpere1 were reported in [22], where a feature-based factor graph solution was used, building upon Incremental Smoothing And Mapping 2 (ISAM2) [13]. Factor graphs is a convenient approach to SLAM, both because they facilitate efficient computational techniques such as ISAM2, and because they are highly flexible, allowing the user to define suitable factors for different information sources such as IMU, GNSS and loop-closure.

In feature-based SLAM it is crucial to be able to extract reliable and stable features from the lidar data, so that the SLAM system can estimate own motion by observing the relative motion of the particular feature points over multiple scans. In this work, the Intrinsic Shape Signatures (ISS) feature extractor was used to extract features, while the Signatures of Histograms of OrienTations (SHOT) descriptor was used to recognize the features between the different keyframes.

The SLAM system was initially implemented as a pure odometry system, which only estimated motion between successive sensor scans. A detailed description of this system, including a comparison of several feature extractors and descriptors, can be found in [21].

The full SLAM system integrates IMU, RTK-GNSS and loop-closure in the factor graph to reduce the drift and allow for more accurate positioning. To enable real-time performance, keyframes are used, and features are only added to the map when milliAmpere1 has moved more than 3 meters since the last keyframe. In this map, the SHOT descriptor is also stored to allow for quicker loop closure detection. To detect the loop closures, a SHOT descriptor is first used, before RANSAC is used to ensure no false positives are detected.

A trajectory used for validation of the lidar-based SLAM system can be seen in Figure 9. This trajectory is approximately 1060 meters and was recorded over 636 seconds.

Results of the system can be seen in Figure 10. For this run, the RTK-GNSS signals was disconnected from the system after 323 seconds. The SLAM system is then running with the lidar odometry, the IMU measurements, as well as the loop closure detection ability for the final 323 seconds. During this run, the loop closure is detected at the dock, which is the start and end point, and the whole trajectory. As seen in the figure, the full trajectory is within the 1 std covariance. The average 2D positional error for the second half of the run is 2.3 meters, while the end-to-end error is 0.9m.

5.4. Fiducial SLAM

Non-GNSS localization is especially useful during docking scenarios, when high-precision navigation relative to a floating quay is needed. Due to tidal water the exact location of the jetty may be slowly changing and cannot be pre-programmed. Furthermore, if the lidar is placed on the top of the vessel, as is the case for milliAmpere1, the lidar may not be able to detect the jetty, neither at long nor at short range. An alternative can then be to place fiducial markers such as april-tags at known locations on the jetty. The pose of the ferry relative to the markers can then be estimated by means of its optical cameras. For milliAmpere1, this approach to localization has been investigated in [9]. Again, the ISAM2 framework was used as a back-end, while the segmentation-based AprilTag detector of [36] was used in the front-end. A similar investigation, utilizing stereo vision and machine learning (Yolo v3), was reported in [34].

Figure 11: The NTNU Shore Control Lab with a prototype of an HMI giving situation awareness and automation transparency to operators.

6. Shore control lab

The NTNU Shore Control Lab is a testing infrastructure built for the purpose of investigating land-based operation of autonomous vessels. The aim of developing autonomous vessels is not to remove human operators altogether – rather, the intention is to coordinate the actions of the autonomy system and operators. The human remains "in the loop," and is always able to take preventive action if needed. The shore control concept is based on three underlying principles: (1) the operator always understands what the autonomy is "thinking," (2) the operator always has sufficient situation awareness to be able to take over control at a moment's notice, and (3) the operator can turn on and off the autonomy at any time. The physical layout and instrumentation of the NTNU Shore Control Lab is based on resilience engineering and human-centered design methods [33]. Details on the lab's research aims and its integration with the rest of the NTNU autonomous ferry infrastructure are presented in [1].

The milliAmpere1 served as a catalyst in the design of the shore control infrastructure, making abstract requirements become specific requirements for land-based supervision. At the time of writing, both milliAmpere1 and its successor milliAmpere2, are being connected to the NTNU Shore Control Center. From the three principles of shore control needs listed above, data transmission was a key design requirement. The vessels transmit data to the Shore Control Lab via a private 5G network with a bandwidth of approximately 10 Gbps. A rooftop base station receives the signals relayed from the vessels. This includes all four mast-head sensors (360-degree optical and infrared video, radar, and lidar), as well as conditional monitoring information related to the power and propulsion system. Navigation information such as GNSS position, speed over ground, and heading is also relayed. Upon entering the control center, video data is converted into the AVoIP protocol for managing the various inputs. A network-connected DP joystick controls the system aboard ferry. Two-way audio transmitted by radio-over-IP will also be enabled for communication between the ferries. The cyber-security of the network is described in [2].

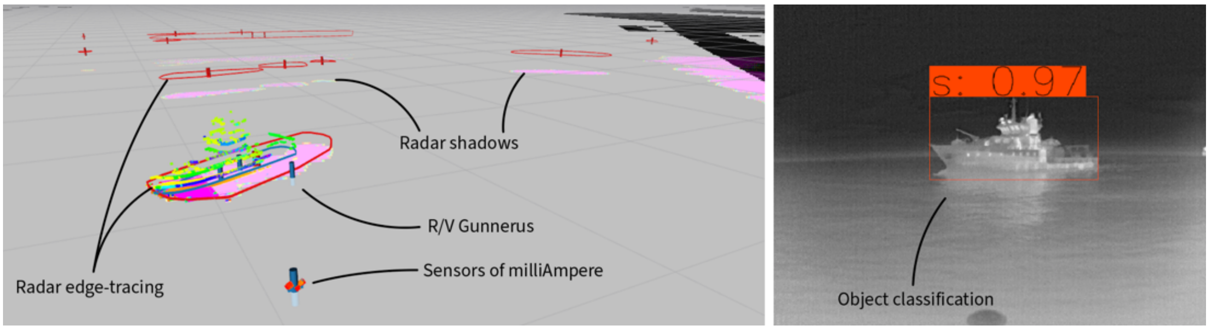

Figure 12: Sensor fusion of radar and lidar (left) and infrared camera (right), which can support human situation awareness and decision making at the NTNU Shore Control Lab.

Some of the questions for investigation at the NTNU Shore Control Lab include:
1. How can we display sensor data in a way that enhances automation transparency?
2. How do we display sensor data in a way that maintains situation awareness?
3. How do we design tasks, procedures, and alarms that ensure that the human controller always knows when to take preventive action?

The sensor data, when transmitted from the ferries to the Shore Control Lab and displayed in a human-computer interface, can be used to test the extent to which human situation awareness is supported. Critical in this regard is maximum response time, T_{MR}. Maximum response time is the amount of time it takes to detect a critical situation, take over control, and gain sufficient situation awareness to appropriately handle a given situation. Besides serving as a core measure in the approval of MASS designs [20], T_{MR} is also an objective measure for comparative assessment of different interface designs.

In such efforts as these, the use of a simulator is crucial, as it enables controlled and repeatable experiments. For this reason, a custom simulator featuring the vessels has been developed in Unity based on the open-source Gemini platform described by [35]. Researchers can build their own traffic scenarios and run trials with participants, varying interface variables and measure the effect on T_{MR}. Collection of operators' biometric data during simulator testing will also allow insights into several important human factors with sound theoretical precedents. Biometric data and their human factor proxies include eye-tracking (visual attention), pupil dilation (cognitive load), as well as heart-rate variability and galvanic skin response (stress). This can allow objective measures that collectively shed light on the extent to which the "traffic picture" can be re-created digitally for interpretation in the mind of an operator. A multi-disciplinary approach is key to such testing efforts, combining randomized human trials experiments and methods traditionally associated with the quantitative behavioural sciences with those disciplines that develop autonomous functionality. The contribution is better design of the human-computer interface (HMI) for autonomous ship systems in the short term, and safer, more robust systems in the long term.

7. milliAmpere2

The full-scale pedestrian ferry milliAmpere2 was launched in June 2021, and has since then completed several tests, including continuous autonomous operation in excess of three hours and autonomous mode with passengers. While milliAmpere1 was designed to enable research on autonomy, the design of milliAmpere2 is to a larger extent governed by the reliability needed for an autonomous ferry that is to be used in continuous operation. The autonomy system of milliAmpere2 builds upon an industrial DP system, and has extensive redundancies to support fail-safe mechanisms. Furthermore, the fragile configuration of two rotating azimuth thrusters is replaced by a configuration of four azimuth thrusters with limited rotation, which control the ferry through their relative forces. Also for milliAmpere2, all closed-loop experiments have made use of radar-lidar fusion. A hazard analysis relevant to both milliAmpere1 and milliAmpere2 has been conducted by [26].

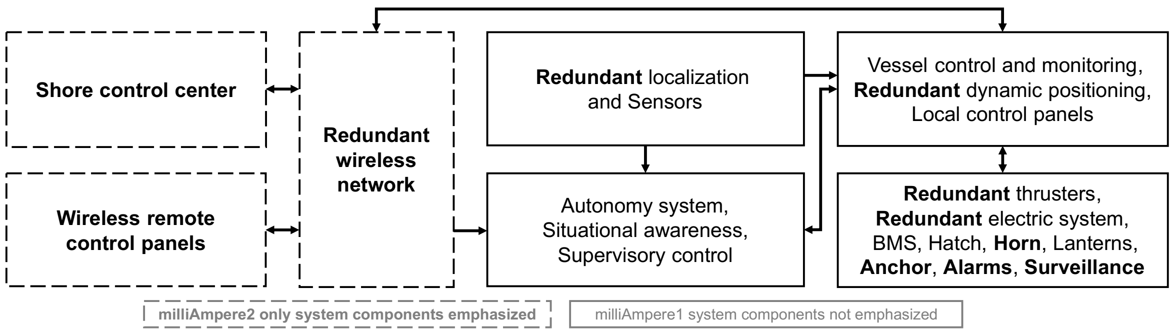

Figure 13: System architecture of milliAmpere2.

8. Conclusions

In this article, we have looked upon several elements of the autonomy systems of the autonomous ferry prototype milliAmpere1. Ultimately, autonomy demands levels of safety that make the system trustworthy. The comprehensive body of experimental research results that milliAmpere1 has been a part of will be valuable when future autonomy systems for other autonomous ship applications like passenger transport are to be designed according to strict safety requirements.

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Acknowledgments

The construction of milliAmpere1 and 2 was funded by NTNU. Furthermore, NTNU has funded research activities related to milliAmpere1 and 2 through the Digital transformation project Autoferry. This work was also supported in part by the Research Council of Norway through projects 296694 (aFerry), 223254 (AMOS) and 309230 (SFI Autoship). Several researchers, postdoctors, PhD candidates, MSc students, BSc students, internship students and technical employees have taken part in the development of milliAmpere1 and related research, and the authors are deeply grateful for all their contributions.