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NTNU Shore Control Lab: Designing shore control centres in the age of autonomous ships

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Abstract. As highly automated ships become unmanned, their operators will move into shore-based control centers. In the last years, NTNU has built an advanced and flexible research infrastructure for performing research on autonomous ships and the monitoring and control of these. The infrastructure comprises of (1) the *milliAmpere1* and *milliAmpere2*, which are two all-electric autonomous urban passenger ferries equipped with advanced sensors and equipment for autonomous navigation, (2) the *Shore Control Lab*, a flexible shore control center, where operators can monitor and control a fleet of autonomous ships, (3) a lab section for researchers to give instructions to operators in the control center, and to record, observe, and analyze their behavior, (4) an observation room adjacent to the control room for stakeholders to observe ongoing experiments in the control room, (5) the ferry simulator *Autoferry Gemini* that allows researchers to create challenging or high-risk scenarios where operators can be stress tested without being a danger to ship, crew and passengers, (6) the mixed reality lab *MRLAB,* where we can test physical designs of urban autonomous passenger ferries in a virtual environment, and (7) a dock for passenger handling and with inductive charging capabilities. In this paper, we first describe the research infrastructure's purpose and scope of operation, as well as the technical design, physical setup, and equipment. Secondly, we present a roadmap for the development of the research infrastructure to meet the future research challenges for autonomous ships and the supervision and control of these. Thirdly, we present a number of research questions that are going to be explored in the lab in the years to come.

1. Introduction

As highly automated ships are becoming unmanned, their operators are expected to move into shore-based control centers. In these centers, a team of operators, trained in navigation, can monitor the status of a fleet of autonomous ships and take over their control when intervention is necessary. There is much knowledge on how to design control rooms for remote control of ships and drones. However, in the age of self-driving ships, there are still gaps in our understanding of how to design control rooms.

In 2020, we started the process of building the *NTNU Shore Control Lab*, which is a flexible research infrastructure for developing and testing remote monitoring and control of autonomous ships, including different physical setups and human-machine and graphical user interfaces for such control centers. The infrastructure comprises of:

- ***milliAmpere*** (hereafter called milliAmpere1) and its sibling ***milliAmpere2***, two all-electric autonomous urban passenger ferries equipped with advanced sensors and equipment for autonomous navigation and for providing the data necessary for giving operators superior situational awareness
- a flexible **shore control centre** where a number of operators can monitor and control a fleet of autonomous ships, including *milliAmpere1* and *2*
- a **lab section** for researchers to give instructions to operators in the control center, and to record, observe, and analyse their actions and behavior
- An **observation room** for developers, product owners, product managers, and other stakeholders to observe experiments, field tests, and usability evaluations of different control room setups and user interface designs
- *Autoferry Gemini*, a **ship simulator** based on the open-source Gemini platform allows us to create challenging or high-risk scenarios where operators are stress tested and new user interfaces are evaluated without jeopardizing the ship, crew, passengers, or equipment
- a **mixed reality lab** where physical designs of urban autonomous passenger ferries, as well as the passenger experience, can be tested and evaluated in a safe, virtual environment.
- **ferry docks** with induction charging and land-based terminals for passengers.

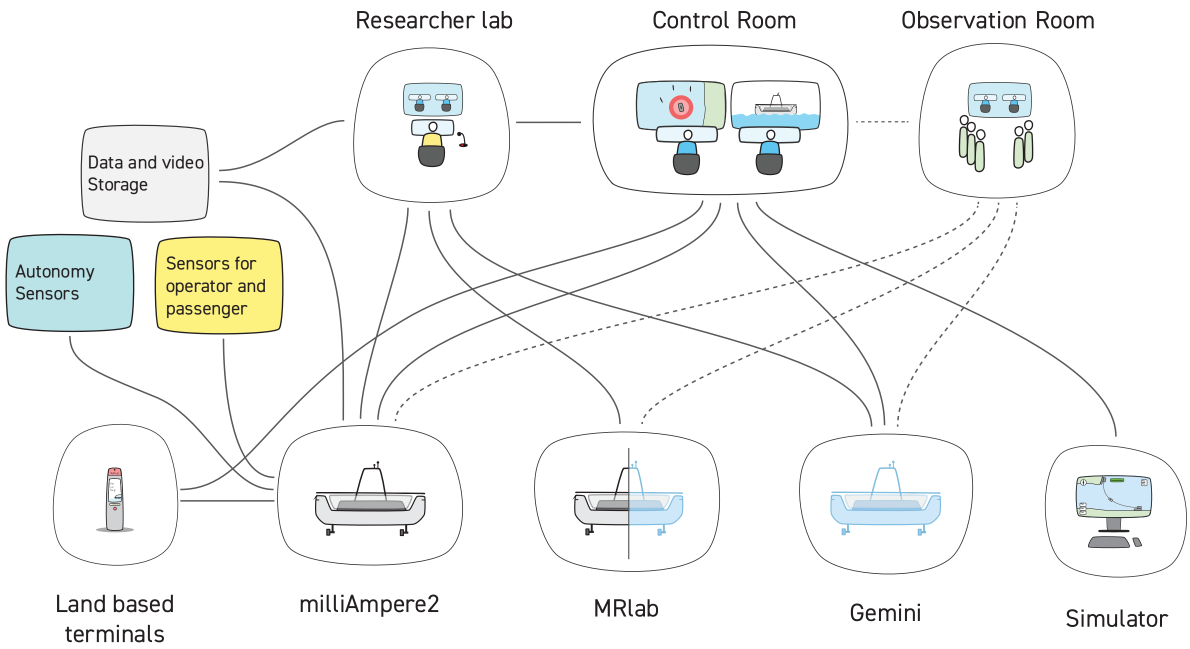

Figure 1: The different parts of the NTNU Shore Control Lab infrastructure and how they are connected

The rest of the paper is organised as follows: In Section 2, we present a review of the current state-of-the-art and trends in remote control centers, both in the maritime domain and other domains, such as vessel traffic service VTS, air traffic control, roads, railways, etc. In Section 3, we describe the research infrastructure, its purpose and scope of operation, as well as a detailed description of the technical design and physical setup. This description also includes the sensors on the ferry, the equipment in the shore control center, and the tools and instruments that the researchers have available in the lab section to measure and analyse the operators' stress levels (e.g. biometrical sensors, eye-tracking, recording equipment). In Section 4, we present a roadmap for the development of the research infrastructure to meet the future research challenges on autonomous ships and the supervision and control of these, together with a number of research questions that are going to be explored in the lab in the years to come.

1.1. State-of-the art in research

Autonomous ships are developing rapidly from concept to creation. Several categories have emerged, including short-sea shipping (e.g., MV Yara Birkeland [1] and SFI AutoShip Project [2]), open-ocean shipping (e.g., MUNIN [3]), urban ferries (e.g., Roboat [4] and milliAmpere [5]), and autonomous surface vessels for data collection [6]. So-called "smart ships" envision a coordinated AI-operator teaming on the bridge [7, 8]. These examples encompass a "Maritime 4.0" research community [9] that combines automation in ships and ports for safer, more effective shipping.

Academic interest in shore control of autonomous ships has increased in tandem with the growth of "Maritime 4.0." In the field of safety and risk science, researchers have examined the role of humans as safety controls in the operation of autonomous ships, applying advanced modelling techniques to predict how critical scenarios like collision avoidance will be coordinated [10-14]. Others have raised the challenges associated with human factors and training requirements of Shore Control Center Operators [15-20]. Meanwhile, applications have expanded from coastal "short-sea" shipping applications to shore control for urban autonomous passenger ferries [21] and inland waterway vessels [22].

In 2021, the International Maritime Organization, the global regulatory agency for international shipping, weighed in. In their much-anticipated "Regulatory scoping exercise for Maritime Autonomous Surface Ships (MASS)," they highlighted where current regulations fall short of addressing the needs for autonomous ship operation [23]. Among the top three "high-priority items," all were related to the Shore Control Center (or the "Remote Control Center" as the IMO calls it) and especially to the roles and responsibilities of the operators working in them. For the autonomous ship as a concept, the coordinating efforts of the Shore Control Center represent its link to real-world operation. In the real world, it is necessary for humans to complete the picture, chaperoning the autonomous ship's conduct in traffic with manned vessels both big and small, maintaining the vessels' integrity preemptively, and appropriately handling unexpected events that no autonomous agent acting alone could adequately address. The Shore Control Lab, in combination with the milliAmpere prototypes, is probably one of the first research platforms dedicated to investigating the relevant questions arising from the vision of safe autonomous ship operation.

1.2. Control rooms in other domains

There is much to be learned from other industries in the field of control rooms embedded in automated systems. In the 1980s, research associated with the digital transformation of control rooms used in the process industries (especially nuclear power plants) addressed issues with how humans interact with technology and led to the inception of whole fields like cognitive engineering [24]. The multi-disciplinary *Computer-Supported Collaborative Work* arose in the 1990s from seminal work focused on line control rooms in the London Underground [25] leading to the use of ethnographic methods in the study of control rooms. Air Traffic Control (ATC) has also been a subject for applied research in safety-critical interaction design [26]. More recently, remote ATCs like the ones in Bodø, Norway [27] and at the German Aerospace Center in Braunschweig are addressing research on the implementation of remote tower centres (ROT). One thing they investigate, e. g. is using additional camera viewing angles and augmenting video feeds with information to enhance the ROT's situational awareness. Additionally, in this ROT, they conduct cognitive work analysis and research with various sensing technologies and interface enhancements [28, 29]. Similar principles to those explored in the aforementioned research study have been utilised to a greater extent in Norway, most notably by the airport operator Avinor, to effectively monitor the airspace in less-operated areas from a distance.

Stanton [30] discuss the design of a future flight deck in which an aircraft has just one pilot who, if required, may get assistance from a ground-based "second pilot" who can operate the aircraft in an emergency like an unmanned aerial vehicle (UAV). This approach is meant to assist in achieving manpower savings while still adhering to the greatest safety requirements. Personnel on the ground must possess the same specialised qualifications as those on an aircraft's flight deck.

Additionally, control rooms are utilised by autonomous underwater vehicles that do a variety of scheduled tasks. Roberts [31], examine the future architecture of submarine control rooms. Consideration is given to factors such as team composition and control room layout, as well as the sensors employed, which were also implemented in a summation environment and serve as a valuable research tool.

Similarly, in the area of powerplants, particularly nuclear powerplants, various research organisations, one of which is the Norwegian Institute for Energy Technology, are examining the design and structure of a control room in more depth (IFE) [32]. Other research organisations are also interested in this subject, and it's worth noting that simulators are often used to study human aspects and the consequences of novel design ideas [33]. This is a very advantageous method for safety-critical situations, as accidents can be fully prevented while new design ideas are being tested. This supports the creation and usage of a simulator in the environment described in this article.

In summary, we may transfer information from other areas to the maritime domain to a certain degree, for example, by using wide-angle camera views, which was researched in aviation. The differences in the technologies used, the dimensions and environmental factors involved, and the knowledge required are too different, which is why shore-based monitoring and control of MASS is a critical research facility for advancing the automation of the Maritime Domain.

1.3. Ongoing projects
The NTNU Shore Control Lab is currently utilised in a number of research projects in collaboration with academic and industry partners, where we have listed some key projects in Table 1.

Table 1: Ongoing research projects utilizing the NTNU Shore Control Lab

Project	Purpose and research aim
Autoferry *2018-2023*	To develop all-electric, autonomous passenger ferries for urban waterways.
SFI Autoship *2019-2027*	A centre for research-based innovation focusing on the development of autonomous ships for safe and sustainable operations.
LOAS 2019-2023	To design and test interaction solutions for “Land-based Operation of Autonomous Ships”
TRUSST *2020-2023*	To develop knowledge and solutions to assure trustworthy, safe and sustainable autonomous passenger transport
MIDAS 2022-2027	To strengthen research and innovation capacity in design and business development for technology companies that develop autonomous solutions for the ocean space
SCAPE *2021-2024*	To develop new innovations that will revitalize urban waterways with zero emission, autonomous passenger ferries
LASH FIRE *2019-2023*	To significantly reduce the risk of fires on board ro-ro ships.
MAS *2021-2025*	To improve the safety level in the petroleum sector through the implementation of human-centered autonomous/digital solutions in safety critical operations

2. Development methodology
After the development of *milliAmpere*1, one of the world’s first prototype of an urban autonomous passenger ferry, the team behind it realised that a more multi-disciplinary approach was needed. The development team, which was a collaboration between the Department of Engineering Cybernetics,

Department of Electronics Systems, and Department of Marine Technology, now contacted the Department of Design, with expertise in human factors, human-centered design, and industrial design, to participate in the development of the successor, *milliAmpere2,* and a shore-based control room to monitor the ferries.

The different parts of the research infrastructure were developed using a range of different methods. The details of the methods used are out of the scope of this paper, but a combination of engineering methods and human centred methods were used. In Table 2, the methods used are listed.

Table 2: The methods used in developing the research infrastructure

milliAmpere1 (2017)	**Gemini simulator (2019)**	**milliAmpere2 (2020)**	**Shore Control Lab (2021)**	**MRLAB (2021)**	**Docs and terminals (2021)**
Engineering Goal-based Risk-based approach Nordic boat standard	Software development Game development Interaction design	Engineering Goal-based Risk-based approach Nordic boat standard Human-centered design Industrial design	Human-centered design Prototyping Interaction design	Human-centered design, Prototyping, Software development,	Human-centered design Prototyping Interaction design

3. Research infrastructure

The research infrastructure consists of two main parts. The first part is four prototypes of an urban autonomous passenger ferry and its docks and land-based terminals (see Figure 1):

- **milliAmpere1**, which is described in detail in [5] and not further described here.
- **milliAmpere2**, which is the successor of milliAmpere1.
- **milliAmpere2 simulator**, which is based on the open-source platform Gemini [35].
- **MRlab**, A full scale mixed reality simulator of milliAmpere2.
- **Dock** with inductive charging capabilities and land-based terminals.

The second part of the research infrastructure is the NTNU Shore Control Lab, which is a research facility for the design of shore control centres of the future. The lab consists of four rooms (Figure 2):

- **A reception area** where test participants are welcomed and briefed (not further discussed in this paper)
- **A shore control centre** currently set up for two operators
- **An instructor station** where researchers can instruct and observe the operators during experiments
- **An observation room** where stakeholders and the development team can observe experiments.

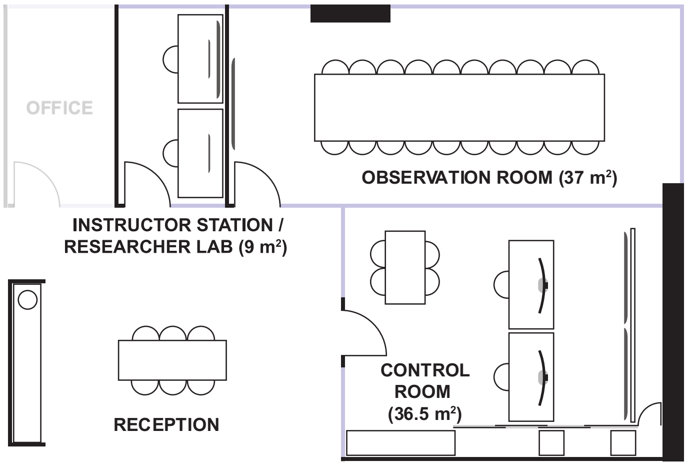

Figure 2: The floor plan of the Shore Control Lab, which consists of a control room, an observation room, an instructor/researcher lab, and a reception area for test participants

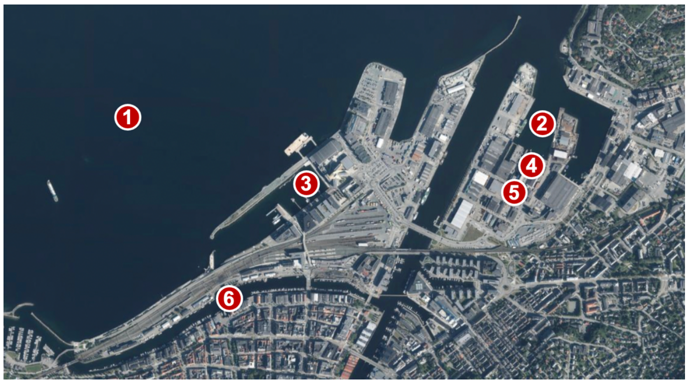

Figure 3: The harbour of Trondheim with (1-3) test areas for autonomous ships, (4) NTNU Shore Control Lab, (5) MRLAB, and (6) milliAmpere2 crossing (Photo: Norgeskart)

The infrastructure is in various locations near the harbour of Trondheim (Figure 3). In the following subsections, we present the details of each of these parts, together with a description of how they are linked together.

3.1. Shore control centre

The control room is designed to let operators (currently two) monitor or control autonomous ships (Figure 4). It can also be used to monitor and control other autonomous or remotely operated systems in various domains, such as ships, drones, or ROVs. The main purpose is to do research related to control room design for autonomous or remote operations and to design innovative solutions for improving the operators' situational awareness.

The main difference between the Shore Control Lab and other remote-control centres is the possibility to run controlled experiments with recordings of sensor data from autonomous ships and lab equipment. It also allows for detailed sound and video recordings of the operators and their interactions with the systems and each other, as well as collecting biometric data from the operator's attention and stress levels. This is further described in the next subsections.

The control room has been designed for flexibility, making it ideal for different setups and experiments as new needs arise. Along the front wall and in the ceiling, there is mounted a rigid grid system that allows for easy mounting or reconfiguring of equipment such as screens, cameras, microphones, etc., as seen in Figure 4. Technical and audiovisual equipment is hidden behind sliding doors. Along the left wall are glass windows with a two-way view to the observation room that can be sealed off with curtains. Care has been given in the design of the room's lighting, acoustics, and cooling to improve the operators' working environment.

The current configuration has two operator stations, each equipped with a 49-inch curved wide screen. On the front wall, two 75-inch touch screens are mounted on a height-adjustable rack so that their working positions can be adjusted both for being viewed at a distance or for touch operation. The operators have access to necessary input devices and a microphone and headset for communicating with crew or passengers onboard the MASS, other ships, VTS or harbour authorities, or the researcher in the instructor station. Every camera or computer display signal can be routed to any screen in any of the rooms in the lab (using AV over IP), adding up to the flexibility of the infrastructure.

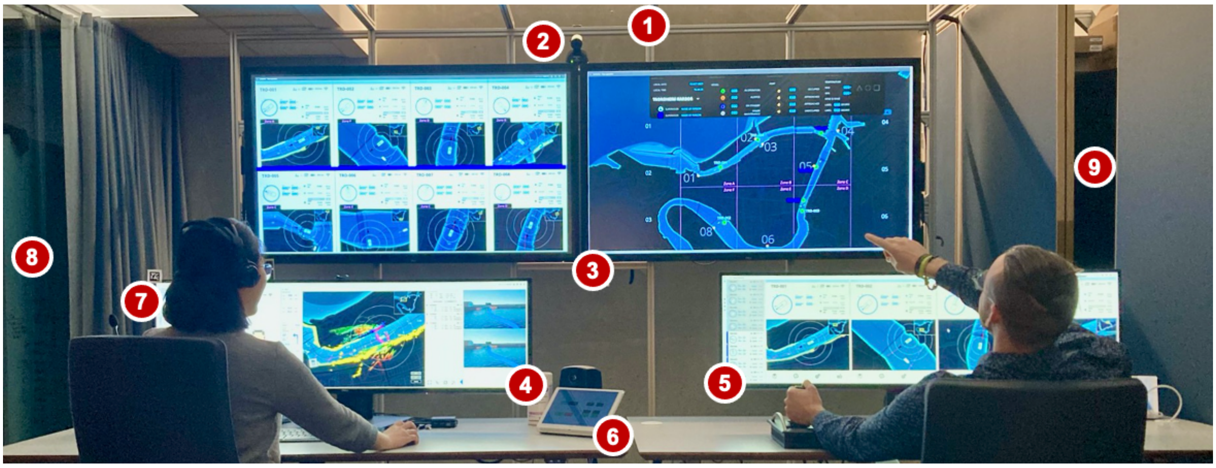

Figure 4: The control room with (1) Aluflex grid for flexibility, (2) cameras, (3) two height adjustable touch screens, (4-5) operator stations, (6) control panel, (7) microphones and loudspeakers, (8) view to observation room, (9) technical equipment (Photo: Erik Veitch)

3.2. Observation Room

The observation room is designed to let researchers, observers, developers, product managers, project managers, and other stakeholders observe experiments or ongoing operations in the control room without disturbing or interfering with them (Figure 5). It can also be used as an emergency room during exercises, real accidents, or extraordinary events.

The observation room seats up to 20 people. It has windows along three of the walls, giving a good view of the harbour area. The room is equipped with a large screen, loudspeakers, microphones, and cameras connected to the system. This allows any video or camera signal in the system to be routed to this screen so that the people in the room can observe what is going on in the lab or on the ship.

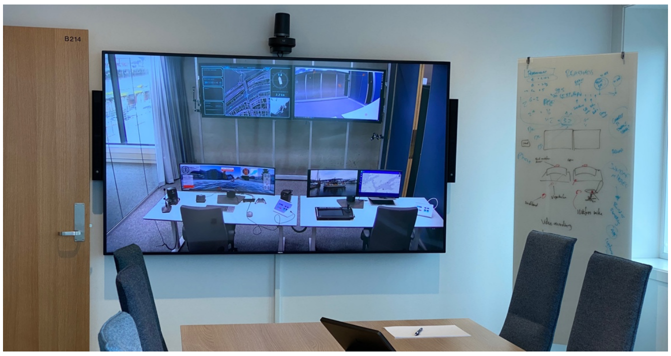

Figure 5: The observation room. (Photo: Ole Andreas Alsos)

3.3. Instructor station and researcher lab

The instructor station/researcher lab is designed for researchers to (1) give the operators assignments or scenarios, (2) to monitor experiments or ongoing operations, and (3) to analyse video and sensor data from experiments and evaluations (Figure 6). With the lab, researchers can do a real-time or delayed analysis of the collaboration, individual behavior, and stress level of the operators and discover usability problems in the user interface.

The instructor station/researcher lab is installed in an office space with two workstations. Here, the instructors and researchers have access to one wall-mounted 42-inch screen that shows sensor data and several video streams from the lab. In addition, they have access to a 49-inch widescreen that is connected to the lab computer. The cameras in the control room can be remotely controlled from the lab. It also has an audio system that allows the researchers to communicate with the operators.

Figure 6: The instructor station / researcher lab. (Photo: Nicholas Lund)

3.4. Urban Autonomous Passenger Ferries, milliAmpere 1 & 2

The milliAmpere2 (mA2) is an all-electric, urban autonomous passenger ferry that is also a research platform for research on autonomous ships (Figure 8). It was based on knowledge from its predecessor, milliAmpere1 (mA1), which was built and launched in 2017 [5] (Figure 7). It was developed as a joint project between several departments at NTNU; Department of Design, Department of Electronic Systems, Department of Marine Technology, and Department of Engineering Cybernetics, were all involved in designing and building it. The ferries' main purpose is to investigate research questions related to sensor fusion, autonomy, situation awareness, passenger flow, and trust. Specifications for the two ferries are presented in Table 3.

Figure 7: The all-electric urban autonomous passenger ferry milliAmpere1 (Photo: Egil Eide)

Figure 8: The all-electric urban autonomous passenger ferry milliAmpere2 (Photo: Egil Eide)

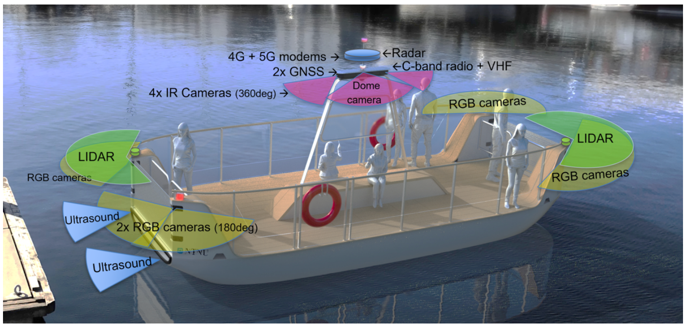

Figure 9: The autonomy sensors onboard milliAmpere2

The milliAmpere2 is equipped with sensors and computer equipment for autonomous operation cameras, ultrasound distance sensors, IR cameras, LIDAR, radar, and GPS (Figure 9). In addition, the ferry is equipped with sensors for operator situation awareness and passenger safety and information, such as a 180-degree dome camera, 3D microphones, loudspeakers, and IMU sensors for registering ferry motion and acceleration. The main purpose of these sensors is to give the operator a feel of the ship so that they can get insight into the ship's state and future intention, in addition to monitor the passengers and surroundings.

The ferry is also equipped with mandatory safety equipment and a user interface for passengers to interact with it. The user interface consists of buttons to start the crossing and to contact the operator, and two touch screens (one on each side of the mast) for information to the passengers.

Table 3: Specifications for milliAmpere1 and milliAmpere2

Specification	**milliAmpere1**	**milliAmpere2**
Length (LOA)	5.0 m	8.5 m
Beam	2.8 m	3.50 m
Draught	0.2 m	0.3 m
Air draught	3.3 m	3.5 m
Max pax	6	12
Propulsion	2 azimuth thrusters	4 azimuth thrusters
Operation speed	3 knots	3 knots
Max speed	5 knots	5 knots
Energy	Electric 24V DC	Electric 48V DC
Batteries	Lead-Acid VRL 24 kWh	Lead-Acid VRL 48 kWh
Power	2 x 2 kW	4 x 10 kW
Sensors	IR camera, camera, RADAR, LIDAR	IR camera, camera, RADAR, LIDAR, ultrasonic

3.5. Gemini

Gemini is an open-source project based on the Unity game engine [36] with the purpose of exploring the role game engines have in autonomy, focusing on maritime applications (Figure 10). Due to the lack of maritime alternatives to simulator frameworks such as *Carla* [37] and *AirSim* [38] and the tight integration these have respectively to cars and drones, Gemini went for a toolbox design that allows the designer to develop different applications untied from vehicle specific frameworks. This allows Gemini to be used in various projects.

One of the projects is to simulate the use of *milliAmpere2* and passenger transport on the Trondheim Canal using a simulator referred to as *Autoferry Gemini*. In the Shore Control Lab, Autoferry Gemini has several important purposes: It allows us to (1) test the autonomy system and the sensors [35], actuators, and control systems in a simulated environment, (2) study the relationship between human operators and autonomy [39], (3) expose both the autonomy and the human operators to rare tail events in a safe environment without the risk of people and equipment, and (4) develop, test, and evaluate different human-machine interfaces for monitoring autonomous ships. The former uses several technologies related to video games, high-performance communication, and autonomous systems. Camera modelling is done using Unity's *High-definition render pipeline* designed for real-time high-fidelity simulations. This is also used to model range sensors by attaching *compute shaders* to the pipeline system. These shaders function as general-purpose GPU programs from which sensor models such as radar and lidar are created. Both sensor and generic Unity data are accessible by external programs using *Google's remote procedure calls*. For Autoferry Gemini, this is used, among others, to emulate the sensory system on *milliAmpere2* to test the situational awareness system on the ferry [5].

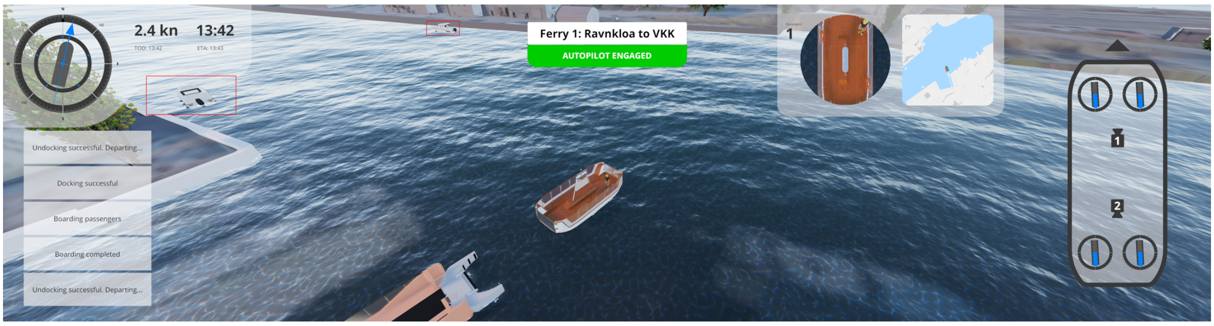

Figure 10: Autoferry Gemini, a simulator for testing and developing HMIs for the operator

In relation to the Gemini simulator, we have started work on a *Scenario Builder* that allows us to quickly create various scenarios that can give the operators missions of varying difficulty and cognitive workload [40]. The same builder can induce rare tail events, where operators are forced to take control of the ferry.

External parties outside NTNU are also using Gemini in their development: (1) The *Njord student challenge*, [41] with the purpose of creating an autonomous ship challenge educating and motivating students in a COVID friendly arrangement. (2) *Zeabuz* simulator [42], with the purpose of verifying their autonomy system for safe operations in urban waterways.

3.6. Mixed Reality Lab

The Mixed Reality Lab (MRLAB) is a 190 m^2 area where we have built two full scale low-fidelity models of the milliAmpere2 superstructure in wood (Figure 11). Its purpose is to test different physical layouts and functionality of urban autonomous passenger ferries in virtual reality. The ferry mockup allows passengers to experience a virtual and tangible ferry trip where they can board the ferry, touch the handrails or mast, and sit on the bench under various weather and traffic conditions. Here, the whole user journey, or parts of it, can be simulated in a highly immersive environment to gather rich feedback from the passengers on their experience and their trust towards the ferry. This allows researchers, industrial designers, and naval architects to test out different physical designs and interaction designs on the ferry and dock in a cheap and risk-free way. Relevant research questions from other parts of the infrastructure can be investigated here in simulations with a high level of realism.

In addition to the two full scale mock-ups of milliAmpere2 mentioned above, the lab consists of VR headsets, hand controllers, simulation computers, and a data collection rig that captures high quality video and sound from the experiments for later analysis.

Figure 11: The MRlab is a mixed reality lab to test different physical layouts and functionality of urban autonomous passenger ferries in virtual reality (Photo: Nicholas Lund).

3.7. Land-based terminals and dock

The ferry docks and land-based terminals are important parts of the research infrastructure that allows for the safe usage of the ferry. The purpose is to do research on (1) induction charging of small-scale ferries, (2) efficient passenger flow on and of small-scale autonomous ferries, (3) passenger interaction with a self-service station for information about the ferry and on-demand booking, and (4) passenger trust in autonomous ferry services.

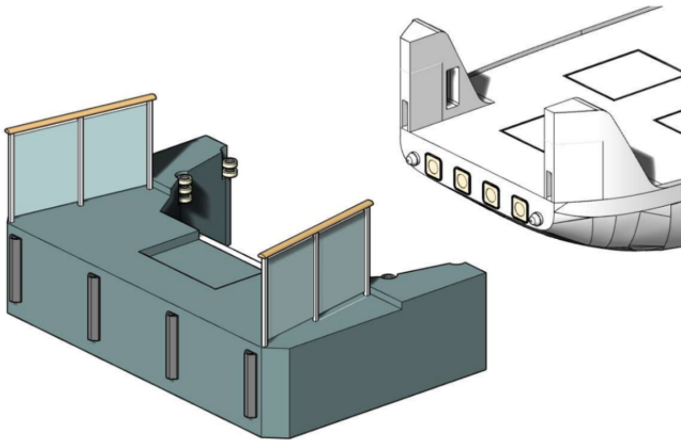

Figure 12: The dock with induction charging (Illustration: Innovation JBA)

The dock, which currently are under construction, consists of two floating docks with automatic induction charging capabilities on the south side (see Figure). In addition, we are currently designing and building a self-service station on each side of the canal where passengers can get information about the ferry service and call it to them if it is located on the other side. A local Global Navigation Satellite Systems (GNSS) reference base station is installed in the area that increases the accuracy for the GNSS position to about 1 cm. Two high-resolution cameras are currently being installed on each side of the canal so that operators can monitor the docks and area where the ferry is operating.

4. Discussion

By combining and connecting different research labs and platforms into a coherent and interconnected research infrastructure, we have created a powerful and flexible basis for investigating a broad range of research challenges related to autonomous ships and the monitoring of these.

4.1. Multidisciplinary

The researchers involved in the investigation of these challenges comes from a broad spectrum of fields and domains, ranging from technology (maritime technology, engineering cybernetics, electronics, cyber security, computer science), design (graphic/information design, interaction design, industrial design), social sciences (cognitive psychology, social anthropology) and economy. This multidisciplinary approach allows us to look at a broader set of research questions and through a range of different lenses. We presume that this form of triangulation will let us conduct research of higher quality.

4.2. Flexibility

The flexibility of the research infrastructure allows for research on more than autonomous passenger ferries. Many other sub fields of autonomous ships and shipping in general can be explored in the labs and on the ferries. For example, we currently conduct activities in the shore control lab in the EU-funded LASH FIRE project, which looks at solutions for fire prevention and firefighting on board traditional ro-ro ships. In addition, other domains can also utilise the infrastructure. We currently (1) develop design specifications for a space control room for the small-scale satellite HYPSO2 [43], (2) implement human-centered autonomous digital solutions in safety critical operations in the petroleum domain, (3) establish a collaboration with the aquaculture industry on automation and remote operations, and (4) bridge technology, design, and business development in the MIDAS project.

4.3. Education

The infrastructure also serves as an excellent education platform where students (and operators and seafarers) can learn, build, experiment, and test out prototypes, HMIs, software, training procedures, etc. It has already been the basis for several student projects and master theses and is currently utilised in a broad range of courses from several departments, such as *Experts in teams*, *Information visualization*, *prototyping physical user experiences*[1], and many more. Master students and PhD candidates from different fields have used the ferries and the lab, such as engineering cybernetics, industrial design, electronics, marine technology, product development, computer science, and cognitive psychology. This makes the infrastructure a hub for multidisciplinary education and research. It is also the location of the Njord Student Challenge [41], where international student teams design systems to control autonomous ships and compete against other student teams.

4.4. Innovation

The research infrastructure also serves as a platform for innovation and commercialisation. The infrastructure is essential for the research-based innovation centre, SFI AutoShip, and has already resulted in several patents. One example is how the technology from milliAmpere 1 and 2 is now commercialised in the spin-off Zeabuz. Two innovation manager associated with the domain, as well as the local technology transfer office, NTNU TTO, is helping faculty and PhD students to take care of innovation opportunities and intellectual property rights that emerge, and to create innovation into the existing industry.

4.5. Dissemination

The labs and ships are powerful dissemination platforms. The tangibility and visibility of the infrastructure makes it ideal to use for disseminating research results. It has already attracted much media attention, both nationally and internationally, which allows us to advocate the benefits and opportunities of autonomous technology. In addition, the video equipment in the lab allows us to broadcast live and professionally produced presentations[2] of our research from the control room to conferences and events all around the world.

4.6. Future development

For future development of the research infrastructure, our current focus is on improving the different parts and connecting them into an integrated whole. Below, we present the roadmap for future development of the research infrastructure, as well as the research challenges we will undertake in the future.

MilliAmpere1 and milliAmpere2: Future plans for the ferries include installing more on-board sensors for operator situation awareness. This includes cameras, ambisonic microphones, and other sensors that allow the land-based operator to “feel the ship”. In addition, we are currently improving connectivity between the ferries and the Shore Control Lab with 5G technology. We are also building prototypes for improved onboard passenger interaction, as well as prototypes for improved automation transparency for nearby ships.

[1] With the following course codes at NTNU: TTK4851, TPD4167 and TPD4126

[2] https://www.youtube.com/channel/UCvIJvommzc5kFg08MA0dRaA

Shore Control Lab: Recent purchases of infrastructure equipment facilitate new technologies that have been in development for the past years. This equipment will soon allow us to address several issues we have had in the development process.

The creation of virtual environments requires huge amounts of 3D content that is often prone to change. Moreover, the data generated from both simulated and real experiments with autonomy creates a massive demand for data storage. To address these issues, we are currently building a storage server to facilitate version control and storage of 3D assets using Omniverse's Nucleus as a backend system. Furthermore, we aim to automate the data gathering process from both the real and synthetic ferries using 5G's area network in conjunction with special-purpose virtual machines or docker containers running on the server. We are also improving the resilience by installing UPS systems and a 5G connection for communication with the ferries.

Another important extension of the lab is to connect it to other control rooms at NTNU, such as the Autonomous Underwater Robotics Laboratory, and other autonomous and traditional ships, such as the research vessel R/V Gunnerus. This will enable research on control room handover.

Gemini simulator: Since Gemini was released, technologies that allow real-time raytracing to have disrupted both the movie and game industries with regards to graphics. The potential use cases that follow are, however, not restricted to graphics, meaning applications that were thought to be impossible for the past 30 years are currently being challenged in multiple fields. This new technique of depth measuring in conjunction with specialised hardware offers new possibilities for running sensor models with higher realism than before. We are therefore in the development process of renewing the sensor models to utilize this new technique.

As Gemini is a toolbox untied from applications, the request for having a more "tangible" project to show the community arises. With the development of a simulation builder tool [40] and the recent development of the MRLAB, a job going forward is to merge the Autoferry and Shore Control Lab applications into a united simulation tool. This would allow us to run the actual autonomy system of the milliampere ferries in relation to both the operator and human passengers in different scenarios. The strength of simulations would in this case not be just for verification purposes of the autonomy system and to avoid accidents, but rather to study how humans and machines interact with each other, strengthening the design process.

MRLAB: Currently, the MRLAB is a hard coded setup which gives future passengers an opportunity to do a realistic virtual ferry trial, thereby capturing their perceptions, feelings, and concerns. The possibility for full-scale immersive simulations can, for instance, be used to explore different driving patterns and what is considered a safe journey in the relation between safety and effectiveness. Communication between autonomous vessels, different user groups, and objects is also an interesting topic to explore through mixed reality. However, there could be a huge potential unleashed when Gemini is attached. Real sensor data and the autonomous system identical to the one aboard the milliAmpere2 could then add further realism to the setup. The synergy will be a powerful tool to both experience and further develop the autonomous ferry system. Applications for this lab can span from practical prototyping of new designs to novel research on abstract themes like trust.

Land-based terminals and docks: The future of the docks is to test out small scale inductive charging, and to build and evaluate the land-based passenger terminals so that we can study passenger trust, flow, and behavior.

With the presented research infrastructure and with our plans for future development, we will have a good platform for investigating a broad set of research questions related to the monitoring and control of autonomous ships in shore-based control rooms. We will also learn much about the design of both the autonomous passenger ferries and the control rooms. A short selection of our long list of short-term research plans includes to:

- study the interactions between humans and technology, such as the ferry and its operators, passengers, and nearby ships
- find out how to equip the ferry with sensors that improve the operator's awareness
- understand how operators, passengers, crew, nearby ships, and other stakeholders trust autonomous technology and how we can *design for trust*
- learn how we can design for *automation transparency* so that operators, passengers and nearby ships can understand the current state and intention of autonomous ships [44]
- find out how the tangible VR experience in the MRLAB can be used in the design process of autonomous ships
- explore HMI designs for a team of operators monitoring a fleet of ships
- design HMIs that reduce the reaction time when manual takeover is required
- understand how videogames can aid HMI for autonomous purposes, such as sensor modelling

The nature of research implies that these questions will only lead to new questions, which we look forward to exploring.

5. Conclusion

In this article, we have described an infrastructure for conducting multidisciplinary research on the monitoring and control of autonomous ships. The infrastructure consists of several prototypes of urban autonomous passenger ferries, both real, virtual, or semi-virtual, which are connected to a shore-based control centre with the possibility to conduct controlled experiments. We believe that this infra-structure will be important in contributing to knowledge on how to design shore control centers in the age of autonomous ships.

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