# Smart Technologies for Unmanned Surface Vessels
## On the Path Towards Full Automation

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*Dedicated to my children*
*Tove, Vera, and Axel*
*and my beautiful wife Sara*

# Abstract

As for the automotive industry, large efforts are being made by industry and academia to create autonomous ships. The solutions for this is very technology-intense, as many building blocks, often relying on AI technology, need to work together to create a complete system that is safe and reliable to use. Even when the ships are fully unmanned, humans are still foreseen to guide the ships when unknown situations arise. This will be done through teleoperation systems.

In this thesis, methods are presented to enhance the capability of two building blocks that are important for autonomous ships; a positioning system, and a system for remote supervision.

The positioning system has been constructed to not rely on GPS (Global Positioning System), as this system can be jammed or be spoofed. Instead, it uses Bayesian calculations to compare the bottom depth and magnetic field measurements with known sea charts and magnetic field maps, in order to estimate the position. State-of-the-art techniques for this method normally use low-accuracy navigation sensors and high-resolution maps. The problem is that there are hardly any high-resolution maps available in the world, hence we present a method of the opposite; namely using high-accuracy navigation sensors and low-resolution maps (normal sea charts). The results from a 20h test-run gave a mean position error of 10.2m, which would in most cases be accurate enough for navigation purpose.

In the second building block, we investigated, how 3D and VR approaches could support the remote operation of unmanned ships with a low bandwidth connection, by comparing respective GUIs with a *Baseline GUI* following the currently applied interfaces in such contexts. Our findings show, that both the 3D and VR approaches outperform the traditional approach significantly. We found the *3D GUI* and *VR GUI* users to be better at reacting to potentially dangerous situations compared to the *Baseline GUI* users, and they could keep track of the surroundings more accurately.

# Acknowledgements

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# Popular Summary

As for the car industry, large efforts are being made to create unmanned ships. The main advantages are increased safety, cost savings, and better sustainability. Fully autonomous cargo vessels are expected to fully autonomously cross the Atlantic ocean before the year 2030. Until then, technology will gradually increase safety and replace work tasks that are nowadays conducted by humans. Even for unmanned ships, humans are expected to conduct important work tasks, but then by teleoperating various systems.

In this thesis, methods are presented to enhance two building blocks that are important for autonomous ships; one positioning system that is not GPS dependent, and one tool for remote supervision of unmanned ships with limited bandwidth.

The positioning system uses a technique called *Particle Filter*. The particle filter compares measured depth and magnetism with known maps, and can with likelihood calculations estimate where the ship is situated. It uses thousands of position estimations (particles) that are spread on the map, building a particle cloud. If the ship, e.g., measures a depth of 10m, but the map shows a bottom depth of 20m where the particle is positioned, it is unlikely that the particle is placed in the correct location, which leads to that this particle is discarded to the benefit of other particles that have better depth match. After each iteration, the particle cloud will then follow the correct position of the ship.

The system for remote supervision of unmanned ships receives position from the supervised ship, as well as information about detected objects in the surroundings. This information, along with information from maps, is used for creating a 3D world and a user interface, where the ship can be supervised in the virtual world. By creating an already known environment from maps, the amount of data sent from the ship can be minimized. A user-study in a simulated world showed that the user-interface in 3D led to fewer accidents and a better overall understanding of the situation, compared to a traditional interface.

# Populärvetenskaplig Sammanfattning

Precis som för bilindustrin, investeras stora belopp på att skapa obemannade fartyg. De huvudsakliga fördelarna är att säkerheten förväntas förbättras, vinsterna kommer att öka, samt att utsläppen kommer att minska. Helt autonoma fraktfartyg förväntas kunna korsa Atlanten helt obemannat innan år 2030, och fram tills dess förväntas tekniken gradvis förbättra säkerheten och ersätta arbetsuppgifter som idag utförs av människor. Även för obemannade fartyg förväntas människor utföra viktiga arbetsuppgifter, men då genom att fjärrstyra olika system.

I denna licentiatavhandling presenteras metoder för att förbättra två olika byggblock som är viktiga för autonoma fartyg; ett positioneringssystem som inte är GPS-beroende, och ett verktyg för fjärrövervakning av obemannat fartyg med begränsad dataöverföringskapacitet.

Positioneringssystemet använder sig av en teknik som kallas *Partikelfilter*. Partikelfiltret jämför uppmätt djup och magnetism med kända kartor, och kan med hjälp av sannolikhetsberäkning estimera var fartyget befinner sig. Till sin hjälp används tusentals positionsuppskattningar (partiklar) som sprids på kartan, vilket bildar ett partikelmoln. Om fartyget t.ex. mäter ett djup på 10 m, men kartan säger att det ska vara 20 m djupt där partikeln är placerad, är det osannolikt att partikeln är placerad på rätt ställe, vilket leder till att partikeln tas bort, till förmån för partiklar som är bättre placerade. Efter varje iteration, kommer partikelmolnet att uppdateras, och därmed följa fartygets korrekta position.

Systemet för fjärrövervakning av obemannat fartyg tar emot position från det fjärrövervakade fartyget, samt information om detekterade objekt i omgivningen. Denna information, tillsammans med känd kartinformation, används för att skapa en 3D-värld och ett användargränssnitt, där man kan övervaka fartyget i den virtuella världen. Genom att bygga upp redan känd omgivning från kartor, behöver inte lika mycket data överföras. En användarstudie i en simulerad värld har visat att användargränssnittet i 3D ger mindre olyckor och bättre överblick jämfört med ett traditionellt användargränssnitt.

# Contents

# Part I

# Background

# Introduction

There have been significant breakthroughs specifically within the last decade when it comes to autonomous vessels. Huge efforts have been seen, both from industry and academia, to enhance the autonomous capability for cars, trucks, airplanes, helicopters, and now also for ships. There are many different advancements in technologies that boost this evolution. Sensors such as cameras, Radio Detection and Ranging (Radar), and Light Detection and Ranging (Lidar) have become better and cheaper as larger volumes have been produced. Artificial Intelligence (AI) algorithms such as Machine Learning (ML), have evolved, and so have the Graphical Processing Units (GPU) that process the ML algorithms. AI methods are often used both for interpreting sensor data such as visual information, but also for solving high-level tasks such as finding the most efficient route between two waypoints. While still having humans in the loop, another important technology is to have reliable communication between a human operator and the unmanned vessel. For ships, new satellite communication systems play an important role, that can support broadband data links almost anywhere in the world [2].

In this thesis, we focus on two research areas to enhance the automation capability of ships, to support the transit towards the unmanned ships. The thesis first introduces the naval domain and how autonomous ships can be beneficial, and then focuses on the specific research areas within navigation and teleoperation. In the navigation sub-project, we have developed an application for position estimation without using Global Positioning System (GPS), and in the teleoperation sub-project we have developed an application for teleoperation of an *Unmanned Surface Vessel* (USV) via a low bandwidth connection.

Throughout the years, the acronyms *Autonomous Surface Craft* (ASC) and *Autonomous Surface Vehicle* (ASV) have also been used to symbolize the same type of vessel as USV. Strictly speaking, there is a difference between *Autonomous*, *Autonomy/Automation* and *Unmanned*. Automation is used for creating autonomous vehicles, which are normally unmanned. An autonomous vehicle by definition cannot be controlled by humans. In this thesis, we do not use this strict definition, but instead define an *autonomous vehicle* to be a vehicle with much autonomy which can to some extent be controlled by a human, e.g. by giving high-level goals, via teleoperation technique. We also use the term *unmanned vehicle*, as a reference to an unmanned, often autonomous, vehicle.

# 1 Thesis Outline

The thesis is divided into two parts; this part, named *Background*, and the second part *Research Papers*. The *Background* first contain an introduction to the areas *naval domain*, *Unmanned Surface Vessels* (USV), and *navigation at sea*. Then related work about *USVs*, *navigation at sea*, and *teleoperation* is presented. A brief description of the implementation and evaluation of the two research projects follows, and is summarized by a discussion and conclusion. The second part consists of three peer-reviewed publications. The first paper presents a method for estimating own position at sea by comparing own bottom depth measurements and magnetic field measurements with known sea charts and magnetic field maps. The second paper describes the design of a GUI intended for teleoperation, which is evaluated in a user-study described in the third paper.

# 2 Background knowledge about the naval domain

As in all domains, the naval domain has its own eco-system with its nomenclature, regulations, and equipment. To set the field that the research is related to, this section provides an overall summary of present ship technology, which is followed by the foreseen future of autonomous shipping with USVs.

## 2.1 Regulations to increase safety at sea

In order to enhance safety at sea, the International Maritime Organization (IMO) has introduced a number of conventions, recommendations, and other instruments [3]. The most important ones are *Safety of Life at Sea* (SOLAS), which regulates safety at sea, *Convention on the International Regulations for Preventing Collisions at Sea* (COLREG), which regulates how to prevent collisions, and *The Standards for Training, Certification, and Watch-keeping* (STCW), which is a convention for training and watch-keeping. SOLAS covers various topics as, e.g., ship safety, fire protection, radio communication, and safety of navigation.

Because of these regulations, shipping and navigation work in the same way almost independently of where you are located in the world. Larger ships have tougher requirements than smaller ships, and, e.g., small pleasure crafts have no technological regulations at all. Military ships normally fulfill the civilian regulations, but are often equipped with more sensors, and complement the technology with additional functions for higher precision.

## 2.2 Main Equipment for Navigation

There are many navigation sensors onboard a ship. The main tool for positioning a ship is a Global Navigation Satellite Systems (GNSS) system. A GNSS receiver receives time signals from multiple satellites, and can with this estimate the position by comparing time delays from the times when the signals were transmitted from the satellites, to when the receiver has received the signals. By this, the receiver can calculate distances to a number of satellites, making it possible to estimate the ship's own position. The most common GNSS system is Global Positioning System (GPS) and Differential GPS (DGPS). DGPS is a GPS with enhanced accuracy, which also receives offset errors from calibrated coastal stations. The GPS system is good at estimating the global position, but *not* very accurate when estimating the current speed and direction. To compensate for this, ships are equipped with a magnetic or gyro compass and a speed log. Some ships are also equipped with an Inertial Navigation System (INS), which works like a high precision Inertial Measuring Unit (IMU). It can dead reckon the position even if the GPS signal is not currently available. The INS position is accurate at first, but then gradually degrades in position performance as time increases. Very expensive INS systems guarantee to have a smaller position error than 1.0 Nautical Mile (NM) (1852m) after 72h of continuous operation time [4].

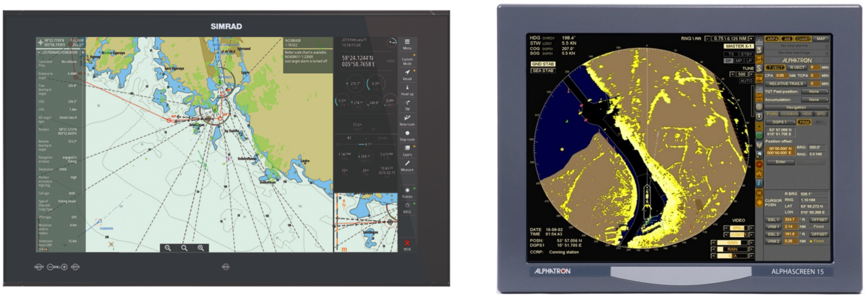
Many regulations are related to the volume of a ship, which is measured in Gross Tonnage (GT). For size comparison, three ships with a GT of around 300GT, 500GT and 3'000GT are presented in Figure 1. A ship with 500GT shall be equipped with an echo sounder system [6], which measures the bottom depth so that it can alert for groundings.

A ship with a greater size than 300GT shall have an X-band radar (frequency of 9GHz), and a ship with a size greater than 3'000GT shall also have a secondary S-band radar (frequency of 3GHz) [6]. SOLAS regulates, e.g., the functionality of the radar equipment, and how the GUI shall be visualized. Detected ship tracks are presented and normally also visualized on the sea chart system, which is called

(a) 300GT (b) 500GT (c) 3'000GT

Figure 1: GT is a measurement unit of volume, and 260GTs is equal to about 1'000$m^3$ [5]. As a size comparison, a tug with around 300GT is seen in (a). (b) presents a fishing vessel with about 500GT, and (c) presents a container ship with about 3'000GT.

the *Electronic chart display and information system* (ECDIS) system. In Figure 2, an ECDIS GUI and a radar GUI is presented.




(a) (b)

Figure 2: (a) An ECDIS GUI, developed by SIMRAD [7]. (b) A radar GUI, developed by AlphaTron Marine [8].

The ECDIS system presents the sea chart for the operator. It is highly regulated what information shall be presented, how the information shall be presented, and how the ECDIS system shall be connected to all the navigation sensors. In many cases, it is beneficial for the operator to have a radar overlay above the ECDIS sea chart, which is a function that is available in many radar systems.

A system called *Automatic Identification System* (AIS) is used to share knowledge about the own ship, such as position, heading, and speed. Larger ships are obligated to carry an AIS. The AIS is connected to the navigation sensors, and transmits and receives information to and from surrounding vessels. The gathered information is normally presented on the ECDIS system.

### 2.3 Main Equipment for Communication

Reliable radio communication is important at sea. Mobile communication technologies such as 3G, 4G, and the future 5G are usable technologies in highly populated areas, as they can provide affordable high bandwidth communication in the vicinity of each base station antenna. Ships are often beyond the coverage area of these antennas, hence mobile communication standards are not used for regulated ship communication. For the same reason, Wifi is not used either.

For safety at sea, SOLAS regulates what equipment needs to be carried in order to send and receive distress signals and safety information as well as for normal communication at sea. The regulation is called *Global Maritime Distress and Safety System* (GMDSS), and is mandatory for all passenger and cargo ships larger than 300GT on international voyages. All these ships need to have terrestrial radio communication equipment, and the ships that are going in specified areas far away from land, also need to have equipment for satellite communication [3].

## 3 Reasons for using Unmanned Surface Vessels

There are many reasons for developing large and small Unmanned Surface Vessels (USV). Some of the most important reasons are Safety, Cost, Sustainability, and Work Environment [2, 9], described in more detail below:

### 3.1 Safety

In the year 2015 3'296 marine casualties and incidents were reported internationally. That year, 115 fatalities, 976 injuries were reported and 36 ships were lost [10]. In the range of 89% to 96% of all collision accidents at sea since 1999 are caused by human errors. Human errors are causing 84% to 88% of tanker accidents, 79% of towing vessel groundings and 75% of fires and explosions [11]. There are many sub-tasks at sea that could be replaced by machines. According to IMO regulations, a lookout on the bridge needs to constantly look for potential threats. This is an important task, but can in the long term be very tiresome. By instead having cameras and radars with autonomous capability scanning the surrounding area, the safety is foreseen to be increased [12]. Another important issue is fatigue. Humans sometimes get tired and exhausted and can have other things on their mind. Alcohol among other things can also influence a human's judgment. A machine can, on the other hand, perform a repetitive task without degradation, and AI systems can even learn from the experience of the total fleet.

Piracy has also become a huge problem for maritime traffic. Armed pirates board large ships and hold the crew hostage until a ransom is paid. An unmanned ship would be a much less attractive target for piracy, as there is no crew to hold hostage. It is also possible to make the ships more difficult to board and control for human intruders. It would also be much easier to recapture the ship without any hostage.

## 3.2 Cost

It has already been concluded many times that autonomous ships will lead to significant cost savings compared to manned ships [2, 13, 14]. The MUNIN research project has compared the largest costs for manned cargo ships, with cost estimations for unmanned cargo ships [15]. The results show that the crew salaries are the largest cost for manned ships, making it possible to save money when using autonomous ships. It is estimated that it will be slightly more expensive with land-based services for autonomous ships though. It is also estimated that the more complex ship design of autonomous ships will increase cost more than the cost is reduced by removing deckhouse and other units that come with a human workforce. In total, the MUNIN project concludes there will be room for significant cost savings when going autonomous. And as the technology, used for autonomous ships, gets more mainstream, the cost savings are foreseen to increase even further.

## 3.3 Sustainability

The environmental impact is also foreseen to be reduced with autonomous cargo ships. By removing units such as the deckhouse, the ships can be constructed lighter or make room for more cargo. The removal of the deckhouse also makes it possible to apply a more streamlined design with less wind resistance. The hotel load, i.e., the power consumption that is needed for humans, will also be reduced. Rolls Royce estimates all these changes in total will reduce the fuel consumption with 10 – 15% [16].

When not having an expensive crew onboard that want to come home to their families within a reasonable time, it will also be possible to reduce the speed, leading to even more fuel savings, making the technology even more environmentally friendly.

On shorter distances, there is a trend replacing diesel engines with batteries. YARA Birkeland is a project in Norway, where a battery powered ship will replace about 40'000 diesel-powered truck transports per year, with all their NOx and CO2 emissions [17]. This ship will initially be manned but is estimated to be fully autonomous by 2020. Solar power, but especially wind can also be used to significantly reduce fuel consumption. Łebkowski elaborates on various types of autonomous ships that use these techniques [18]. If speed is less important, it would actually be possible to use wind as the main propulsor.

### 3.4 Work Environment

The crew members will need new and more complicated skills, as the mechanical and electronic complexity increases on ships. At the same time, fewer people are willing to spend weeks or months away from home and family, especially from developed countries [2]. This has led to a large shortage of seafarers [19], and most parties agree that this will be a problem in the long run [14]. By using autonomous or remotely controlled ships, where ships are controlled from control centers by specialists, the problem is foreseen to be contained.

### 3.5 Reasons for using small Unmanned Surface Vessels

Even though most of the benefits are the same for large and small USVs, there are some benefits that are valid in particular for small USVs. When removing the crew from small USVs, they will be very cheap to operate, making it possible to use a larger fleet of vessels. When there are no humans onboard that have any costs, they will also have greater endurance, and it will be possible to use them in areas or weather conditions where it would be dangerous for humans to operate. Typical missions can be Search And Rescue (SAR) missions or military reconnaissance missions.

## 4 Levels of automation

To achieve the benefits of USVs, it is often easier to gradually improve the automation capability in an iterative approach, instead of going from no automation to full automation in one step. I believe the solutions are comparable to what can be seen in the automotive industry. In this industry, the Society of Automotive Engineers [20] (SAE) has decided on six levels on automation, see Table 1.

On level 1, the systems are working to assist the driver, so that the safety is increased. This is already done to some extent for maritime traffic, but the technology could probably do much more in this area. Sensor capability can be increased,

Table 1: Levels of automation in the automotive industry [20].

| Automation Level | Meaning |
|---|---|
| 0 | No Automation |
| 1 | Driver Assistance |
| 2 | Partial Automation |
| 3 | Conditional Automation |
| 4 | High Automation |
| 5 | Full Automation |

with, e.g., machine learning algorithms interpreting camera images. And as more and more sensor data can be digitally interpreted, a better situational awareness can be created by the system. This overall picture of the surrounding world can be presented to the operator directly or can be evaluated further by the machine, to evaluate potential safety threats. These threats can then also be presented to the operator. By creating better GUIs where the right knowledge is presented for the operator at the right time, the cognitive load can be reduced while giving the operator the best knowledge about the surrounding world.

When a car goes from SAE-level 1 to SAE-level 2, some autonomous driving features are enabled, but the driver needs to take immediate action when a dangerous situation arises. On level 3, the driver can safely read a book or see a movie, but must be ready to intervene when the car alerts the driver. On level 4, the driver can go to sleep, as the car is fully autonomous as long as it is in some defined areas or situations. On level 5, the steering wheel can be removed completely, as the car can manage all situations by itself [21]. When having level 4 or 5, it is foreseen that accidents are reduced significantly. When the car is driving on level 2 or 3 on the other hand, the car will be in command for most of the time. But when there is a difficult situation where the car cannot guarantee safety, such as when having snow or fog, the human will need to drive. Then the human will not get as much driving experience as before, but will still need to master the most difficult situations. This might lead to accidents.

When the cars have at least almost full automation, level 4 or 5, there will still be situations which are hard to solve for the car. One example can be if a tree has fallen over a road, blocking it, far away from the city. The car will then slow down and stop, but will perhaps not understand that it can go straight through the thin tree limbs. If the car is not equipped with a steering wheel, one possibility is to teleoperate the car from a control center. Then a human can remotely slowly guide the car past the tree. Even if the automotive industry does not speak much about this technology, most car companies that are developing autonomous vehicles also develop teleoperation technology [22]. Teleoperation of ships is seen as a key technology in the transferring process towards autonomous ships [2]. The functionalities to increase safety, situational awareness and reducing the cognitive load are applicable for teleoperation applications in the same way as the functionalities are applicable to manned ships. Another use-case for teleoperation is to use full automation without teleoperation for long transits, and when arriving at the destination, the human takes control over the situation via teleoperation technique. This use-case can, e.g., be used during SAR missions to minimize human workload.

## 4.1 Building Blocks for Autonomous Ships

As for the automotive industry, there are many building blocks that comprise an autonomous ship. The vessel needs to have applicable sensors, where the most important ones are:

- Navigation sensors
- Visual camera
- Infra Red (IR) camera
- Radar
- AIS
- Lidar

The collected sensor data needs to be interpreted, and most often, machine learning algorithms can be helpful in this step. To use machine learning, a large amount of training data needs to be collected. The sensor data from the different sensors then is fused into tracks, so that surrounding objects are not presented multiple times. These tracks are compiled into a situational picture, giving the machine a good situational awareness (overall picture) of the surrounding world. The machine then needs to decide what to do next, and make up an effective plan to perform the actions. To be able to learn from previous experience, the machine also needs to obtain and collectively save knowledge from upcoming experiences, and then act according to the fleets' collective knowledge base when new recognizable situations arise.

## 5 The Path towards fully autonomous ships

The ships will not become fully autonomous instantly. It is instead foreseen that the capabilities will gradually improve in an evolutionary way. Rolls Royce foresees the following steps [2]:

1. Year 2018 - Remote Support, operation of certain functions
2. Year 2020 - Remote and Autonomous Local Vessel
3. Year 2025 - Remote and Autonomous Short Sea Vessel
4. Year 202X - Remote and Autonomous Ocean Going Vessel (The time depends on regulation constraints)

The ships need to evolve in various fields. The overall tasks the autonomous ships need to master are:

1. Know where the own ship is located
2. Know what is around the ship - Situational Awareness
3. Predict what is going to happen next
4. Make decisions autonomously or present the overall picture to a remote human who makes a decision
5. Act according to the decision, e.g., make a turn

As can be seen, there are many various tasks that are important for autonomous ships, which all need their sub-tasks and subsystems. We have chosen to develop two subsystems; a positioning system that does not use input from a Global Navigation Satellite System (GNSS) system, and a teleoperation subsystem which can be used when having a limited bandwidth capacity.

## 5.1 Positioning System without using GNSS System

To be able to determine the own position at sea, at all times, is vital. The position can be determined in many ways. Nowadays, normally a GNSS system is used for this, where the Global Positioning System (GPS) is the most common system. The big disadvantage with GNSS systems is that the navigation capability is dependent on the received signal from the satellites both is received and is correct. This is not true at all times, especially if someone is jamming the signal transmission.

In these cases, it is vital to be able to estimate the position in another way. One way of doing this is presented in Paper I.

## 5.2 Teleoperation with limited bandwidth

Especially in the next 20 years, it is foreseen that teleoperation of ships will be used to enhance the capabilities of unmanned ships. As the ships get smarter, the decisions can gradually be moved from the human operators to the machines. For huge ships far away from the coastline, satellite communication provides the communication channel for this. On small USVs near the coastline, the satellite antenna would often be too bulky. The satellite communication equipment is also expensive to both buy and to use.

An alternative approach is to rely on Very High Frequency (VHF) radio equipment. VHF transceivers are standard equipment at sea. The technique is affordable, small, and has a long range. The drawback is that the bandwidth is very limited, with the same capacity as a data modem used before the year 2000. With this constraint in mind, we have developed a teleoperating interface, which is presented in Papers II and III.

Even though the interface is developed with teleoperation in mind, the design is also applicable for manned vehicles, where an Augmented Reality (AR) Head Mounted Display (HMD) would be used instead of a Virtual Reality (VR) HMD. In this scenario, I believe the same benefits with better safety, better situational awareness, and lower cognitive load would boost the performance of manned vehicles as well. This provides scope for further studies.

# 6 Research Questions

The previous sections have described several challenges at sea which are likely to be reduced by using USVs instead of manned ships. To actualize USVs, teleoperation is often seen as a key technology to bridge the gap between *no automation* and *full automation*. It is also vital to be able to determine the own position at all times, both for manned and unmanned ships. All this leads us to our key research question:

**How can smart techniques assist humans operating ships?**

This question entails the following more detailed questions:

- How can a human operator teleoperate a *USV* through a *low bandwidth connection*, giving the user a good and safe overview of the situation, while maintaining a low cognitive load?

- How can a human operator teleoperate a *USV* through a *high bandwidth connection*, giving the user a good and safe overview of the situation, while maintaining a low cognitive load?

- How can a human operator control and supervise a *manned ship*, giving the user a good and safe overview of the situation, while maintaining a low cognitive load?

- When the ship is navigating with jammed or spoofed GNSS reception, is it possible to estimate the position accurately enough for navigation purpose, by using a high accuracy INS and by measuring the bottom depth and the magnetic field?

# 7 Methodology

The research in all three papers has been carried out in a fashion inspired by *Design Science*. In this science type, the research has an explicit intention to improve the functional performance of an artifact, much resembling normal engineering work in the industry. Our artifacts have been the particle filter in Paper I, and the teleoperating GUI in Paper II and III.

Figure 3 shows a summary of the workflow used for the projects related to the papers, which starts with a problem formulation and an idea of how to solve the problem. The idea has then been analyzed, and an initial design solution has been evolved. These ideas lead to an implementation or improvement of the artifact. The artifact is then evaluated, most often, to get findings on things that should be improved. This leads to a new idea, and the loop continues. After several iterations, the design is completed for a more extensive evaluation (with new findings),

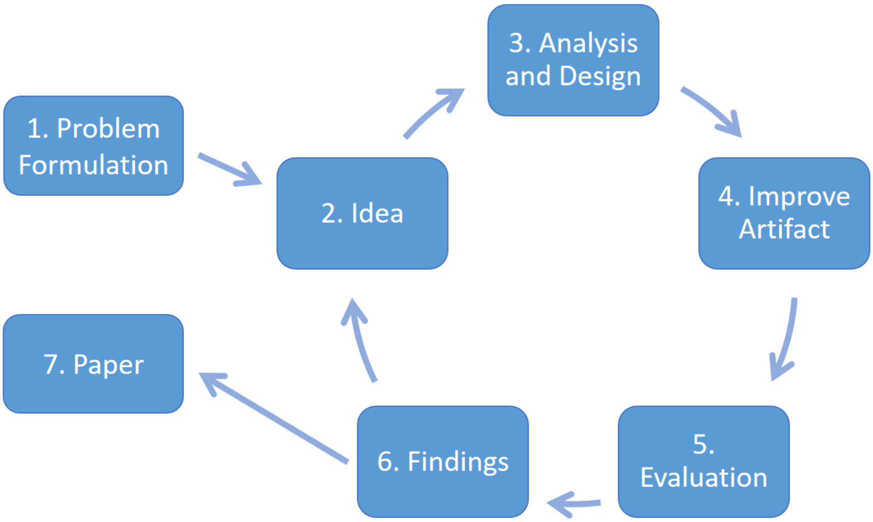



Figure 3: The work process in *Design Science* is started by a problem formulation, which leads to an idea of how to solve it. The solution is analyzed and a design is evolved and then implemented in the artifact. The enhancement is then evaluated, and findings are found, which can lead to new ideas. The work then continues in an iterative loop.

which has been conducted, in Paper I, by comparing the performance of the particle filter using various settings and input data. In Paper III, the evaluation has been conducted in a user study.

## 8 Contributions

This section describes the contributions of this thesis. Paper I describes the positioning method and the Papers II–III describe the teleoperation tool. The main contributions are the following:

1. **A positioning method for GPS-denied environments.** For terrain navigation, the current state-of-the-art approaches use low-accuracy navigation sensors and a particle filter to compare bottom depth measurements with high accuracy terrain maps to estimate the position. The problem is that there are hardly any areas in the world where that kind of maps are available, hence our particle filter algorithm instead does the opposite, namely relying on normal sea charts and normal magnetic field maps, but using high-accuracy navigation sensors instead. While previous research in this topic has been applicable to nearly all vessels in areas where uncommon 3D-terrain maps are available, our research is applicable to vehicles with expensive navigation sensors, but in nearly all areas (Paper I).

2. **A comparison of fusion methods for the positioning method for GPS-denied environments.** Not only bottom depth measurements have been used for the positioning method, but also the magnetic field value. The input data for the Correction Step of the particle filter can be fused in various ways, and a comparison between methods are evaluated and presented (Paper I).

3. **A GUI for teleoperation of a USV.** As vehicles get unmanned, but still not smart enough to handle all complex situations, there is a need for good teleoperation systems. Drones have used teleoperation for a long time, and systems for cars and ships are starting to be used. State-of-the-art systems normally rely on a high bandwidth connection, through Wifi, 3G/4G or satellite, to transfer video streams. Our developed teleoperation system instead relies on a low bandwidth connection, used to provide surrounding objects to a 3D world. The GUI design in the 3D world is inspired by applicable research about navigation for manned ships. The developed GUI

can be presented in 3D on a computer screen as well as in VR. To evaluate the performance, a user-study has been conducted, where it is shown that the VR GUI and the 3D GUI outperformed a traditional GUI (Papers II and III).

# Related Work

The ultimate goal is to reach full autonomy for at least larger ships, where the ships can leave the harbor, cross the Atlantic ocean, and then dock in a foreign port, all done safely and reliably without human intervention.

The ultimate goal lies several years ahead though. Levander [16] estimates that the technology will be ready for fully autonomous ships before the year 2030, and sees regulations as the biggest obstacle to be operational before that year. To reach the goal, some technologies must evolve to make the ships smarter than today. And when having smarter techniques while the human is in control, it is important to enhance the interaction between the human and the machine. By this, the command can gradually be transferred to the machine. In this thesis, I am therefore investigating how unmanned ships are evolving, how ships can position themselves, how safety during navigation can be enhanced while reducing human workload, how situational awareness is created and transferred to the humans, and how USVs can be teleoperated.

## 1 The Path Towards Fully Autonomous Ships

Many civilian and military companies, as well as academia, are putting a large effort into developing USVs. To provide an overview of what has already been done in the field of USVs, examples of projects from the last 25 years have been assembled. These can also be seen as sample platforms that could use the research outcome from this thesis.

### 1.1 Small Unmanned Surface Vessels

The first small USV was named *ARTEMIS* and was developed in 1993 by academia, namely by MIT Sea Grant College Program [23], see Figure 4. Since then, many more small USVs have been developed by universities with increasingly complex


Figure 4: The USV Artemis, developed by MIT in 1993 [23].

capabilities. Universities, in general, have a need for affordable sea platforms that can collect valuable research data at sea, and in this field, the USV plays an important role. The need for USVs has often been combined with research about how to develop functions for an efficient USV. The ALANIS project developed by CNR-ISSIA Genova is an example of this [24], as well as the Delfim project [25], see Figure 5.

Figure 5: *Delfim* is an USV developed at ISR/IST to support gathering of data from a submerged craft [25].

In Amsterdam, USVs called *Roboat*, see Figure 6, are used in a large-scale research project to explore the possibilities with using small unmanned vessels for transportation of goods and people [26].


Figure 6: The Roboat is a small USV developed for shipping small sized goods and people through the canals in Amsterdam [26].

Small USVs are also foreseen to be useful during security patrols and environmental monitoring. These missions are often costly, because of the long-running missions. Camilli describes their USV, seen in Figure 7, and how the robust design of a Wave Adaptive Modular-Vessel (WAM-V) is a good type of vessel for these missions [27].

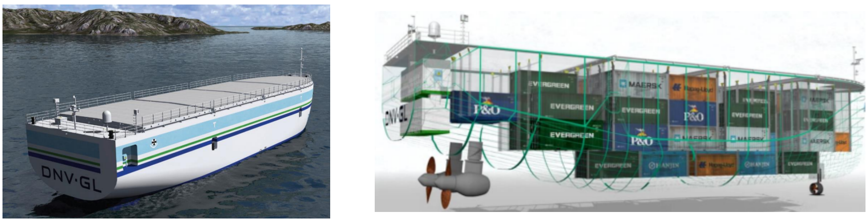

Figure 7: A USV that could possibly be used for environmental monitoring or security patrols [27].

## 1.2 Large Unmanned Surface Vessels

As already described in the Introduction on Page 1, the industry sees large benefits when it comes to large USVs. In a similar way as in the car industry, environmentally friendly technologies such as battery-powered vehicles often go hand in hand with the automation level. Here follows a couple of examples of recent projects with large USVs:

### ReVolt

The ReVolt project was launched in 2013, and is a battery-powered USV developed by *Det Norske Veritas Germanischer Lloyd* (DNV GL) [28]. A 1:20 scale model has been produced as a test-bench for sensor fusion and collision avoidance development by a university. It is developed to move slowly at a speed of 6 knots, making it possible to reduce the power consumption significantly. The ship, with its interior design, is shown in Figure 8.



(a) (b)

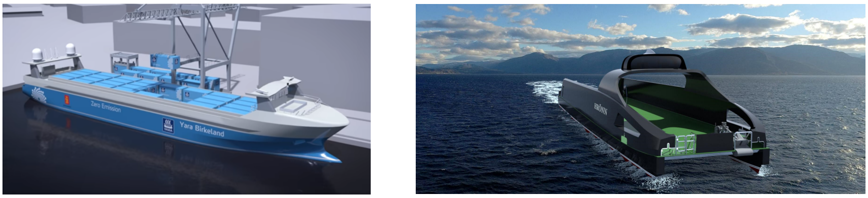
Figure 8: (a) An unmanned container ship developed by DNV GL [28]. (b) The interior design shows that by removing cabins, deckhouse and other equipment that comes with a human crew, there has been more space available for containers.

### Kongsberg

Another Norwegian company named *Kongsberg*, is also evolving techniques regarding USVs. The battery-powered USV YARA Birkeland, seen in Figure 9a, will begin testing of autonomous capabilities in 2019, and is foreseen to gradually reduce manning until 2022 when it will be fully autonomous [17]. Another example of a USV developed by Kongsberg is the multi-purpose ship Hrönn, see Figure 9b, which will serve the offshore industry [29].

### Rolls Royce

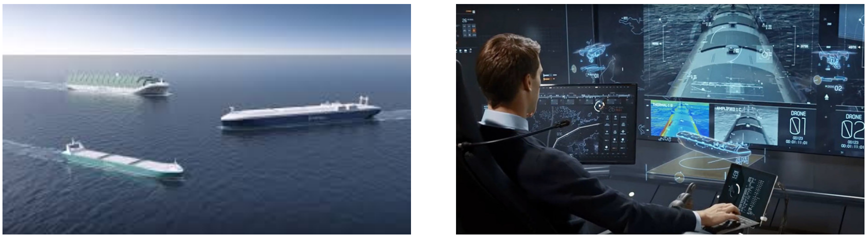
Rolls Royce in Finland is currently developing an eco-system with various ship types. They believe the transit towards large USVs will become a disruptive change for the shipping industry, and as already stated on Page 10, they believe USVs will be used for crossing the Atlantic ocean fully autonomously before 2030 if regulations are changed to support the new technology in time [2]. They also believe human operators and expert technicians will be important to cope with




(a) (b)

Figure 9: (a) The Container USV YARA Birkeland, developed by Kongsberg [17]. (b) The USV Hrönn, developed by Kongsberg [29].

the fact that the machine still needs help in complicated scenarios. In Figure 10, three ship types are visualized, as well as a human operator that supervises a ship remotely during an over-sea mission.




(a) (b)

Figure 10: (a) Three various ship types, designed by Rolls Royce. (b) A human operator is supervising the USV when crossing the ocean, and is ready to guide the ship when necessary.

## 1.3 Military Unmanned Surface Vessels

Also in military industry, USVs are foreseen to play an important role, complementing the manned vessels. The vessels are much cheaper to operate, hence a larger number of vessels can be used. The USVs can be out at missions for a much longer period of time, and can operate in more dangerous operations than manned vessels. There are many military projects evolving in the military industry, where mainly the USA and China are leading the way:

### DARPA's Sea Hunter

The Sea Hunter, see Figure 11, developed by *Defense Advanced Research Projects Agency* (DARPA) in the USA, is a prototype USV produced to support the development of a USV that can chase submarines. Compared to what it costs to operate a Destroyer, they claim it will be about 40 times as cheap to operate this USV. It is estimated that some ships will be operable before the year 2023, and it is said that the USVs will always be under some sort of human control [30].

Figure 11: A prototype USV developed by DARPA in the USA, to hunt for submarines during month-long missions [30].


Figure 12: The Chinese USV SeaFly-01 [31].

**Unmanned Surface Vessels in China**

China is also developing many military USVs. One example of this is the SeaFly-01, see Figure 12, which has a maximum speed of 45 knots and can be used, e.g., for coastal patrols, armed confrontations, submarine detection, and water-quality monitoring [31].

### 1.4 Areas for Improvement

Even though there exist many research projects with USVs, there are many areas which need to be improved. It is important to develop systems for safe shipping. To do this, the position must be determined at all times and conditions, the situational awareness must be compiled accurately, and good action decisions must be taken at all times. While humans are in the loop, reliable and accurate interaction must be performed between the human and the vessel. In the next two sections, related work for the two sub-projects of this thesis will be presented, namely navigation and teleoperation.

## 2 Navigation at Sea

To do accurate navigation at sea, many sub-tasks need to be mastered. The most fundamental thing is to know where the own ship is located. By knowing this, all fixed objects around the ships can be found in the sea chart. The rest of the objects need to be discovered by sensors or humans. The route of the ship then needs to be planned so that no groundings or collisions occur, and so that the destination is reached efficiently.

### 2.1 Finding out the Ship's Location

There are many ways to find the correct location of a ship. A couple of decades ago, the most used method was to know the original position when leaving the harbor, and then update the position in the sea chart as the ship was moving a known distance in a direction according to the compass. This method is called *dead reckoning*. In this technique, it is also possible to compensate for the vessel's estimated drift and sea current. But if one is not able to estimate the drift and sea current accurately, the position error starts increasing, as each estimation of the position is relative to the previous one, which means that the position error is accumulated over time.

This deficiency can be overcome in different ways. By regularly determining the position compared to known landmarks, the accumulation of error is reset. But if landmarks cannot be found because one is on open water, either there is a need for increasing the accuracy of the dead reckoning by using better equipment (e.g., compass, logs (for speed), gyro, accelerometers, inertial sensors), or there is a need to use information about the environment that can be seen out on open waters. During the 18th century, the celestial navigation was invented, which uses angle measurements to the sun, moon, and stars to greatly improve the long-term accuracy of navigation. Nowadays the celestial navigation has almost completely been abandoned because Global Navigation Satellite Systems (GNSS) systems can determine the position accurately and efficiently. The most common and oldest GNSS system is GPS, but there are also other systems, e.g., Galileo and Glonass [32].

The GNSS systems have made it very simple to determine a vessel's position with good accuracy, but there are still some disadvantages. One important disadvantage is that the ship needs to rely on external information from the GNSS satellites which is sent to the GNSS receiver onboard. It is quite simple to jam the radio reception from the GNSS satellites, which results in that it is not possible to determine the position anymore. Even worse, it is possible to spoof the GNSS transmission information with advanced equipment, resulting in that an incorrect position is provided [33].

**Bayesian positioning estimations**

If a dependency on the GNSS system is not desired, there are other methods that can replace or complement this method. One method is to use Bayesian calculations for position estimation. The technique has been used for decades for some airplanes, where, e.g., Gustafsson et al. [34] describe how the systems on an airplane measure the altitude and compare it to a known terrain map with a Particle Filter (PF) algorithm, thereby estimating the position. There are also many papers describing how ships can use the same technique, where the bottom depth is measured by an echo sounder system or a sonar system [35, 36, 37, 38]. More specifically, Autonomous Underwater Vehicles (AUV) have a big need for position estimations, as they cannot use a GNSS system when below surface, which has led to much research covering this topic, where various types of sonar systems and algorithms have been studied [36, 39, 40, 41, 42, 43, 44, 45, 46]. The current research in this field has mainly focused on achieving good performance of the positioning systems when having a limited performance of the sensor suite, but nearly unlimited accuracy of the map. In these conditions, there is much research that shows that a PF can be used for position estimation [35, 36, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46]. The problem is that there are not that many areas where high-resolution maps have been created. Another problem is that the bottom terrain needs to vary enough for the PF to work, and in some areas, the bottom terrain is quite flat [35]. A solution to these two problems would be to use normal bottom sea charts and to complement the depth measurements with other measurements, which is what we do in Paper I, where we complement the bottom depth measurements with magnetic field measurements. To increase the performance, we use a high-accuracy INS, which is available mainly on some larger ships.

Earth is surrounded by a magnetic field, where each ferromagnetic element disturbs this field. These disturbances can for indoor environments be even greater than the natural magnetic field of Earth [47]. For indoor environments, numerous ferromagnetic elements create a complex magnetic field where the magnetic vector varies greatly depending on the location. The magnetic field is also quite stable if no major furniture or iron walls are moved. This information can be compared to a magnetic map using a PF, and in conjunction with some sort of odometry, such as wheel encoders or inertial sensors, it has been possible to localize a human or robot [48]. Le Grand et al. [47] only use cheap smartphone sensors, and the magnetic field and acceleration are used for determining the position of the human user.

Although Le Grand et al. [47] and Frassl et al. [48] have explored indoor environments, the same technique is applicable to outdoor environments. The magnetic field does not fluctuate as fast as in indoor environments, but on the other hand, it is more stable, because no furniture or building parts are moved around as in the indoor environments. There are satellite maps available covering the entire magnetic field of Earth, and in some areas of the world, higher resolution maps have been created, e.g., by low flying airplanes. Hence, the magnetic field has been used in our PF algorithm in Paper I for estimating the position of the ship. Our implementation shows that the magnetic field intensity serves as a good complement to bottom depth measurements when it comes to improving the accuracy and robustness of the position estimation.

The bottom depth and the magnetic field are good candidates to use for the PF algorithm when estimating the position, but there are other alternatives. In addition to the bottom depth, Karlsson et al. [39] also use range measurements to land objects in another PF algorithm. This range is measured by a radar and is compared to a sea-chart database.

It is also possible to not only use the depth measurement directly vertically to the bottom. If the ship is equipped with a sonar system, it is also possible to use multiple bottom depth measurements covering a larger area at once. This increases the performance of the PF, as it is possible to evaluate if the bottom readings match the map with better precision [42]. Another way to improve the performance is to use the sediment layers of the bottom, where the lower layers' depth most often varies more than the sea floor [35].

## 2.2 Navigation at Sea and Cognitive Load

The traditional way to navigate at sea is to use a paper sea chart, showing an abstracted map of, e.g., islands, groundings, depths measurements, and sea marks. The paper sea chart is constructed with north facing up. During the last two decades, there has been a transition on bigger ships to use electronic chart systems, where the sea chart is instead visualized digitally on a computer screen. The main benefit is that the own ship's position, normally received from the GPS, is visualized at the correct location on the sea chart. The sea chart can be presented with north-up or head-up reading rotation.

The human ability to mentally rotate a map or sea chart, so that the symbols in the map can be matched with surrounding real-world objects, is rather limited. Shepard et al. [49] showed that the time to recognize that two perspective drawings are showing the same three-dimensional shape is linearly increasing to the angular difference of the perspectives. This means that a human can match the ship's surrounding quite well when steering in north direction when reading a north-up oriented sea chart, but will need more time reading the same north-up oriented sea chart when steering in the opposite direction. Operators often choose to present the sea chart with north-up and the radar with head-up rotation [50], thus mental rotations are needed both between those two systems and between the systems and the surrounding real world.

Another way of presenting a map is to view it from the driver's perspective. This is normally done in a GPS navigator for car drivers. The benefit is that the driver can quickly understand which roads and buildings on the map that match the roads and buildings in the real world surrounding. By letting the machine do the mental rotations instead of the human operator, valuable time is saved, and many accidents are thereby likely to be avoided.

Porathe [51] compares four map views in a simplified indoor environment where persons navigate on a floor trying to navigate fast but striving to avoid simulated groundings. The compared views are:

1. Traditional paper sea chart (north-up)
2. Electronic chart system (north-up)
3. Electronic chart system (head-up)
4. 3-D map with an ego-centric view

The results of this test show that (4) gives the fastest decision makings, least groundings, and is perceived as the most user-friendly. The results also show that using an electronic chart system gives better results than using paper charts.

Some user groups are more skilled than others when it comes to interpretation and mental rotations of maps, but for all user groups, (4) gives the best results, followed by (3), (2) and (1) [52]. An interesting finding is that persons who have long experience from using electronic chart systems still perform better when switching to 3-D maps, despite that they are not used to it.

With the results in mind, Porathe [50] suggests using a 3-D map with the ego-centric view as a navigation aid, viewed on a computer screen or tablet. Witt [53] has also proposed a similar solution with a tablet where the ego-centric view helps the operator reducing the cognitive load. Our GUI presented in Papers II and III, with the ability to teleoperate a USV is influenced by these results, as we place the operator directly into the 3D world where the surrounding world easily can be matched with the sea chart.

## 3 Teleoperation of ships

Teleoperation can be used for remote controlling machines/robots, e.g., industrial robots [54], ground robots [55, 56], cars [57, 58, 59], drones [60, 61] or ships [62]. The different fields have various delay requirements. Lu et al. [56] investigate how this delay time effects the teleoperating capability when teleoperating a ground vehicle, and [56, 57, 59] elaborate on how to perform teleoperation of cars, where it can be even more difficult in city traffic due to its high dynamics.

While teleoperating a machine/robot, it is also important to improve the human's perception of what the machine's sensors detect of the surrounding world.

Williams et al. [63] elaborate on how VR, Augmented Reality (AR) and Mixed Reality can strengthen visualization, and thereby the total communication between a robot and a human, and how various viewpoints, e.g., the ego-centric view can be used. Hedayati et al. [60] have a more specific use-case, where it is explored how AR can be used for augmenting a drone's field of view for a user collocated with the drone. When not collocated, VR is often a better presentation technique. Hosseini et al. [58] and Shen et al. [57] show how VR can enhance the situation awareness when driving a car.

Some research has also been investigating how AR can reduce cognitive load when navigating. In these applications Head Mounted Displays (HMD), normally with see-through technology, augment important information, such as sea lanes, conning information, and information about own and other nearby ships from e.g. the AIS information [64, 65, 66, 67, 68]. In our application, AR is not possible, because we can not look at the surrounding real world as we are remote from it. Instead, we use the approach to augment the important information in the Virtual Environment (VE).

# Implementation and Evaluation

Two sub-projects have been conducted, which this thesis is composed of; one *Positioning System* and one *Teleoperation System*. Each of the sub-projects has its own design and implementation, and has resulted in a couple of papers. An overall description of the design is given in this chapter, while the details are found in Papers I – III, that are included in this thesis.

## 1 Positioning System

The positioning system sub-project uses a Particle Filter (PF) to estimate the position of a vessel, which was developed in many iterations. The initial design is described in Reference [69]. An enhancement of the program is described in Reference [70], which was then further evolved into the final design, described in Paper I.

The method presented in this paper uses a PF to compare the measured bottom depth and magnetic field measurements with known maps, in order to estimate the own position. The PF algorithm has the following steps:

1. **Initialization** - Generate N particles and give them a random starting position around a manual estimation of the starting position.

2. **Prediction** - Move each particle according to the velocity vector predicted by the INS. Then move each particle according to a random velocity vector, in order to simulate the velocity vector error of the INS.

3. **Correction** - Calculate the weights for each particle given the maps and each particle's position. The weights are calculated for the depth, magnetic field and a combination of those two. Normalize the weights.

4. **Re-sampling** - The particles are re-sampled according to a predefined distribution from subsets, see Figure 14.

5. **Iteration** Go to step 2.

## 1.1 Correction Step

In the third step of the algorithm; *Correction*, the measured values are compared to known maps in order to estimate the position. The process of how this works in the developed algorithm is presented in Figure 13. The figure shows how the weights for the PF are calculated separately in the *Depth Workflow* and the *Magnetic Workflow*.

### Depth Workflow

The original sea chart is seen in (a1) in the figure. From the sea chart, all bottom depth points are extracted (a2), and so are all the bottom depth lines (a3). From the bottom depth lines, a *Minimum Bottom Depth Map* is created (a5), where the minimum bottom depth at all positions can be looked up. A Probability Density Function (PDF), (a7), is then obtained for each location of the particles by using either only data from (a2), or a combination of data from (a2) and (a5), depending on if the bottom lines should be used or not. A simulated map for *ground truth* has been drawn in a drawing tool, with smooth color gradients (a4). The purpose of this map is to resemble the real world terrain as much as possible. As the ship moves in the map, it measures the alpha-value from the grey-scale ground truth image, which is converted to a bottom depth measurement (a6). The bottom depth measurement (a6) is then used in combination with the PDF (a7) for each particle, to calculate the weights for each of the particles (a8). (a8) answers the question; **How likely is it that the specific particle is placed at the correct location, given my measured bottom depth?**

### Magnetic Workflow

A ground truth map of the magnetic values is drawn in a drawing tool (b1), with the intention to as much as possible resemble a real-world variation of the magnetic field. As the ship moves, the magnetic field is measured in the correct location of the map (b5). High-resolution maps are not normally available, hence a low-resolution map is created by downsampling the ground truth, where each pixel corresponds to an area of 185x185m (b2). The downsampled map is used to

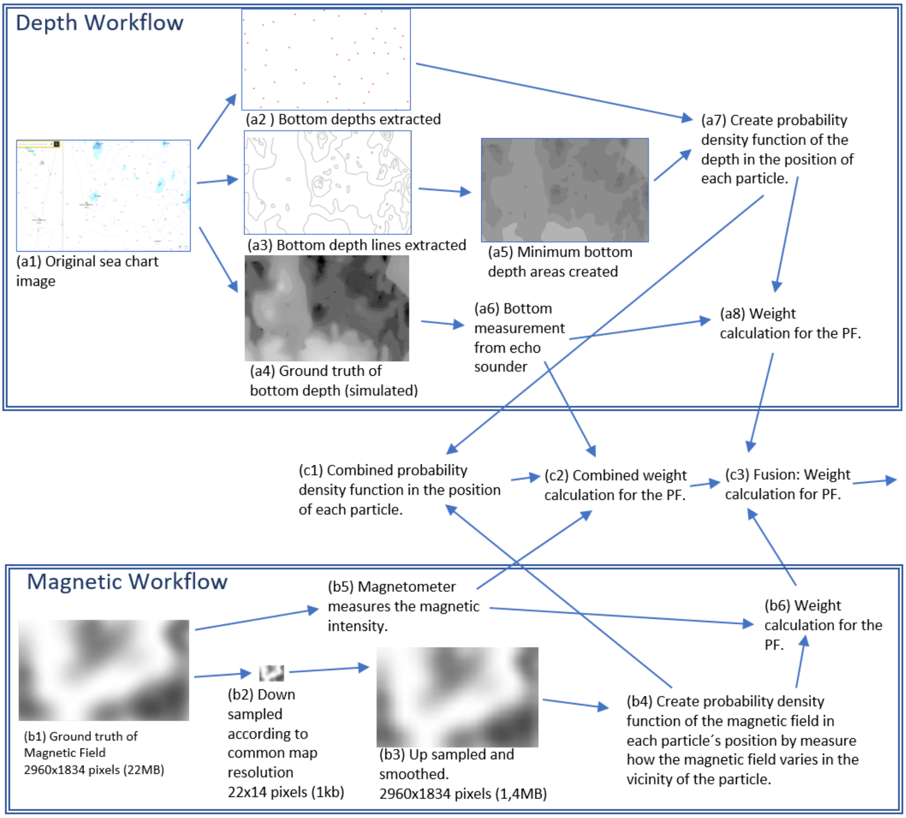



Figure 13: The process of how to go from a sea chart and a magnetic field map, to weights, used in the *Correction Step* in the PF.

estimate a high-resolution map by upsampling and smoothing it (b3). A PDF is created for each location of the particles (b4). The weights for all particles (b6) are calculated by comparing the PDF (b4) with the measured magnetic field (b5). (b6) answers the question; **How likely is it that the particle is placed at the correct location, given my measured magnetic field?**

### Fusion of Workflows

From (a7) and (b4), a combined PDF is created (c1). This PDF is used in (c2) to calculate weights for each particle. (c2) answers the question: **How likely is it that the particle is placed at the correct location, given my measured bottom depth and the measured magnetic field?** The weights from bottom depth (a8), the magnetic field (b6), and the combined weights (c2) are fused, to a joint weight (c3).

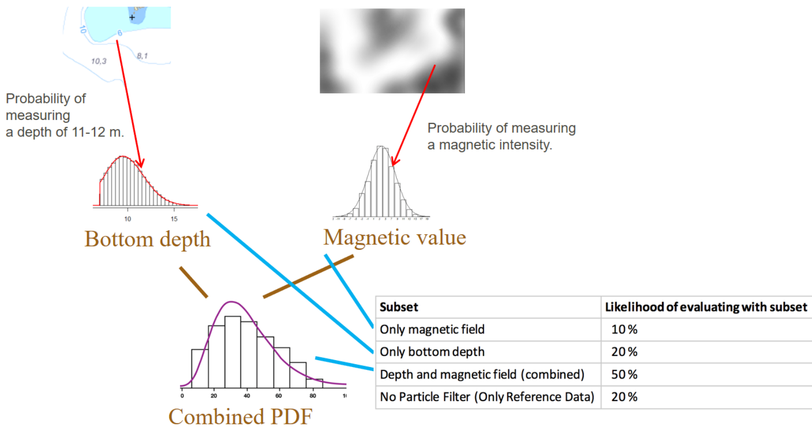



Figure 14: A PDF is created for each location of the particles. For the bottom depth, the PDF shows how likely every bottom depth is, given the sea chart. The PDF for the magnetic field shows how likely various magnetic field values are. When measuring a bottom depth or a magnetic field value, the PDFs are then used to estimate how likely the bottom depth or magnetic field value is. The combined PDF is used to figure out how likely a particular bottom depth measurement and a magnetic field measurement are in combination. The subset table is used to determine how large a portion of the particles that should be evaluated according to each method.

In the last step (c3) in Figure 13, the results from the different weights are fused. This is done by evaluating a portion of the particles according to each of the methods. In Figure 14, 10% of the particles are evaluated according to (b6), 20% of the particles according to (a8), 50% of the particles according to (c2), and 20% are just dead reckoned according to the INS movement. In Paper I, we compare how the performance changes when using various sizes of these subsets.

## 1.2 Example images from running the program

The images in Figure 15 show how the ship moves in the west direction. After passing the 20m bottom depth line, the PF is able to discard many of the wrongly positioned particles (to the south-east) and is thereby able to estimate the position more accurately.

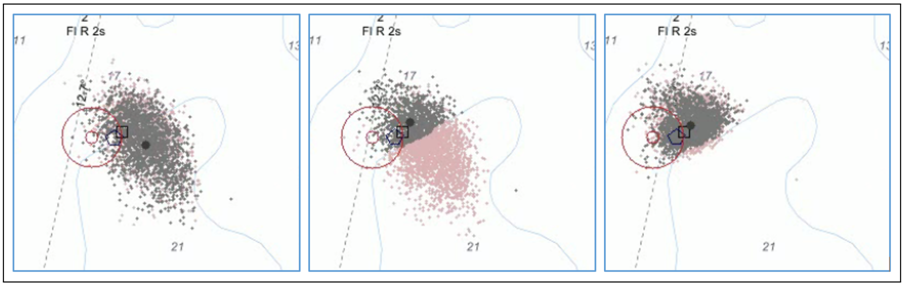



Figure 15: For symbol legend, see Table 4 on Page 70. In the left image, the particle cloud is spread to the east from the true position. The center image shows how the particles to the south-west of the 20m bottom depth line are discarded, when the echo sounder system onboard the ship measures a depth of below 20m. In the right image, the discarded particles are no longer shown.

## 1.3 Performance of the algorithm

The results from Paper I show that when fusing the different PF methods in a 20h long test, the mean of the position errors for the high-end INS has been calculated to be 10.2m when using the bottom depth lines, and 30.5m when not using them. This accuracy is most often good enough to use for navigation. After around 20h, the performance of the INS is so bad that the performance is reduced significantly. Table 2 shows a 24h test setup from Paper I. In, e.g., test (1), all the particles are evaluated according to the bottom depth in the Correction Step, giving a mean position error of 22.5m. In (2), all the particles are evaluated according to the magnetic field measurements, giving a worse accuracy of 28.9m. In test (4) and (5), the particles are evaluated by combining various methods, giving the better performance with a mean position error of 17.0m and 16.8m. The performance of the PF increases when using the more accurate source Depth, compared to the Magnetic Field. By also using multiple fused sources, the accuracy is increased even further. It would also be possible to add other independent sources as well, e.g. visual direction to objects such as lighthouses.

Table 2: Test setup and results for a 24h long test with a high-accuracy INS.

| Evaluation method | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Depth | 100 | 0 | 0 | 30 | 25 |
| Magnetic Field | 0 | 100 | 0 | 15 | 10 |
| Depth ∩ Magnetism | 0 | 0 | 100 | 55 | 65 |
| Skip PF (Only INS) | 0 | 0 | 0 | 0 | 0 |
| KF Mean (m) | 22.5 | 28.9 | 19.8 | 17.0 | **16.8** |
| KF maximum error during 24h (m) | 120.0 | 72.9 | 77.9 | 74.0 | 84.9 |

In Figure 16, a graph is showing two test runs of the program, where a combination of evaluation methods is used for the Correction Step. The difference between the two graphs is that one of the test runs have used the information from the bottom depth lines in the sea chart, and the other has not. Even though the performance decreases while not using the depth lines, it still manages to maintain a mean position error of only 34.0m. The graph also shows that the performance of the INS, and thereby the performance of the PF gradually decreases after 1200min (20h).

## 1.4 Prediction Step - a future enhancement

All the particles are moved according to a high-performance INS, which are very accurate in the beginning, but then gradually lose performance as time increases. The algorithm works well as long as the INS is still performing reasonably well, but have currently no function to remedy high drift errors as the INS lose performance. In a real-world scenario, a ship is normally also equipped with a compass and a log that measures the speed, hence a real-world implementation would preferably use

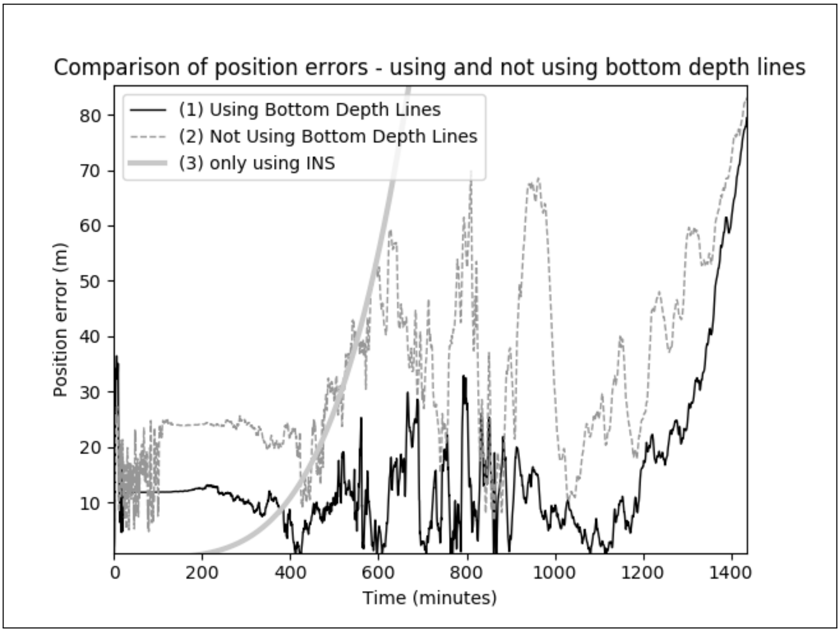



Figure 16: The high-accuracy INS is used. The performance is influenced by using or not using the bottom depth lines in the sea chart. Even though the performance is lower when not using them, it still manages to track the correct position during the 24h test. A mean position error of 34.0m is maintained.

the compass direction and speed instead of the INS value when the INS is starting to drift.

## 2 Teleoperation system

The second sub-project focuses on how a GUI can be implemented to remotely supervise a small USV, while the communication bandwidth between the USV and the operator is limited, which is a realistic scenario during, e.g., a Search and Rescue (SAR) mission. The sub-project has resulted in two of the included papers, see Paper II and III. Of particular interest is to see how the user's *situational awareness* and *cognitive load* are affected when using such GUIs in comparison to using traditional ones. To answer these questions, we propose a 3D-visualisation of the ship's surroundings either on a computer screen or in a Virtual Reality (VR) setup. The reason for using 3D-visualization and VR has to do with the fact that the perception of such GUI much resembles how a human normally perceives the world, which is assumed to be beneficial for the communication between the human and computer. The design of the GUI is based on ideas from the available research regarding manned ships to increase the situational awareness while maintaining a low cognitive load.

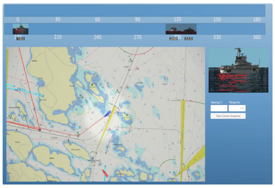
Our assumption is that we can create an easy-to-use GUI which provides a good situational awareness, and thereby increase the safety, by:

- Creating the GUI in 3D, and preferably present it in VR.
- Providing different views of the surrounding environment, optimized for various situations.
- Augment objects and information directly in the 3D world.

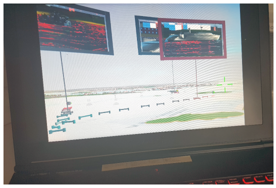
Our hypotheses are that a user operating a GUI built by these foundations will have a better overall understanding of the situation, and will observe potential dangerous situations earlier.

Three different GUIs have been developed; one *Baseline GUI*, representing traditional navigation tools, one 3D tool presented on a laptop, called *3D GUI*, and one 3D tool presented in VR, called *VR GUI*. All these GUI types are presented in Figure 17.

The application for Teleoperation is implemented in Unity 3D [71], which is a development tool normally used for making 2D and 3D games. A 3D world (called *Unity World*), developed by the shipyard Saab Kockums AB [72], was used



(a) Baseline 2D GUI



(b) 3D GUI on a laptop

(c) VR GUI

Figure 17: Three types of GUIs have been developed. (a) is a 2D GUI, that represents a traditional GUI. (b) and (c) are created in 3D, where (b) is presented on a laptop and (c) in VR.

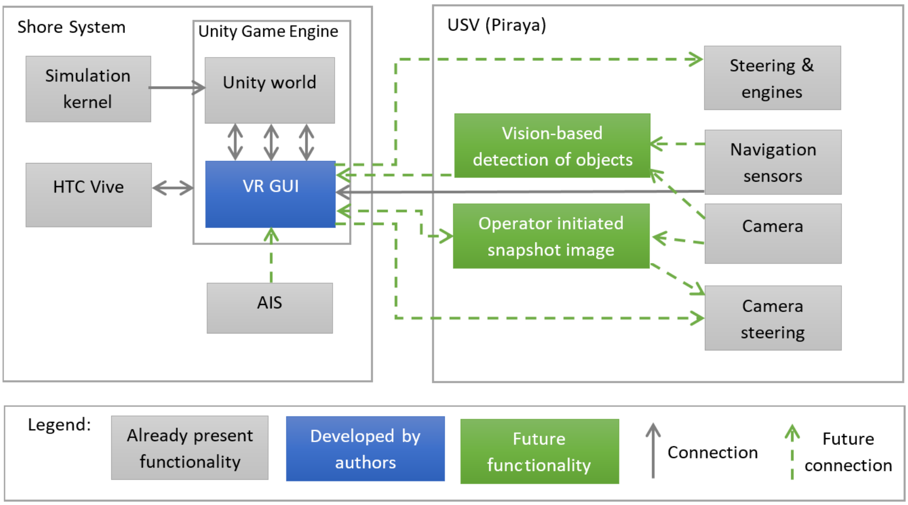



Figure 18: The VR GUI (or 3D GUI) is the main application where the interface is created for the operator. It presents the GUI in the Unity World, which is a 3D Virtual Environment (VE) with a virtual world positioned in the own ship's location with surrounding ships simulated by the Simulation Kernel. In the current implementation, the real world USV's position can be transferred to the VR GUI, so that the virtual USV is presented at the correct location in the VE. Many functions or interfaces are not yet implemented in the real world, but are instead simulated. These are marked with green boxes and dashed green lines. The steering interface is not implemented yet in the simulation tool.

as a foundation for the GUI, see Figure 18. A USV, also produced by Saab Kockums, has been used for initial testing. Some functionality, such as ship detection, is not implemented onboard the real world USV yet. By this, most of the implementation and testing has been conducted virtually instead. The Simulation Kernel is, in this case, simulating also the own ship, and the cameras are taking photos from the VE.

To evaluate the application, a user-study has been conducted with 16 participants, see Paper III. Figure 19 shows how the images and GPS position feeds the VE with data so that a 3D world can be created with a virtual ship in the middle of the world in the same location as the real-world USV. Also, AIS information is presented. The GUI is then presented for the operator, who supervises the own vessel's route. It is only possible to supervise the USV, as any steering is not yet implemented.

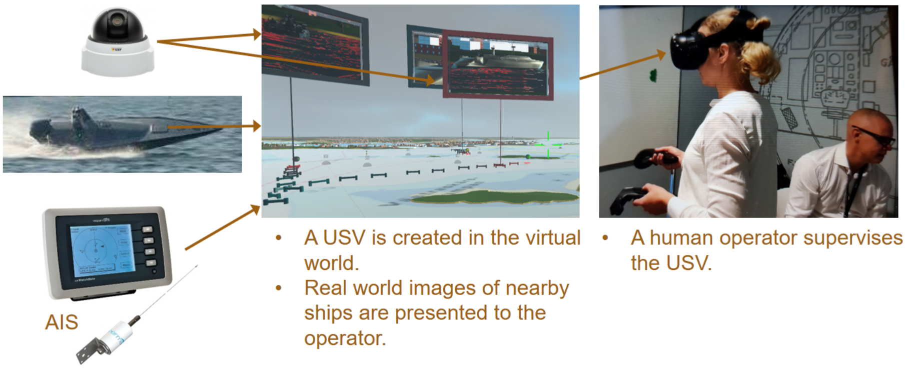



Figure 19: The location of the USV is used for creating a VE around this location. The sensor data from the camera and AIS detects ships, which are presented in the VE. The VE is then overlayed with the GUI, and presented for the human operator.

## 2.1 Performance of the 3D GUI and VR GUI

The user-study of the GUI gave some interesting results, in more detail described in Paper III. It was investigated, how 3D and VR approaches could support the supervision of a USV with a low bandwidth connection, by comparing respective interfaces with a GUI following the currently applied interfaces in such contexts.

Our findings show, that both the 3D and VR approaches outperform the traditional approach significantly.

It was found that the users were calmer during the study and could keep track of the situation more accurately. They also reported that they expected the *3D GUI*, and especially the *VR GUI* to be the best tool of the three choices for an expert user with many hours of training.

# Discussions and Conclusion

This chapter ends the first part of the thesis with discussions and conclusions about the work.

## 1 Discussion

### 1.1 Future of Unmanned Ships

There is a long way to go before autonomous ships will be commonly used. A lot of research and development projects are going on though, and as unmanned ships and ships with lean manning get more affordable, it is likely that the fleet will gradually degrade their manning. The shipping industry will not need to develop all building blocks themselves, as they will need similar technology as, e.g., the automotive industry, where great efforts are made on making fully autonomous cars within the next coming years. The building blocks still need to be adjusted to fit the naval domain though. Some areas where the technology needs to be adjusted are:

- Positioning of a ship is normally not done in the same way as for cars. Ships need their own methods and algorithms for robust positioning systems.

- Traffic rules at sea are not the same as for cars. The ships need to obey these rules. Planning algorithms from the car industry might work as a basic tool to build from.

- Training data for, e.g., image recognition is not the same. A large amount of data collection needs to be done. The same algorithms as for cars can possibly be used.

## 1.2 GPS free Navigation

The implemented PF gives quite a good accuracy during many hours of time when using data both from bottom depth measurements and magnetic field measurements. The accuracy is better when using the bottom depth lines from the sea chart, which is reasonable, as wrongly placed particles then can be discarded with better precision. The PF performance is not as good as GNSS-based accuracy, but for most cases accurate enough for most navigation purposes. If there is a demand for even higher accuracy, there are alternatives to increase the position accuracy in many ways, e.g.:

- The INS position error is increasing exponentially, and after a specific time, the INS produces less accurate estimations than the compass and the speed log. By fusing the measurements from the INS, the compass and the speed log, the best velocity estimations at all time would be given, boosting the performance of the PF.

- In Paper I, the magnetic field strength and the bottom depth are used. Also, other measurements can be fed into the same algorithm, both increasing the position accuracy, but also the robustness. By having a sonar that measures the depth at many places at the same time, it will be possible to pinpoint the location with greater precision. It is also possible to boost the performance by measuring the direction to other objects such as masts, lighthouses, islands, and stars. These measurements can be done by cameras or radars.

As can be seen, there are many alternatives to GNSS systems when navigating. By combining multiple sources, it is possible to construct a robust and accurate positioning mechanism. The drawback is that time must be spent on evolving the algorithms, and more computing resources must be used onboard the ships. As computing resources get less costly, the technology is likely to become more mainstream.

## 1.3 Teleoperation of USVs

To be able to use semi-autonomous systems, teleoperation will be a key technology to bridge the gap until the vehicles will be able to take all decisions by themselves. The most well-used teleoperation GUI is to use one or multiple computer screens, where a 2D GUI is shown along with at least one GUI part that is dedicated to streaming real-time video from the vessel. Our hypothesis was that a 3D GUI, and especially when presented in VR, would increase the operator's ability to uphold an overall understanding of the surrounding situation, and thereby the safety. This hypothesis was proven to be true, as the user study presented in Paper III showed that the VR GUI and the 3D GUI presented on a computer screen increased the performance compared to the traditional GUI on a computer screen. Persons that already had experience in 3D games or VR, had even higher scores, indicating that expert users would benefit even more from this new technique. The VR HMD evolution also goes quickly. There are already HMDs that can produce a 3D world with quite good performance, and this fast evolution will continue.

One of the benefits with VR is that the surrounding world can be presented in a way that reminds of how humans normally perceive their environment. Another benefit is that there are also hardly any limitations when it comes to how the GUI can be presented for the operator. The human can have various surrounding worlds, the GUI can be placed in the air augmenting objects, or present multiple virtual screens. A virtual control room can be created for the specific operator's task, and other relevant human operators can be placed nearby as avatars. The GUI presented in Paper II and III is far from perfect, but it still gives a taste of the endless possibilities that come with VR.

If professional VR GUIs are used, it is important to know to what extent VR can be used. Is it practically possible, or even healthy, to use VR 40 hours per week, or should the use of VR be restricted to only accommodate special tasks? Will this change, as VR HMDs improve in performance? This is an important question, but will not be the scope of further investigations by the author.

## 2 Future Work

The scope for my future work is to investigate building blocks of technology that will contribute to the path towards fully autonomous ships, and specifically how safety and situational awareness can be enhanced for the humans that are needed in the loop. I believe that the tasks conducted onboard a ship can be modularized into building blocks, where each block is easier or harder to automate. In the beginning, the task of a building block is most often best performed by a human. But as technology evolves, the machine can gradually do a larger portion of the task, first supporting the human operator, then do the task supported by the human operator, and finally do the whole task by itself. So far, I have investigated how two of these building blocks can be enhanced. There are multiple other building blocks that I would like to study:

- **Image recognition at sea.** Semi-autonomous cars are gathering data, to train neural networks to recognize objects in the traffic. I am interested in doing the same thing at sea. A big difference is that not as much data can be easily collected, as there are fewer ships than cars. The images will mainly constitute of water and sky, so it should be possible to do a fairly robust object detection. To remedy the lack of a large training set, *Transfer Learning* might be used in combination with simulated images and data augmentation for creating the first layers in the network.

- **AR or VR on manned ships.** Currently, I have created a VR GUI for remote supervision of a small USV with a bandwidth constraint. Comparable solutions can be constructed for manned ships as well. Then the bandwidth constraint would be removed, and all the sensors onboard the vessel could together with smart fusion techniques and AI contribute to the ultimate situational awareness experience for the human operator. The GUI can be constructed for AR with the operator on the real world bridge, or for VR, where the operator is placed in a virtual control room giving more flexibility to the GUI. These GUIs could be compared to a state-of-the-art GUI for ship navigation. This project can also use various types of fusion methods to compile what should be shown for the human operator.

- **Enhanced GPS-denied positioning.** The GPS-denied positioning algorithm could also be enhanced. Currently, it only uses the INS for the Prediction step. By combining compass, speed log, and INS, it would get a better velocity estimation for a longer period of time, which would boost the performance of the algorithm. The performance of the Correction Step could also be enhanced. Currently, it only uses the magnetic field and bottom depth. It would be interesting to see how the performance changes if bearings are given to landmarks, measured by, e.g., camera systems. One idea is to navigate in the simulated 3D world used for the teleoperation subproject, and place the virtual ship on a position in accordance with the PF's position estimation. By augmenting, e.g., lighthouse positions, the human operator would instantly see if the position is off when seeing that the lighthouse and the augmentation for the lighthouse do not match. The operator could then adjust the bearing of the augmentation, which could feed back a correction to the PF. The benefit would be that the operator can see if the position makes sense (the augmentation matches the lighthouse), and can make adjustments of the position, helping the algorithm.

# 3 Conclusion

Much work remains to be done in the quest for fully autonomous ships. Many building blocks need to be developed, and in this thesis, the development of two of these blocks have been studied.

In the first sub-project, we have seen that smart techniques can be used as a complement to positioning systems relying on satellites. During a 20h long test, a mean of the position error was measured to be 10.2m, when using the high-end INS, bottom depth measurements and magnetic field measurements. The performance of the PF got better with more and better input data, as the PF then could discard particles which were placed in incorrect locations.

The second sub-project investigated how 3D and VR approaches could support the remote operation of a USV with a low bandwidth connection. Our findings showed that both the 3D, and especially visualized in VR, outperformed the traditional approach significantly. We found the 3D GUI and VR GUI users to be better at reacting to potentially dangerous situations compared to the Baseline GUI users. The users also expected the 3D GUI, and especially the VR GUI to be the best tool of the three choices for an expert user with many hours of training.

# Scientific Publications

## 1 Summary of the included papers

**Paper I**

**Underwater Terrain Navigation During Realistic Scenarios**

**M. Lager**, E. A. Topp and J. Malec
Multisensor Fusion and Integration in the Wake of Big Data, Deep Learning and Cyber-Physical System - An Edition of the Selected Papers from the 2017 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI 2017), Springer (pp 186-209)

**Summary:**
The paper presents a method for estimating own position at sea by comparing own bottom depth measurements and magnetic field measurements with known sea charts and magnetic field maps. The method uses a Particle Filter, that moves thousands of particles (position estimations) according to own INS, and then calculates the probability that each particle is correctly located by comparing the sensor measurements with the maps. After each iteration, more likely particles will survive and less likely will be discarded, and the position is thereby continuously estimated. To increase the performance even further, a Kalman Filter has been used. The paper also elaborates on how the performance is changed when weighting different sensor measurements differently, or when having various performance on the INS. The results from the simulated tests, described in this paper, show that for the high-end INS, the mean position error is 10.2m, and the maximum position error is 33.0m during a 20h test.

**Paper II**

**Remote Operation of Unmanned Surface Vessel through Virtual Reality - a low cognitive load approach**

**M. Lager**, E. A. Topp and J. Malec
The first International Workshop on Virtual, Augmented and Mixed Reality for Human-Robot Interaction 2018 (HRI 2018)

**Summary:** The paper describes a design of a VR GUI for teleoperation of a USV, where there is a bandwidth constraint between the operator and the USV, that makes it impossible to transmit high-resolution images or video streams. The intention has been to create a GUI that provides at least as safe navigation, as when an operator navigates onboard a ship. To accomplish this, the strength of 3D and VR has been used, where surrounding objects are augmented directly in the 3D world, giving a user experience that resembles how humans normally perceive their environment. Three main views have been suggested, which all have their strength and weaknesses depending on the situation.

**Paper III**

**Remote Supervision of an Autonomous Surface Vehicle using Virtual Reality**

**M. Lager** and E. A. Topp
Submitted to Autonomous Intelligent Vehicles 2019 (IAV 2019)

**Summary:**
The paper presents a user-study of the GUI presented in Paper II, where 16 participants have supervised a simulated USV, going through the archipelago. The user-study has studied how safety, situational awareness, and the cognitive load is changing depending on if the user uses a traditional GUI, a 3D GUI presented in VR, or a 3D GUI presented on a computer screen. Our findings show, that both the 3D and especially the VR GUI outperform the traditional GUI significantly. A short version of this paper has been accepted to HRI 2019.

## 2 Contribution Statement

Author and co-authors are abbreviated as follows: Mårten Lager (ML), Elin A. Topp (ET) and Jacek Malec (JM).

ML is the main author of Papers I–III. Papers I–II have been co-written with ET and JM, and Paper III has been co-written with ET. For all these papers, ML provided an initial version of the paper, which was then revised to final form in collaboration with co-writers. The overall project ideas presented in the papers have been proposed by ML, and have then been discussed and enhanced in collaboration with co-writers. All the implementation work has been carried out by ML. The user-study in Paper III was carried out by ML.

## 3 Other Contributions

The following papers are related, but not included in this thesis.

**Long-Term Accuracy in Sea Navigation without using GNSS Systems**

**M. Lager**, E. A. Topp, and J. Malec
In Proc. of the 30th Annual Workshop of the Swedish Artificial Intelligence Society (SAIS 2017), Karlskrona, Sweden.

**Underwater Terrain Navigation Using Standard Sea Charts and Magnetic Field Maps**

**M. Lager**, E. A. Topp, and J. Malec
In Proc. of the 2017 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI 2017), DOI: 10.1109/MFI.2017.8170410.

**Remote Supervision of an Unmanned Surface Vessel - a Comparison of Interfaces**

**M. Lager**, E. A. Topp, and J. Malec
Accepted as a Late Breaking Report to the IEEE/ACM Conference on Human-Robot Interaction (HRI 2019), Daegu, Korea.

# Part II

# Research Papers

# Paper I

# Paper I

# Underwater Terrain Navigation during Realistic Scenarios

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## Abstract

Many ships today rely on Global Navigation Satellite Systems (GNSS), for their navigation, where GPS (Global Positioning System) is the most well-known. Unfortunately, the GNSS systems make the ships dependent on external systems, which can be malfunctioning, be jammed or be spoofed.

There is today some proposed techniques where, e.g., bottom depth measurements are compared with known maps using Bayesian calculations, which results in a position estimation. Both maps and navigational sensor equipment are used in these techniques, most often relying on high-resolution maps, with the accuracy of the navigational sensors being less important.

Instead of relying on high-resolution maps and low accuracy navigation sensors, this paper presents an implementation of the opposite, namely using low-resolution maps, but compensating this by using high-accuracy navigational sensors and fusing data from both bottom depth measurements and magnetic field measurements. A Particle Filter uses the data to estimate a position, and as a second step, a Kalman Filter enhances the accuracy even further.

In "Multisensor Fusion and Integration in the Wake of Big Data, Deep Learning and Cyber Physical System", Springer, (MFI 2017), (pp 186-209), DOI: 10.1007/978-3-319-90509-9_11.

The algorithm has been tuned and evaluated using both a medium and a high-accuracy Inertial System. Comparisons of the various tuning methods are presented along with their performance results. The results from the simulated tests, described in this paper, show that for the high-end Inertial System, the mean position error is 10.2m, and the maximum position error is 33.0m during a 20h test, which in most cases would be accurate enough to use for navigation.

# 1 Introduction

The use of Global Navigation Satellite Systems (GNSS) has revolutionized the navigation at sea since the first GNSS Global Positioning System (GPS) was launched in 1994. It is affordable, easy to use, and provides accurate position estimations. One of the biggest advantages is that it does not use the previous position estimation as a base for the next one and thereby avoids accumulating position errors, which happens when dead-reckoning the position using a compass or an Inertial Navigation System (INS). With this advantage, a GNSS system can maintain an accurate position no matter how long time it was since leaving the harbor with a known position.

There are still some disadvantages with GNSS though. One important disadvantage is that the ship needs to rely on external information from the GNSS satellites which is sent to the GNSS receiver onboard. It is quite simple to jam the radio reception from the GNSS satellites, which results in that it is not possible to determine the position anymore. Even worse, it is possible to spoof the GNSS transmission information with advanced equipment, resulting in that an incorrect position is provided [33].

If a dependency on the GNSS is not desired, Bayesian calculations can be used for position estimation. The technique has been used for decades for some airplanes, where, e.g., [34] describes how the systems on an airplane measure the altitude and compare it to a known terrain map with a *Particle Filter* (PF) algorithm, thereby estimating the position. There are also many papers describing how ships can use the same technique, where the bottom depth is measured by an echo sounder system or a sonar system [35, 36, 37, 38]. More specifically, Autonomous Underwater Vehicles (AUVs) have a big need for position estimations, as they cannot use any GNSS, which has led to much research covering this topic, where various types of sonar systems and algorithms have been studied [36, 39, 40, 41, 42, 43, 44, 45, 46].

However, there is other information which can be used by particle filters for positioning. [47] and [48] suggest how to estimate a position in an indoor environment with a PF comparing magnetometer measurements to a known magnetic map of a particular room.

The current research in this field has mainly focused on achieving good performance of the positioning systems when having a limited performance of the sensor suite, but nearly unlimited accuracy of the map. The available research for ship navigation has also mainly focused on one sensor type at a time. In this paper, we propose a solution where we do it the other way around, which is more in-line with a real-world scenario on bigger ships than on AUVs. The main research question is, therefore: **Is it possible to navigate accurately enough without GNSS systems, only relying on high-performance navigation sensors, normal sea charts and standard magnetic maps?** In this paper, we show, that by using both depth data and magnetic data at the same time and fusing this information, the position accuracy is increased, and it is possible to overcome the difficulty with poor map accuracy in either the depth or magnetic domain. As the last step to boost the position accuracy even further, we also propose to use a Kalman Filter (KF).

The algorithm has been evaluated using various configurations, both when using a medium and a high accuracy inertial system.

This paper is an extended version of an already published paper [70], and is organized as follows: In Section 2, an overview of other related work is given focusing on PF estimating the position by measuring bottom depth and magnetic field. Based on the currently available research, limitations and opportunities of this approach are described in Section 3. Section 4 and 5 describe our contributions. First, the software is described, and then the simulation results and tuning are discussed. In Section 6, concluding remarks are given.

## 2 Related Work

As our system is based on the fusion of different measurement data types, each of which being used in similar or related contexts and approaches, we describe related work organized by these data types and their appearance in filtering techniques.

### 2.1 Depth data in the particle filter

It has already been named that in possession of a high-resolution bottom map PF can be used for position estimation by measuring the bottom depth [35, 36, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46]. There are some problems with the technique though. There are not that many areas where high-resolution maps have been created. Another problem is that the bottom terrain needs to vary enough for the PF to work, and in some areas, the bottom terrain is quite flat [35]. A solution to these two problems would be to use normal bottom sea charts and to complement the depth measurements with other measurements.

## 2.2 Magnetic data in the particle filter

Earth is surrounded by a magnetic field, where each ferromagnetic element disturbs this field. These disturbances can for indoor environments be even greater than the natural magnetic field of Earth [47]. For indoor environments, numerous ferromagnetic elements create a complex magnetic field where the magnetic vector varies greatly depending on the location. The magnetic field is also quite stable if no major furniture or iron walls are moved. This information can be compared to a magnetic map using a PF, and in conjunction with some sort of odometry, such as wheel encoders or inertial sensors, it has been possible to localize a human or robot [48]. In [47] only cheap smartphone sensors are used, and the magnetic field and acceleration are used for determining the position of the human user.

Although [47] and [48] have explored indoor environments, the same technique is applicable for outdoor environments. The magnetic field does not fluctuate as fast as in indoor environments, but on the other hand, it is more stable, because no furniture or building parts are moved around as in the indoor environments. There are satellite maps available covering the entire magnetic field of Earth, and in some areas of the world, higher resolution maps have been created, e.g., by low flying airplanes. Hence, the magnetic field has been used in our PF algorithm for estimating the position of the ship. Our implementation shows that the magnetic field intensity serves as a good complement to bottom depth measurements when it comes to improving the accuracy and robustness of the position estimation.

## 2.3 Using other data in the particle filter

The bottom depth and the magnetic field are good candidates to use for the PF algorithm when estimating the position, but there are other alternatives. In addition to the bottom depth, [39] also uses range measurements to land objects in another PF algorithm. This range is measured by a radar and is compared to a sea-chart database.

It is also possible to not only use the depth measurement directly vertically to the bottom. If the ship is equipped with a sonar system, it is also possible to use multiple bottom depth measurements covering a larger area at once. This increases the performance of the PF, as it is possible to evaluate if the bottom readings match the map with better precision [42]. Another way to improve the performance is to use the sediment layers of the bottom, where the lower layers' depth most often varies more than the sea floor [35].

The strength of the PF algorithm is that it is very flexible when it comes to which measurements to use. The important thing is that the measurements shall vary enough when changing position and that it shall have varied in the same way (or in a predictable way) when the map was created, and when doing the PF measurements. Other candidates which could be used for the PF algorithm are:

- Celestial navigation items such as star positions, where a star either is present in a proposed direction or is not.
- Gravitation, which varies depending on where the ship is located on the earth.
- Various types of available bearing measurements, depending on which sensors the ship is equipped with. For instance, bearing measurements to visual objects, radio and radar sources with known map locations can be used, if the ship's sensors are able to estimate the bearing to that kind of sources.

## 3 Limitations with current research

The referred papers show that it is possible to do accurate position estimations if high-resolution maps are available to compare new measurements with. Many of the studies also evaluate how accurate the position estimation can become when these high-resolution maps are available. However, there are some limitations with these approaches, as it is rather rarely the case that such maps exist, even in coastal areas. The reality is that different areas have been mapped with various accuracy, where high-traffic areas more often have better accuracy and resolution than less-traffic ones. The algorithm for positioning in, e.g., [48], assumes that it can get the true bottom depth in any position of the map, but from a normal sea chart it is more likely that it is possible to compute some sort of likelihood distribution of the bottom depth for each position.

Excluding AUVs, the user platforms that are most likely to have a need for a system for accurate position estimation techniques which eliminates the need for GNSSs, are not cheap ones with moderate navigation systems. The most probable platform is instead an advanced vessel with accurate and expensive navigation sensors, where the RD (ship reference data), speed, bottom depth and magnetic field can be measured with high accuracy.

In this paper, a scenario more fit to the real world is investigated; namely, a platform estimating the position using high accuracy sensors, normal sea charts and magnetic field maps. The purpose of combining depth and magnetism is that the condition for estimating the position by using solely depth data or magnetic field data varies depending on location. By combining the data, it is possible to increase the performance and overcome large position errors where one of the maps has lower accuracy.

The algorithms used for the high accuracy INS can also be used for a medium accuracy INS, which is an INS more in line with an INS that are normally being used on high-end AUVs. The algorithm performance has been evaluated also for these platforms.

# 4 Combining depth and magnetic data

The key problem we have is that we would like to estimate the ship's position (denoted by $x_t$), but we are only measuring other related information such as how the ship is moving, bottom depth and magnetic field (denoted by $y_t$).

If the measurements and transition functions were linear and the measurement and process noise Gaussian, the immediate application of a KF would have been the optimal choice to compute the position [73]. In our case the transition functions are non-linear and the measurements have no Gaussian distribution, but instead a highly multi-modal distribution. There are some non-optimal extensions to KFs to handle the issues with non-linearity and not having a Gaussian distribution [74]. However, PFs are more flexible and have a built-in capability to handle multi-modal distributions. Therefore, the PF algorithm has initially been used for our implementation. However, as indicated above, we improve the accuracy of our method by applying a KF in a second filtering step, as is described later.

On a ship, the Inertial Navigation System (INS) uses accelerometers and gyroscopes to continually calculate the ship's orientation and velocity with high accuracy, without the need for external references. The INS outputs this data as the ship's Reference Data (RD) which is used in the state model.

The state can contain different variables depending on what sensors are available and how complex we want the algorithm to be. Because our currently developed implementation is made for simulation purposes, variables for compensating sensor directions and ship drifts can be left out. Therefore the state (1) contains solely the position, where $X_t$ and $Y_t$ are coordinates in some suitable coordinate system.

$$x_t = (X_t \;\; Y_t)^T \tag{1}$$

The model of the state change, with the discrete sample time $\Delta$, is given by (2).

$$x_{t+1} = f(x_t, u_t, w_t) = \begin{pmatrix} X_t + v_t \Delta sin(\varphi_t) \\ Y_t + v_t \Delta cos(\varphi_t) \end{pmatrix} + w_t \tag{2}$$

In this equation $u_t = (v_t \ \ \varphi_t)^T$ is the input signal, which consists of the speed $v_t$ and compass angle $\varphi_t$. The $w_t$ is the process noise.

We now have the model for how to go from one state to the next one, and from the sea chart and magnetic field map, we can get information about how the depth and magnetic field $y_t$ depend on the position in the state $x_t$. In this setting, the PF can be used for estimating the position.

## 4.1 Kalman Filter for enhancing the performance

The PF provide position estimations as well as quality attributes of the measurements, which can be acquired from the covariance of the particle cloud. Due to the map dynamics, the PF's position estimation can change rapidly around the true position.

The dynamics of how the position error increases with time is modeled as the *Process Noise* of the KF, and by feeding the KF with the position estimations as the *Observed State*, the KF is able to estimate a smoother and more accurate position of the ship.

## 4.2 High level algorithm

The model has been implemented in Python in order to investigate how the performance of a PF is influenced by using depth measurements, magnetic field measurements and a combination of those. For depth calculations, a standard sea chart has been used from outside the city of Karlskrona in Sweden, see Figure 20. The program can read the bottom depth measurements and bottom depth lines from the sea chart. The simulated ship is, on the other hand, reading depths from a manually created high-resolution map, see Figure 21, which has been created to as far as possible mimic the real terrain at the seabed. In a comparable way, a simulated magnetic field map has been created, along with a low-resolution magnetic map, comparable to publicly available magnetic field maps.

The high-level behavior of the model using the PF algorithm (see Figure 22) is as follows:

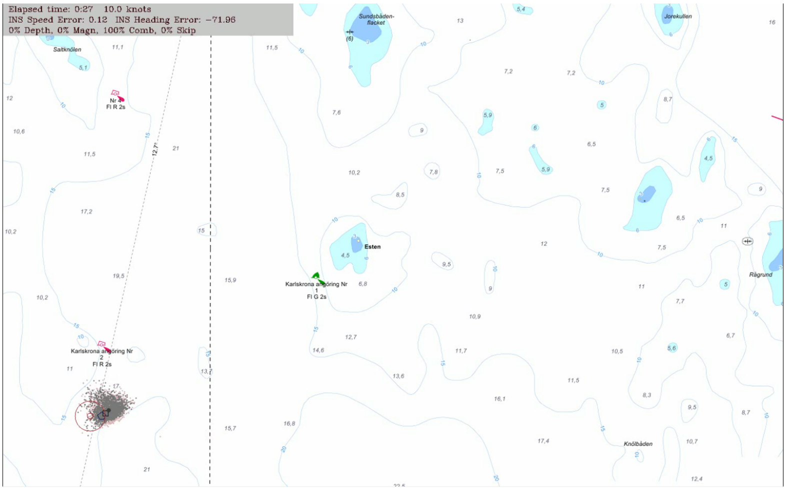


Figure 20: A screen-shot from the program. As an underlay, the used sea chart is shown. In South-west, the particles are following the simulated ship's position. (The area is about 2 Nautical Miles (NM) wide.)

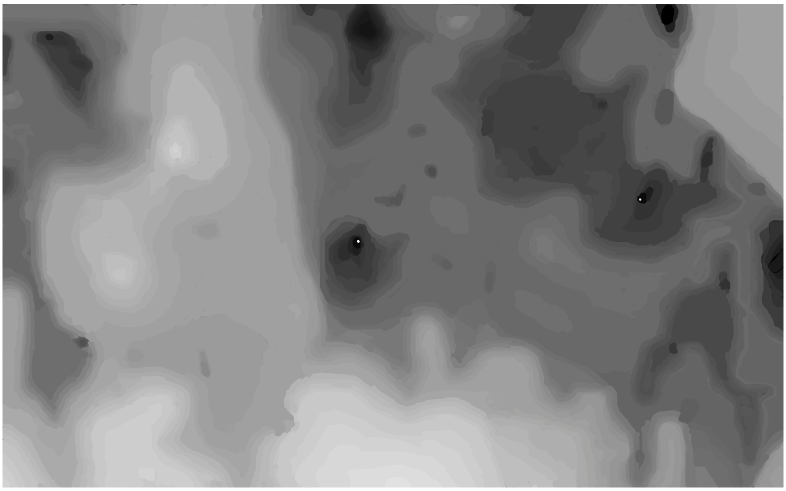

Figure 21: A corresponding high-resolution map, manually created. The aim has been to as far as possible estimate how the terrain is formed in real life. The simulated ship is measuring bottom depth by reading a value from the current position from this image.

1. **Initialization** - Generate N particles and give them a random starting position around a manual estimation of the starting position.

2. **Prediction** - Move each particle according to the velocity vector predicted by the INS. Then move each particle according to a random velocity vector, in order to simulate the velocity vector error of the INS.

3. **Correction** - Calculate the weights for each particle given the maps and each particle's position. The weights are calculated for depth, magnetic field and a combination of those two. Normalize the weights.

4. **Re-sampling** - The particles are re-sampled according to a predefined distribution from subsets defined as in Table 3.

5. **Iteration** Go to step 2.

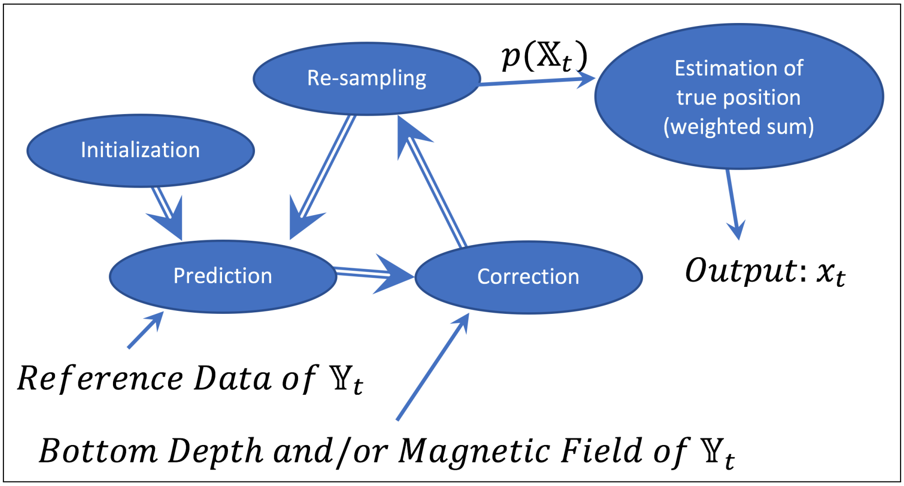


Figure 22: A block diagram of the Particle Filter used in our implementation. After initialization, the particle filter iterates between *Prediction*, *Correction* and *Re-sampling*. After the *Re-sampling Step*, a probability of each state $p(\mathbb{X}_t)$ is estimated from the particles. From this, a weighted sum of all particles can be used as an estimation of the true position.

The *Correction Step* needed some tools in order to operate, which are described below:

### Map data

To make the *Correction Step* operable, there must be data supporting the likelihood calculations, which estimate how likely it is that the current measurement has been performed at a given location. If a high-resolution sea chart is available, where it is possible to see the exact depth at every location, this is easy. On the other hand, we cannot assume that high-resolution and high accuracy maps will be available for every possible area. Therefore, a combination is desirable, using high accuracy maps (either depth or magnetic) where available and normal sea charts for bottom depth information if only those are available.

To support the PF algorithm for the case when high-resolution maps are not available, two functions have been created; one for bottom depth estimation from sea charts, and one for magnetic field estimation from magnetic maps.

The function for bottom depth estimation first reads the position of a particle and then gathers the closest bottom depth measurements from the sea chart. These measurements are then weighted according to the distance from the particle ($weight = 1/distance$). In Figure 23, an example is shown where the bottom depth in a particle's position indicated by the star, is to be estimated. The depth measurement of 10.6m will be given higher weight than the other measurements. From these values, a weighted mean and a weighted standard deviation are calculated, which is used for creating a probability density function (PDF) with a normal distribution. The 10m-bottom depth line specifies that there is not less than 10.0m in the star's location. The 15m-bottom depth line specifies that there is probably not a depth of more than 15m (but there might be in some rare cases). In our implementation, we have set an (arbitrary) margin of 2.0m, and will approximate it as there cannot be any depth greater than 17.0m. Therefore, the PDF for the position in the image will be truncated below 10.0m and above 17.0m.

A magnetic chart does not look in the same way as the depth charts. Figure 24 shows a publicly available map of an area in Sweden, which has been created by flying on low altitude measuring the magnetic field. Each pixel in the map corresponds to an area of 185x185m. The function that estimates the magnetic field in the position of a particle, first interpolates the low-resolution image, creating a high-resolution image. Then it is possible to estimate the magnetic field directly by reading the magnetic field value from the position in the image. By comparing the estimated magnetic field with the values in the surrounding area, a standard deviation can be estimated. This is used for creating a normal probability distribution also for the magnetic field.

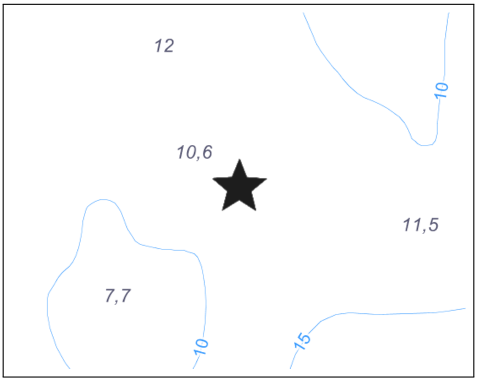


Figure 23: A sample detail of a sea chart. The position of a particle is indicated with a star. Bottom depth measurements are available as well as bottom depth lines. These values and lines are used for creating a probability density function.

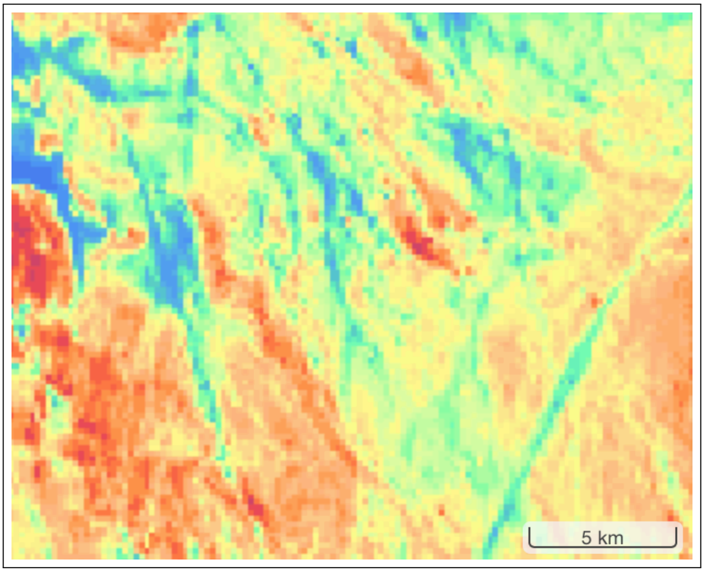


Figure 24: The figure shows a publicly available magnetic field map. Each pixel corresponds to a square with a width of 185m.

### Fusion of sensor data

On an advanced ship with high-precision navigation sensors, it can be acceptable to use the navigation sensors for dead reckoning without using global positioning techniques for some time. It will take a long time before the drift of the INS has become large enough for resulting in a completely inaccurate position. When using the PF algorithm to correct the position, it is therefore important not to spoil the advantages of the already well-working navigation system by leaning too much towards estimation of the position based on the PF compared to the dead-reckoning algorithm. The worst thing that could happen was if all particles at the correct position eventually were discarded, which can happen if the local measurements are not accurate enough, the maps are not accurate enough, the particles are too few, or the map measurements have been changed, e.g., due to some external effect. To meet this challenge, we propose dividing the particles into subsets at the beginning of each Re-sampling step. Then the particles in each subset are corrected according to the correction rule for the particular subset. There are different alternatives of how to divide the particles into subsets, when using magnetic and bottom depth data for the PF algorithm. We propose the following four subsets:

1. One subset of particles is weighted according to bottom depth measurements compared to a sea chart.

2. One subset of particles is weighted according to magnetic field measurements compared to a magnetic field map.

3. One subset of particles is weighted according to a combination of the bottom depth and magnetic field measurement (obtained by multiplying the probabilities). By combining both magnetic fields and bottom depth distributions into a single one, $\mathbb{Y}$, the PF has a better ability to calculate the probability density $p(x_t \mid \mathbb{Y}_t)$. The drawback is that particles can be discarded incorrectly if any measurements or the maps from the two subsets are inaccurate.

4. The last subset of particles has equal weights, where only the dead-reckoned position changes from the RD matters.

By letting various portions of particles be evaluated by the different subsets, the advantages can be taken from each solution. The size of each subset can then be determined by the quality of the bottom depth and magnetic maps/measurements compared to RD accuracy. The advantage of using multiple subsets is that, e.g., bad magnetic measurements or maps will not damage the subsets where magnetism is not taken into consideration. The drawback is that it will take a longer time before the PF converges to the correct position.

If bottom depth gives a better performance than the magnetic field in some area, the particles can be divided, e.g., according to Table 3.

Table 3: Example distribution of particles

| Subset | Distribution of particles |
|---|---|
| PF with bottom depth | 20% |
| PF with magnetic field | 10% |
| PF combining depth and magnetic field | 50% |
| No PF, just move particles according to RD | 20% |

In this way, the strength in combining data to support the PF is used by half of the particles. The other half of the particles are more carefully used so that some particles will survive even if local measurement errors occur or maps are inaccurate.

## 5 Evaluation and tuning of the algorithm

The program is written in Python, running on Ubuntu Linux in VirtualBox, on a high-end PC laptop. Even though the program is getting limited resources in the virtual environment, it still manages to simulate one hour of simulated time with 10000 particles, in one real hour. Each iteration lasts for 7.2 seconds. During the test runs, 500 particles were used for the high-accuracy INS and 5000 particles for the medium-accuracy INS. The algorithm is today made for simulation purpose and has not been tested in real-world conditions.

The following test runs first examine the performance of the algorithm when correcting 100% of the particles according to a single source of data. Then the performance is investigated when various combinations of these data sources are used. The last investigation is to see what happens when a portion of the particles are dead reckoned instead of using the PF. KF enhancement is used during all the tests, to see how this influences the performance. All the tests are being done using both a medium-accuracy INS and a high-accuracy INS.

## 5.1 Test setup

In the test runs, a normal sea chart and a magnetic map with the same resolution as publicly available magnetic field maps (comparable with Figure 24) were used. Echo sounder data and magnetometer data were simulated by reading values from manually created high-resolution maps, see section 4.2.

The particles are evaluated if they are within the map area. If any particle is outside the map, they survive to the next iteration and are just dead-reckoned. By not being able to evaluate these outliers in a correct way, the performance of the algorithm is reduced. Hence, the route is chosen in a way so that particles seldom end up outside the map, especially for the high-accuracy INS.

During each test run, a ship was going around on the map for either 60min or 24h, depending on which INS that were being used. A predefined trajectory was used, so that multiple runs could be done using the same trajectory, thus making it possible to compare the performance in between. After the journey, the test was restarted using another configuration of subsets. When all runs were completed, the mean position error and covariance was calculated, and the PF position error, KF position error and INS position error were plotted. The INS in the tests was set to have an error of either 1NM (1852m) after 1h or 1NM after 24h, which is what some INS manufacturers guarantee for their medium and high-performance products. In the performance plots, see Figures 27 and 34, it is shown that this error dramatically increases with time.

A typical example of the symbols used in the program can be seen in Figure 25. The symbols are summarized in table 4.

## 5.2 Example images from running the program

The images in Figure 26 show how the ship moves in the west direction. After passing the 20m-bottom-depth line, the PF is able to discard many of the wrongly positioned particles (to the south-east) and is thereby able to estimate the position more accurately.

## 5.3 Test 1 - Comparing subset methods

In the three runs in this 60 minutes test, 100% of the particles have been corrected using one of the subsets; bottom depth, magnetic field and a combination of those, see Figure 27. The test has been done using the medium-accuracy INS. Because the INS's ability to estimate the velocity of the particles is rather limited, because of the INS's poor performance, the PF has trouble following the correct

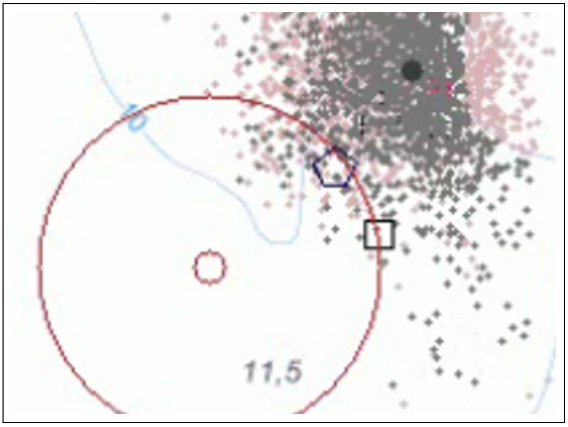


Figure 25: The symbols in the program is summarized in table 4. The particles are indicated with small dots, where the brighter dots are discarded during the current iteration. The big dot marks the mean of the particle cloud. The INS position estimation is indicated by a circle, where the bigger ring grows with time to show the position uncertainty; the INS manufacturer guarantees that the ship is located inside the bigger circle. The correct position is indicated with a square, and the KF position estimation is indicated by a pentagon. Thereby, the wanted behavior is that the pentagon comes as close as possible to the square.

Table 4: Legend for figure 25

| Symbol | Meaning |
|---|---|
| Small grey dot | Surviving particle |
| Small bright dot | Discarded particle |
| Large grey dot | Mean of particles |
| Square | True ship position |
| Pentagon | KF position estimation |
| Circle | INS position estimation with uncertainty area |

position. This can be seen especially for the depth in the graph (1) and (2), but also for the magnetic field in the graphs (3) and (4). By combining the depth and magnetic field, so that the PF is corrected according to the subset where both the depth and magnetic field match the measured values, the particles are not to the same extent fooled to incorrect locations. The combined graph (5) has better performance, and by further enhancement of (5) by using a KF, (6) has a mean position error of only 79m. More information about the configuration and performance can be found in table 5. A video of (5) and (6) in Figure 27 can be seen on `https://youtu.be/4m8AsuuYhF0`.

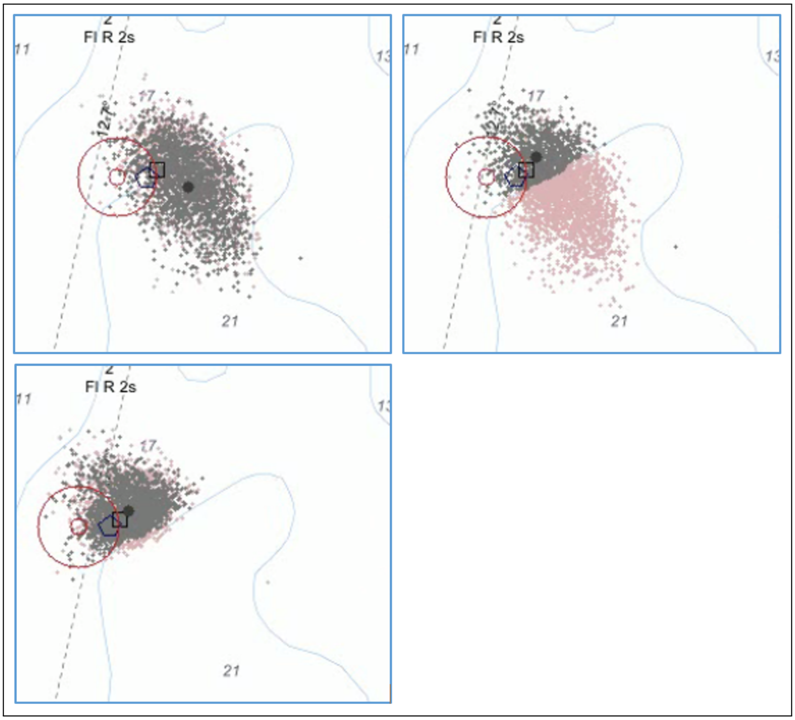


Figure 26: For symbol legend, see Table 4 on Page 70. In the left upper image, the particle cloud is spread to the east from the true position. The right image shows how the particles to the south-west of the 20m bottom depth line are discarded, when the echo sounder system onboard the ship measures a depth of below 20m. In the left bottom image, the discarded particles are no longer showing.

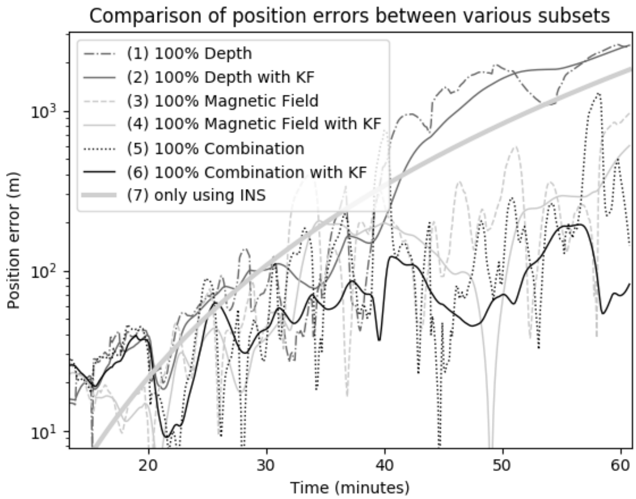


Figure 27: Test 1: The PF with the correction from depth does not manage to track the correct position, seen in the graph (1) and (2). The performance is also rather limited for the magnetic graphs (3) and (4). By combining depth and magnetic field, the performance is increased in (5). The performance is enhanced even further by using a KF, seen in the graph (6). More information about the configuration and performance can be found in table 5.

Table 5: Test setup for graphs in Figure 27

| Evaluation method | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| Depth | 100 | 100 | 0 | 0 | 0 | 0 | 0 |
| Magnetic Field | 0 | 0 | 100 | 100 | 0 | 0 | 0 |
| Depth ∩ Magnetism | 0 | 0 | 0 | 0 | 100 | 100 | 0 |
| Skip PF (Only INS) | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| PF Mean (m) | 917 | - | 221 | - | 176 | - | - |
| PF Covariance | 677k | - | 42k | - | 50k | - | - |
| KF Mean (m) | - | 860 | - | 164 | - | **78.9** | - |
| KF Covariance | - | 681k | - | 15k | - | 1740 | - |

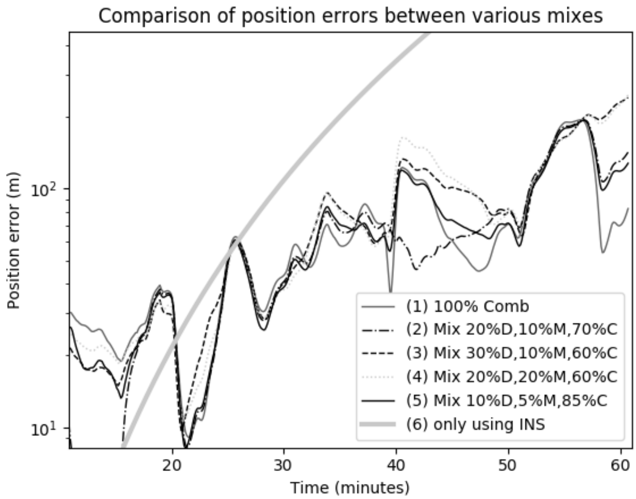


Figure 28: Test 2: Various mixes of the subsets have been evaluated. There is no clear difference between the distributions though. (1) gives the best mean by using the KF, but (5) seems more robust due to the lower covariance. More information about the configuration and performance can be found in table 6.

Table 6: Test setup for graphs in Figure 28

| Evaluation method | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Depth | 0 | 20 | 30 | 20 | 10 | 0 |
| Magnetic Field | 0 | 10 | 10 | 20 | 5 | 0 |
| Depth ∩ Magnetism | 100 | 70 | 60 | 60 | 85 | 0 |
| Skip PF (Only INS) | 0 | 0 | 0 | 0 | 0 | 100 |
| PF Mean (m) | 176.3 | **155.2** | 167.2 | 165.9 | 167.4 | - |
| PF Covariance | 49800 | 37500 | 45451 | 43000 | 43000 | - |
| KF Mean (m) | **78.9** | 80.7 | 99.6 | 102.0 | **83.4** | - |
| KF Covariance | 1737 | 1740 | 2830 | 3020 | **1700** | - |

## 5.4 Test 2 - Comparing various mixes of subset methods

In the five runs in this 60 minutes test with the medium-accuracy INS, various distributions have been used for the 3 subsets, investigated in section 5.3. The idea is that by having a portion of the particles corrected by various subsets, they are more likely to overcome difficult areas in the map where the particles can get lost from the correct position. By studying the behavior of the PF, no major difference is found though. Various distributions seem to be beneficial in different situations. Because of the lack of a clear result, a distribution somewhere in the middle has been chosen. This gives the distribution of 85% from the subset *Combination*, 10% from *Depth* and 5% *Magnetic Field* for the next step for further studies. More information about the configuration and performance can be found in table 6.

## 5.5 Test 3 - Comparing various mixes of subset methods for a high-accuracy INS

In the five runs in this 24-hour test, the 3 subsets investigated in section 5.3 has been tested with the high-accuracy INS instead, which guarantees a position error of less than 1NM after 24h. In the first three runs in this test, 100% of the particles have been evaluated using only one subset; bottom depth, magnetic field and a combination of those, see Figure 29. The sea chart has greater accuracy and resolution than the magnetic field map, and it is, therefore, the expected result that bottom-depth correction should give better performance, which is also the result. The third test run is correcting 100% of its particles according to a combination of the two first. This increases the performance even further. In the fourth and fifth run, a portion of the first three evaluation methods are used. The size of the various portions are first based on the performance of the individual methods, and the subset sizes have then been adjusted after empirical tests to gain the best performance. This method gives even better results than the third one. The reason is probably that sometimes the PF benefits from handling the particles in a smoother way. The most important thing when having a high-performance INS is not to let the particle cloud lose track of the correct position, and by having used multiple suggestions from various subsets, it is less likely to lose track. One example where the particle cloud loose track of the correct position will be presented later in Figure 33.

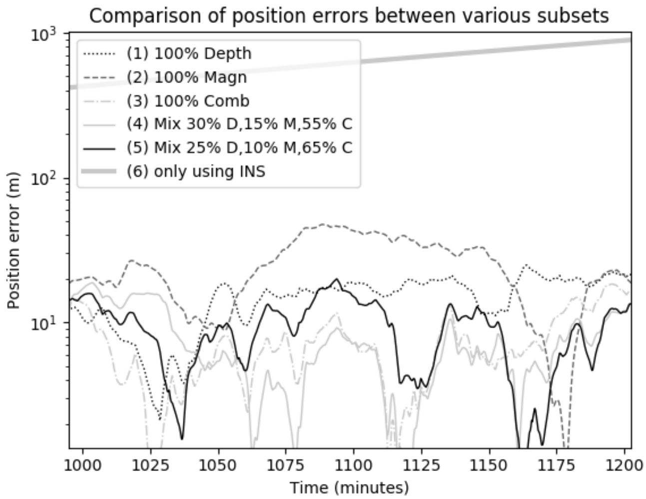


Figure 29: Test 3: The graph presents 200min of the second half of a 24h test. By using the high-accuracy INS, the particles can follow the correct position with good accuracy. By combining the subsets from (1) and (2), the accuracy is increased even further. It is not until after 22h, the mixed subsets have a position error greater than 42m. More information about the configuration and performance can be found in table 7.

Table 7: Test setup for graphs in Figure 29

| Evaluation method | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Depth | 100 | 0 | 0 | 30 | 25 | 0 |
| Magnetic Field | 0 | 100 | 0 | 15 | 10 | 0 |
| Depth ∩ Magnetism | 0 | 0 | 100 | 55 | 65 | 0 |
| Skip PF (Only INS) | 0 | 0 | 0 | 0 | 0 | 100 |
| PF Mean (m) | 23.8 | 38.7 | 25.6 | 22.2 | 21.3 | - |
| PF Covariance | 635 | 720 | 304 | 279 | 317 | - |
| KF Mean (m) | 22.5 | 28.9 | 19.8 | 17.0 | **16.8** | - |
| PF with KF Covariance | 539 | 217 | 204 | 160 | 227 | - |
| KF max error during 24h (m) | 120 | 72.9 | 77.9 | 74.0 | 84.9 | - |

**Comparing of PF performance with and without KF**

In this section, the subset (5) in Figure 29 and table 7 is studied further. In Figure 30 the position error can be seen when using and when not using a KF to enhance and smoothing the performance. 200 minutes from the second half of the 24h test are studied. The graph shows the position error of the INS, which is around 600m. The PF gives a position error of around 40m during these 200 minutes, while the KF enhancement of the PF gives a mean error of around 10m.

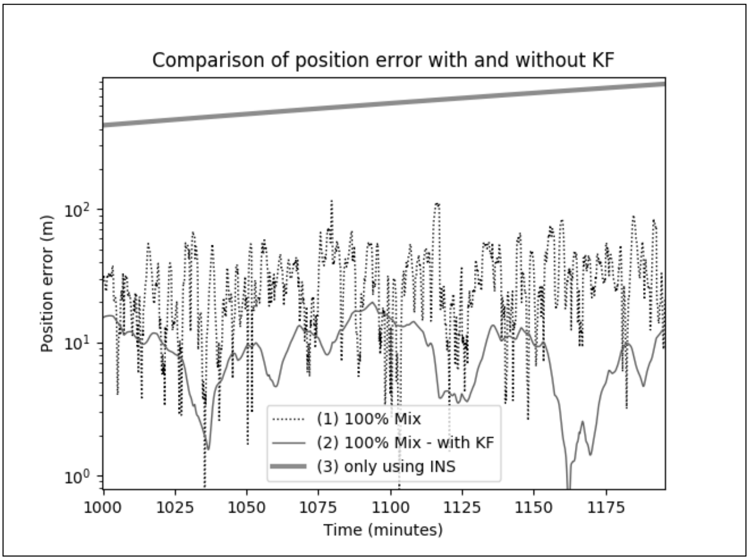


Figure 30: The graph presents around 200min in the second half of a 24h test from the subset (5) in Figure 29. The PF with the mix of evaluation methods significantly increases the position accuracy, compared to the position estimation from INS. The position accuracy is enhanced even further with the KF, by lowering the mean position error from around 40m to around 10m, during these 200 minutes.

## 5.6 Test 4 - Investigating the performance when a portion of particles are dead reckoned

When having a high-accuracy INS, it is possible to maintain the position during long periods of time without using GPS, PF, or other methods. In this test, the performance is evaluated when a portion of the particles are not using the PF, but

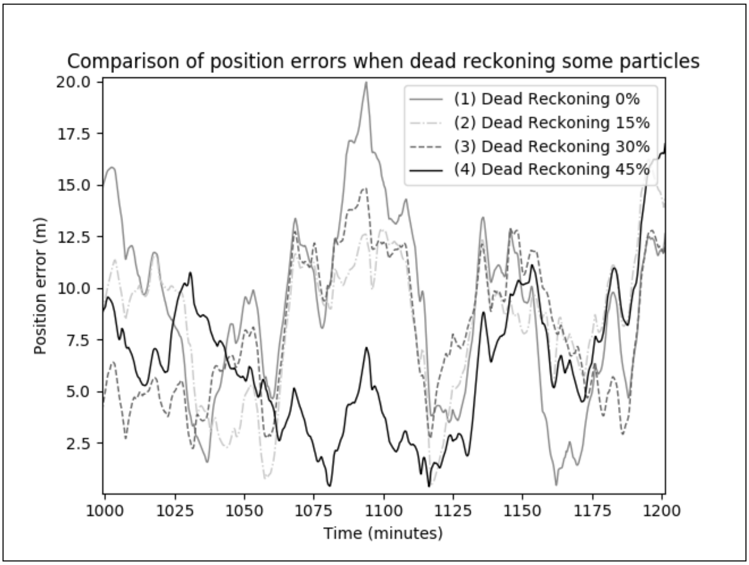


Figure 31: Test 4: The graphs show that the performance of the algorithm is actually increased, when a large amount of the particles are dead reckoned, instead of using the PF. By dead reckoning 45% of the particles, the position error is maintained less than 33m for 23h. The mean position error during the first 20h is 10.2m. More information about the configuration and performance can be found in table 8.

Table 8: Test setup for graphs in Figure 31

| Evaluation method | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Depth | 25 | 21.25 | 17.5 | 13.75 |
| Magnetic Field | 10 | 8.5 | 7 | 5.5 |
| Depth ∩ Magnetism | 65 | 55.25 | 45.5 | 35.75 |
| Skip PF (Only INS) | 0 | 15.0 | 30 | **45.0** |
| PF Mean (m) | 21.3 | 24.8 | 22.5 | 18.3 |
| PF Covariance | 320 | 240 | 255 | 212.6 |
| KF Mean (m) | 16.8 | 20.2 | 17.7 | **14.9** |
| KF Covariance | 226.6 | 197 | 190 | 197.5 |

instead are dead reckoned by the velocity from the INS. Figure 31 shows that by dead reckoning a large portion of the particles, the algorithm performance can be increased. This is probably happening because the ability to lose track of the correct position is lowered by trusting more in the INS. The mean position error during the first 20h is 10.2m. More information about the configuration and performance can be found in table 8. A video of (4) in Figure 31 can be seen on `https://youtu.be/EFamUSUsIOs`.

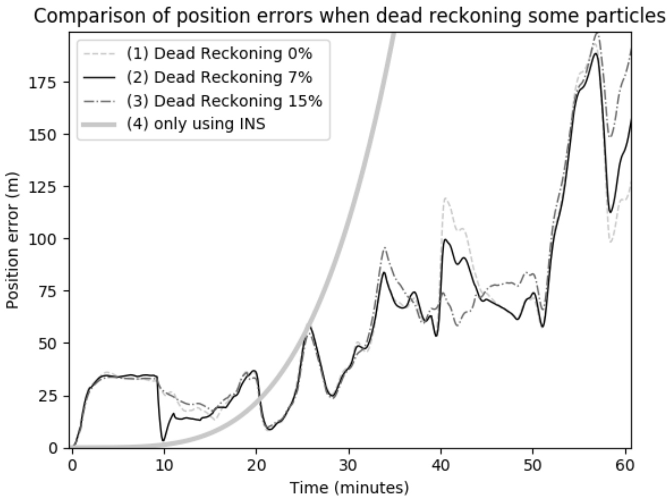


Figure 32: Test 5: The graphs show that the performance of the algorithm is increased a bit when 7% of the particles are dead reckoned, but there is no clear difference in contrast to the difference received when using the high-accuracy INS. By dead reckoning 7% or 15% of the particles, the position error is maintained below 100m for 50min. More information about the configuration and performance can be found in table 9.

Table 9: Test setup for graphs in Figure 32

| Evaluation method | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Depth | 10 | 9.3 | 8.5 | 0 |
| Magnetic Field | 5 | 4.65 | 4.25 | 0 |
| Depth ∩ Magnetism | 85 | 79.05 | 72.25 | 0 |
| Skip PF (Only INS) | 0 | **7.0** | 15.0 | 0 |
| PF Mean (m) | 167.4 | 161.4 | 150.7 | - |
| PF Covariance | 43000 | 41700 | 36000 | - |
| KF Mean (m) | 83.4 | **82.4** | 86.9 | - |
| KF Covariance | 1690 | 1700 | 2225 | - |

## 5.7 Test 5 - Investigating the performance when a portion of particles are dead reckoned

When instead using the medium-accuracy INS, it is no longer possible to rely as much on the performance of the INS. As in section 5.6, this test evaluates the performance when a portion of the particles are dead reckoned instead of using the PF. The test shows that it is more beneficial to trust more in the PF than the INS, even though there is no clear difference. The best performance was acquired when dead reckoning 7% of the particles, see Figure 32, which also can be seen on a video on `https://youtu.be/OVVO53qduWg`. More information about the configuration and performance can be found in table 9.

## 5.8 Test 6 - Comparing performance when not using the bottom depth lines

The bottom-depth lines provide the PF with accurate information about which depth interval there is in an area. This helps the PF discarding particles with an incorrect depth value, increasing the performance of the PF. On the other hand, it will in some cases delete particles in the vicinity, pushing the mean away from the correct position. This phenomenon can be observed in Figure 33. When not using bottom depth lines, it is, therefore, converging slower and the particles are spread in a larger area, but the mean of the particles is still located near the correct position.

In many areas, the sea charts are not equipped with bottom-depth lines. With this in mind, it is interesting to evaluate the performance also without using them, which has been done in these two test runs. The first test run compares the performance of the high-accuracy INS during a 24h test, see figure 34 and a video on `https://youtu.be/v2H26Olyr6c`. Even though the position error is larger when not using the depth bottom lines, the mean position error from when using the KF enhancement still is maintained at 34.0m, and the position error does not overshoot 70m until the very last minutes of the test.

The algorithm for the medium-accuracy INS also shows a good performance. It maintains a position accuracy comparable to when using the depth lines until 40min, see figure 35 and a video on `https://youtu.be/p69zQzMSciU`. After about 45min, it has problems tracking the position due to the big velocity error in the INS.

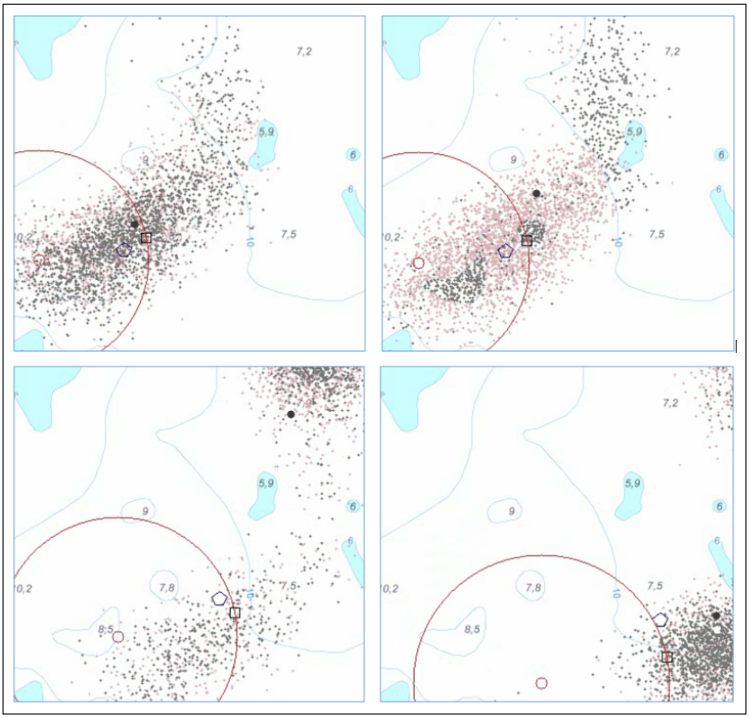


Figure 33: In this image, the particle cloud is initially (top left image) spread around the ship (indicated by the square). When passing a grounding (top right image), most particles are discarded and split into smaller sub-clouds. The mean of the particle cloud moves to the biggest sub-cloud (bottom left image), far from the correct position. A few moments later (bottom right image), the particles located in the wrong location, has been discarded after further evaluation of the particles. A position has been estimated by a KF, using the position estimation from the particle filter along with the INS data. The Kalman position estimation is indicated by a pentagon. In the four images, it can be seen that the KF gives a more stable and accurate position estimation, as it does not respond to the fast position variations from the particle filter.

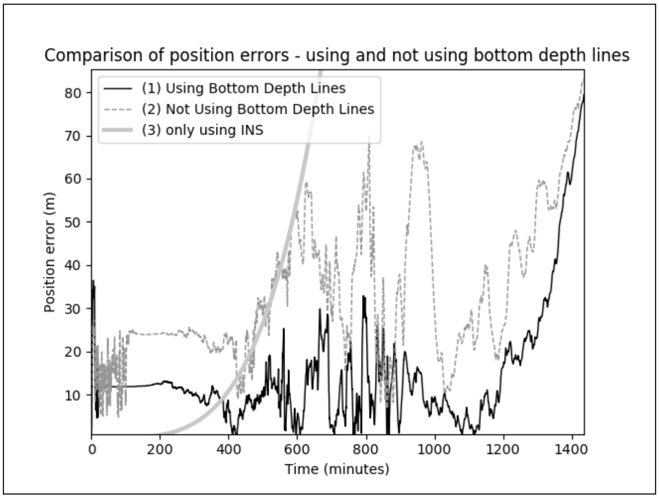


Figure 34: Test 6:1: The high-accuracy INS is used. The performance is influenced by using or not using the bottom depth lines in the sea chart. Even though the performance is lower, it still manage to track the correct position during the 24h test. A mean position error of 34.0m is maintained.

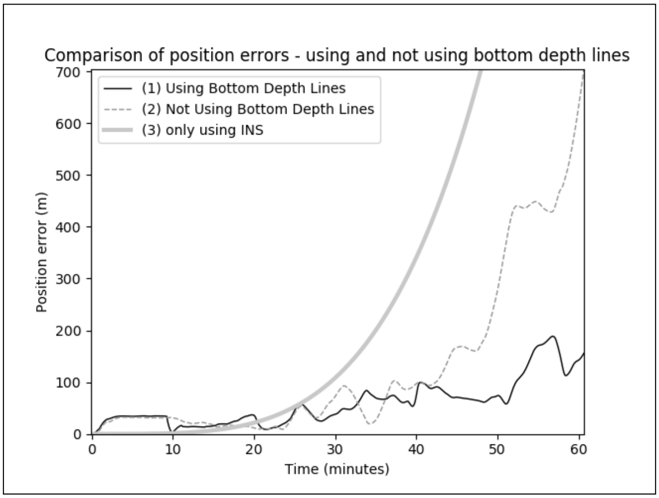


Figure 35: Test 6:2: The medium-accuracy INS is used. It shows a good performance during 45min, even though the bottom depth lines are not being used. After this time, it has problem tracking the correct position.

### 5.9 Further development and testing of the algorithm

The algorithm has only been tested with simulated data so far, but the plan for the future is to test it on a ship, using digital sea charts and magnetic maps. The position can then be compared to a GPS position. When testing at sea, it will also be important to keep track of the water level, as the tide will influence the performance significantly due to the importance of correct bottom depth measurements.

## 6 Conclusion

It has already been shown that PF algorithms can be used for estimating positions [34, 48, 73, 74], and it has even been shown that it is possible to accurately estimate a ship's position if high-resolution maps are available [35, 36, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 75]. This paper describes how this technique can be used in solutions more suitable for real-world scenarios, where only normal sea charts and magnetic field maps are available. The paper has shown how the performance varies depending on only using one or multiple inputs to the PF, and how the performance can be enhanced by using a KF. It has also been shown how the performance of the INS influences the position accuracy when using the PF.

When fusing the different PF methods in a 20h long test, the mean of the position errors for the high-end INS has been calculated to be 10.2m when using the bottom depth lines, and 30.5m when not using them. This is not as good as GNSS-based accuracy, but probably accurate enough for most navigation purposes. When using the medium-accuracy INS, the mean position error for a 40min long test was 35.4m when using the bottom depth lines, and 37.1m when not using them.

Whether it is possible to navigate accurately enough without GNSS systems, only relying on high-performance navigation sensors and normal sea chart and magnetic charts, still remains unclear. Further testing with real ship data in multiple areas is therefore necessary.

## ACKNOWLEDGMENT

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# Paper II

# Paper II

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# Remote Operation of Unmanned Surface Vessel through Virtual Reality - a low cognitive load approach


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## Abstract

An unmanned ship can be designed without considering human comfort, and can thus be constructed lighter, smaller and less expensive. It can carry out missions in rough terrain or be in areas where it would be dangerous for a human to operate. By not having to support a crew, lengthy missions can be accepted, enabling, e.g., reconnaissance missions, or reducing emissions by lowering the speed.

Breakthroughs with autonomous systems enable more advanced unmanned surface vessels (USVs), but to be able to handle complex missions in a dynamic environment, a human operator is still assumed an effective decision maker. Thus, we propose a method for remote operation of a USV, where the operator uses (VR) to comprehend the surrounding environment. Great importance has been given



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to the ability to perform safe navigation, by designing a Graphical User Interface (GUI) that guides the operator through the navigation process, by presenting the important information at the right place in the right orientation.

# 1 Introduction

Autonomous Surface Vessels (ASV) have evolved during the last decades [76], and have now reached a maturity level where they are starting to be used commercially. We believe there are many potential benefits, including:

- Cost-effectiveness, where the expensive human operator can be removed. By removing the operator, the ship will no longer be constructed for human comfort, and the cost can thereby be reduced even further.
- Human work environment. By reducing the crew size, the risk of a shortage of seafarers is reduced.
- Safety. By developing algorithms for safe navigation, the ship can operate continuously without making human errors.
- Persistence. An unmanned vehicle can be used during long periods of time when there is no humans on-board who have a limited amount of working hours.
- Ability to operate in hazardous conditions, e.g., rough weather or during anti-piracy operations.

Even bigger oceangoing commercial container and bulk ships are being developed for unmanned usage [25], and are anticipated to be in commercial service in 10-15 years [2]. The foreseen benefits are increased safety, but also reduced workload for humans. As a consequence of a significantly reduced crew-size, it will also be possible to reduce the speed of the ships, lowering the fuel consumption, and thereby the environmental impact [2, 14].

Compared to car traffic situations, traffic at sea is often characterized with more available time for decision making. Many ships also travel most of their route at open sea, where there is hardly any traffic at all. On the other hand, when entering a highly trafficked harbor during bad weather, many complex situations arise, which gives a need for either human decision making or intelligent autonomous algorithms.

Also in other situations, it might still be beneficial or even crucial to allow for human decision making. Hence, we assume that allowing a human operator to have both an insight into the situation an unmanned, maybe to a certain degree autonomously navigating vessel is, and the opportunity to take at will control over the vessel, can be very beneficial to overcome the gap between manned and fully autonomous vessels.

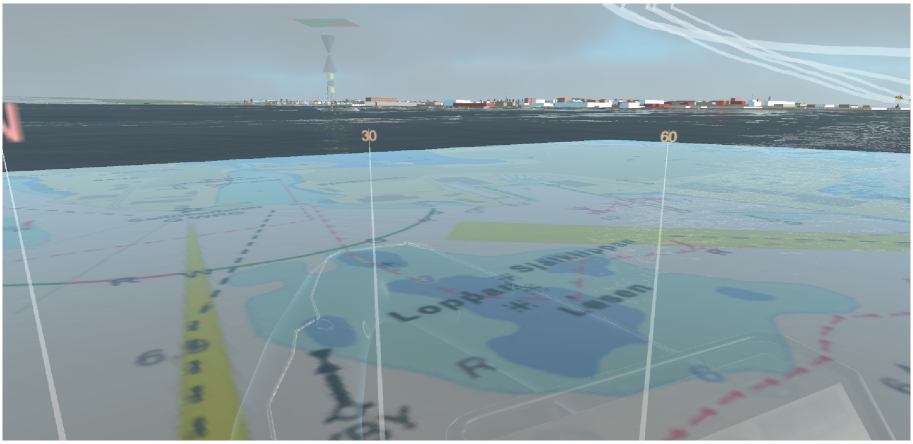


Figure 36: The GUI from the project, presented in the Virtual Environment. The sea chart is rotated to fit the surrounding world, and the sea marks are increased in size to be simpler to detect.

However, during complex situations at sea, it can be hard for even a human to interpret and match the surrounding environment with the information from the navigation equipment. There are several situations where the navigation operators, due to the high cognitive load, have mixed up sea marks, directions or landmarks, which in many cases have led to fatal accidents [50].

We propose thus a Graphical User Interface (GUI) developed for remote operation of an Unmanned Surface Vessel (USV). The GUI is created for VR utilization so that the operator can experience being situated on board the ship. The real world environment is re-created from sea charts into the Virtual Environment (VE). The GUI is then placed in another layer in the VE, where, e.g., seamarks augment directly the operators' view of the environment, making it easy for the operators to interpret them, see figure 36.

To evaluate the GUI, sea trials have been conducted in an archipelago by a USV called *the Piraya*, developed by *Saab Kockums AB* [72].

Naval officers have been involved in the implementation and have given a brief initial evaluation of the GUI.

This paper is organized as follows: In Section 3, an overview is given of how other research has investigated how the cognitive load can be reduced during navigation. These learnings have been used in our GUI created in our project, presented in section 4. Section 4.6 presents a brief operator evaluation, concluded by a discussion in section 5.

## 2 Scope

There are many scenarios where VR and (AR) can be used in order to enhance Situational Awareness (SA) at sea. On a bridge, AR can be used for augmenting the surrounding environment with information from the ship's sensors. In a control room on board a ship where there are no windows, VR can be used in the same way, but in this case, the surrounding environment also needs to be created virtually, or by streaming video from all available directions. In this scenario on board the ship, sensor information such as video can be added directly to the Virtual Environment (VE).

In order to bound the scope of our study, we have chosen to focus our work on a GUI with the task to control a USV, where the USV has a limited bandwidth connection to the GUI which inhibits video or high-resolution images to be sent. The implementation can easily be extended to also fit the other scenarios. For these, however, features in the GUI need to be added or changed, and an AR HMD (Head Mounted Display) needs to be used for the bridge scenario.

## 3 Related work

Much research has investigated how the operators can interact with the navigation systems, in order to increase safety. There has also been done a lot of research regarding USVs, where remote control often is an essential part. However, we have not found any research done in the combination of these two areas.

### 3.1 Safe navigation with low cognitive load

The traditional way to navigate at sea is to use a paper sea chart, showing an abstracted map of, e.g., islands, groundings, depths measurements and sea marks. The paper sea chart is constructed with north facing up. During the last two decades, there has been a transition on bigger ships to use electronic chart systems, where the sea chart is instead visualized digitally on a computer screen. The main benefit is that the own ship's position, normally received from the GPS, is visualized at the correct location on the sea chart. The sea chart can be presented with north-up or head-up reading rotation.

The human ability to mentally rotate a map or sea chart, so that the symbols in the map can be matched with surrounding real-world objects, is rather limited. Shepard et al. [49] showed that the time to recognize that two perspective drawings are showing the same three-dimensional shape is linearly increasing to the angular difference of the perspectives. This means that a human can match the ship's surrounding quite well when steering in north direction when reading a north-up oriented sea chart, but will need more time reading the same north-up oriented sea chart when steering in the opposite direction. Operators often choose to present the sea chart with north-up and radar with head-up [50] rotation, thus mental rotations are needed both between those two systems, and between the systems and the surrounding real world.

Another way of presenting a map is to view it from the driver's perspective. This is normally done in a GPS navigator for car drivers. The benefit is that the driver can quickly understand which roads and buildings on the map match the roads and buildings in the real world surrounding. By letting the machine do the mental rotations instead of the human operator, valuable time is saved, and many accidents are thereby likely to be avoided.

Porathe [51] compares these four map views in a simplified indoor environment where persons navigate on a floor trying to navigate fast but striving to avoid groundings. The compared views are the already mentioned:

1. Traditional paper sea chart (north-up)
2. Electronic chart system (north-up)
3. Electronic chart system (head-up)
4. 3-D map with Ego-centric View

The results of this test show that (4) gives the fastest decision makings, least groundings, and is perceived as the most user-friendly. The results also clearly show that using an electronic chart system gives better results than using paper charts.

Some persons are more skilled than others when it comes to interpretation and mental rotations of maps. Porathe [52] has divided the persons into subgroups depending on previous map experience, gender, and age. Persons with map experience, males, and younger persons generally perform better, but disregarding which group that compares the four different map views, the results remain the

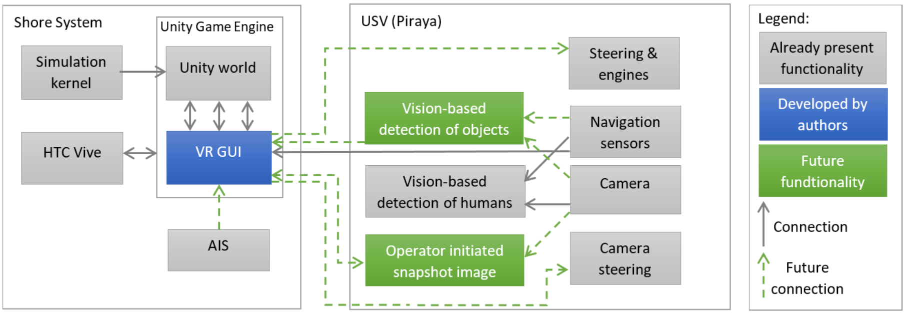


Figure 37: Architecture Overview. The VE with the GUI is created ashore (left part of the image). The USV (right part of the image) has functionality for steering the ship and camera, and sends cropped camera images, USV position and USV orientation to the GUI.

same; (4) gives the best results, followed by (3), (2) and (1). An interesting finding is that although persons have a great experience from using an electronic chart system, they still perform better when switching to 3-D maps, despite that they are not used to it.

With the results in mind, Porathe [50] suggests using a 3-D map with the ego-centric view as a navigation aid, viewed on a computer screen or tablet. Witt [53] has also proposed a similar solution with a tablet where the ego-centric view helps the operator reducing the cognitive load. Our GUI is influenced by these results, as we place the operator directly into the 3D world where the surrounding world easily can be matched with the sea chart.

Much research has also been done investigating how AR can reduce cognitive load when navigating. In these applications Head Mounted Displays (HMDs), normally with see-through technology, augment important information, such as sea lanes, conning information or AIS information. [64, 65, 66, 67, 68]. We use the same technique to augment important information in the VE instead of overlaying it on top of the real world.

## 3.2 Remote control of USV

Since there is no fully autonomous USV developed yet, USVs in general still need some remote operation. Respective GUIs often contain a map where the USV is positioned, along with functions for describing the status of the USV [77, 78].

We have not been able to find any research describing remote operation in VR though.

# 4 Navigation and Control in Virtual Reality

## 4.1 Platform Description

The Piraya boats used in the project have a length of 4 m and a maximum speed of approximately 20 knots [79]. They are equipped with GPS for position measurement and a PTZ-camera (Axis Q6155-E) for video streaming. During operation, the position and attitude data are sent to the GUI, so that the GUI is positioned in the correct location in the VE. Sea-trials have been carried out to log entire trips, which have been used during the development of the GUI, along with simulations of comparable scenarios.

## 4.2 Architectural Description

There are two main parts in the architecture; the *Shore System* and the *USV (Piraya)*, see figure 37. The main contribution of this paper is the *VR GUI* in the*Shore System*. It is integrated with the *Unity world* that provides the VE, including the simulated ships. The VE is updated according to the *Simulation kernel*.

In the *USV*, already present functionality was used for steering the USV as well as the camera. These functions are planned to be integrated with the *VR GUI* in the future. A function that has been developed for detecting persons in the water (simulated by orange buoys) was also used. When this function detects a buoy, it sends a small cropped image to the *VR GUI*, where the real world image can be visualized in the VE. In the future, functionality for controlling the camera directly from the GUI is foreseen to be added. Another valuable function is to be able to detect other objects than buoys. Cropped images from other detected objects, e.g., boats could then be sent to the *VR GUI*.

## 4.3 Goals with the GUI implementation

The intention is to create an easy-to-use GUI for remote operation of a USV. It is important to uphold a safe navigation, and the goal is to create a system which is at least as safe as a comparable ship of its size. Thereby, the USV and the GUI must have functionality for creating a good understanding of the vessel's environment and the USV needs to have functionality for making some decisions about what information that should be sent to the GUI. The GUI also needs to give the operator better navigation tools than normal ships, to compensate for the operator not being on-board.

In this paper, the first baseline of the GUI is presented, which will be evaluated so that it can be evolved to finally meet the goals.

## 4.4 Main Operational Views

Two different main views have been created; *Egocentric view* and *Tethered View*. These will in the future be complemented with the *Exocentric View*, which will show the USV in the middle of a north-up sea chart. Each of the views has their own benefits and shall be seen as a complement to each other.

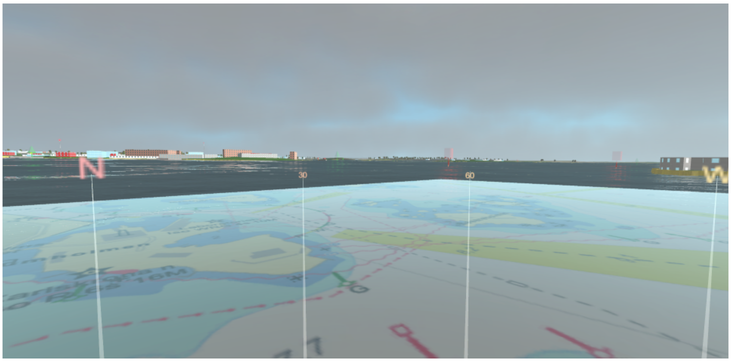


Figure 38: In the ego-centric view the camera is placed on-board the USV so that the operator experience being on-board. The center of the sea chart is placed in the operator's location and rotated so that it is consistent with the orientation of the world.

### Egocentric View

The *Egocentric View* in figure 38 visualizes the world from the USV's (ego) perspective, hence it simulates what the surrounding environment looks like. The camera has good bearing accuracy but poor range accuracy. From the egocentric view, the range is of lower importance, hence information from passive sensors such as cameras are well visualized in this view. By capturing real-world images of landmarks and comparing the bearings to the sea chart, it will be obvious if the current GPS position diverges from the correct position, as the landmark bearings will not match the chart.

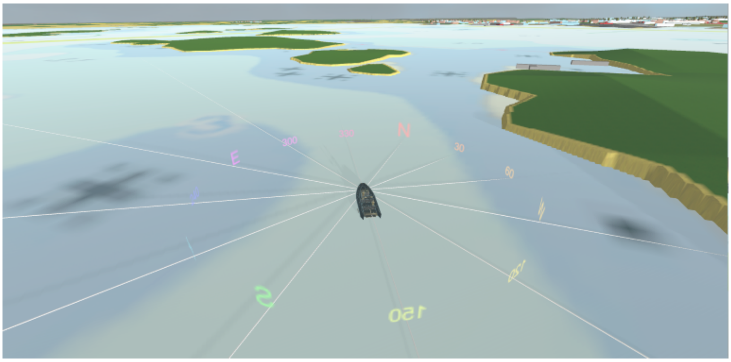


Figure 39: The USV is visualized from above in the *Tethered View*.

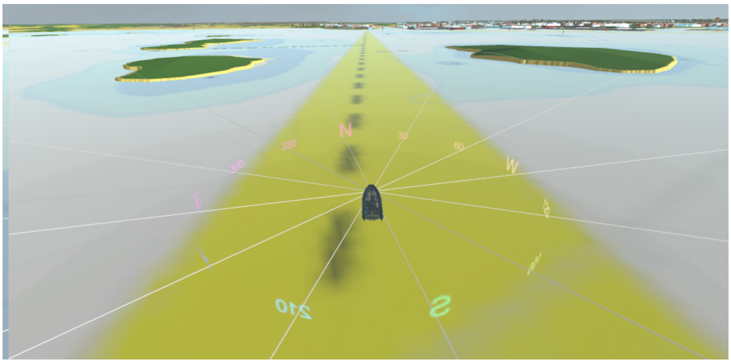


Figure 40: *Tethered View*. The USV is going in the yellow light segment from a lighthouse.

### Tethered View

The *Tethered View* is created by a camera hanging after the USV up in the air, viewing the USV from above, see figure 39. The operator has a good overview of the USV and what is around it, and can at the same time see where the USV is situated on the sea chart. In figure 40 the USV is going to the right in the sea lane in the direction towards a lighthouse where yellow light is emitted.

## 4.5 Features to reduce the cognitive load

Several features have been implemented to support navigation and situational awareness, while still limiting the cognitive load.

### Sea chart

A sea chart is visualized both in *Egocentric View* (see figure 42 and 36 and in *Tethered Veiw* (see figure 39 and 40). In the *Tethered View*, the sea chart is shown instead of the water. The operator can see where groundings or sea marks are located and adjust the steering to adjust to the map.

In the *Egocentric View* the viewing camera is located at the center of the sea chart, showing the surrounding area of the USV. The sea chart is always arranged in the correct orientation so that the operator easily can match surrounding objects and islands to the symbols in the sea chart.

### Orientation and Compass Rose

It is important to be able to uphold an orientation at all time. To help the operator, the following clues are given:

- The sea chart is quadratic and is always heading north, together with all text and numbers on the chart.
- The sun is visible at all time in a direction that matches the time and day of the year.
- The *Compass Rose* is visible at all time

The *Compass Rose* is visible both during *Egocentric View* (see figure 38) and *Tethered View* (see figure 39 and 40). Other research has shown that the usage of different colors can increase the orientation capability, and by overlaying colors, the time to translate to a rotation can be shortened [80, 81]. Thus, the *Compass Rose* has been colored according to a circular rainbow pattern, with the potential benefit that the operators in time will learn to associate the different colors with the related orientations. The *Compass Rose* can be seen in figure 41.

### NoGo-areas

There are many parameters which influence under-keel clearance. First, the accuracy of the current position needs to be estimated, resulting in an area in where the

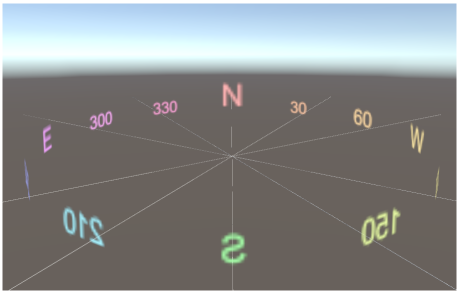


Figure 41: The angle indicator on the compass rose shown above the sea chart, have been color coded according to a rainbow. By doing so, the intention is that a human operator will eventually learn which color corresponds to which orientation.

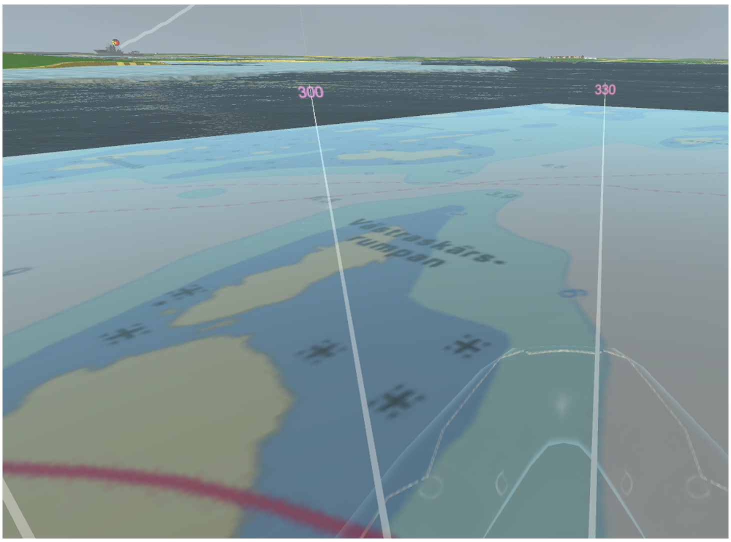


Figure 42: The area in the sea chart with depth below 3m are lifted up above surface as icebergs, so that the operator easily understands that it is a dangerous area.

USV is located. Then this area is compared with the bottom topography of the same area. The last step is to compensate for current draught and for the current water level. All these steps are time-consuming and hard to do for a human. A computer can instead perform the calculations. Porathe [50] suggests coloring the water in his proposed 3D-images so that the operator knows where not to go. We have proposed a comparable way, by showing icebergs where it is too shallow. In the images, the operator is warned when shallower than 3m, see figure 42.

### Sea marks

Seamarks are in general hard to detect at sea. The problem is that they are small, and in rough weather, it is time-consuming to first find the seamark in the sea chart, then try to estimate in what direction they are located in, and then finally trying to detect it when still far away.

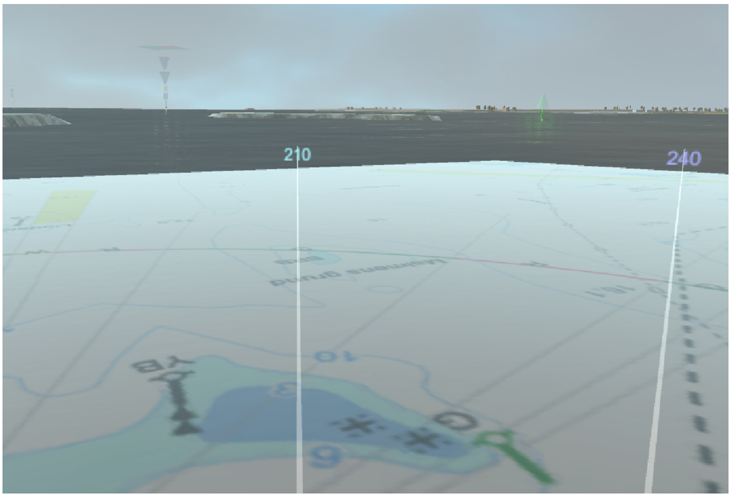


Figure 43: The sea marks are increased in size to be more easily detected. By following the lines from the compass rose, it gets easier to find out which sea marks that match which symbols in the sea chart.

By having a sea chart that is always rotated in the correct way, it is easy to estimate which sea marks that belong to which in the sea chart, see figure 43. The sea marks are also ten times bigger than reality, which makes them easier to detect.

Cardinal marks are sea marks which mark out in what compass direction there is a grounding. In the VR GUI, they are complemented with a red-green area above them, indicating in which direction the grounding is located. This is shown in figure 44, as well as that the iceberg marks the same grounding.

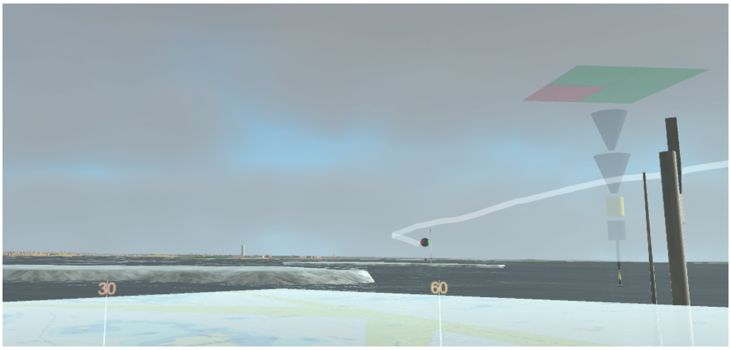


Figure 44: The South Cardinal Mark marks the grounding north from the Cardinal Mark (to the left in the image). The grounding is also marked with an iceberg.

### Tracking of ships

The Automatic Identification System (AIS) is mandatory for bigger ships. The system provides information about, e.g., identification, position and heading, to nearby ships. By receiving this information directly to the GUI, it is possible to present real-time information about the bigger ships in the surrounding to the USV.

In the GUI, the information from the AIS is presented in three ways:

- The type of ship is translated into available 3D-models of various types of ships. The 3D-model is then presented in the VE, see figure 45.
- The heading from the AIS is used for coloring a sphere according to standard ship lantern configuration, see figure 45. If, e.g., most of the sphere is green, the operator can instantly conclude that the ship is moving to the right.
- A *Contact Evaluation Plot* (CEP) is normally used to present fused bearing tracks when at least one of the sensor data originates from passive sensors, such as cameras or passive sonars [82]. The CEP presents the bearing tracks in a time-bearing format. In the VR GUI, the CEP lines at this time only originate from the AIS. The CEP provides the operator with an overview of all the surrounding ships, where the relative motion, as well as ship maneuvers, can be detected, see figure 46.

Figure 45: From the AIS data, the ship type, position and heading is extracted. From the ship type, a suitable 3D-model is chosen. The sphere is positioned above the position, and is colored according to the heading.


Figure 46: The bright bearing-lines in the sky indicates that both visual ships are steering to the right. The ship to the right is farther away, which is visualized with the thinner line. The ship to the left is going at a constant speed but has made a turn approximately 25 seconds ago. 30 seconds of history is presented in the CEP.

### Presenting real-world images

An algorithm for detection of buoys has been developed for the USV, where the buoys simulate people in the water with life vests. The algorithm uses the camera images and can calculate the bearing and range to the detected buoys. By using this information, the images can be cropped to only contain the object of interest, and send this cropped image through the low bandwidth connection for presentation in the GUI, see figure 47. The operator can then study the image, and decide if the USV shall move closer to examine the object more carefully.

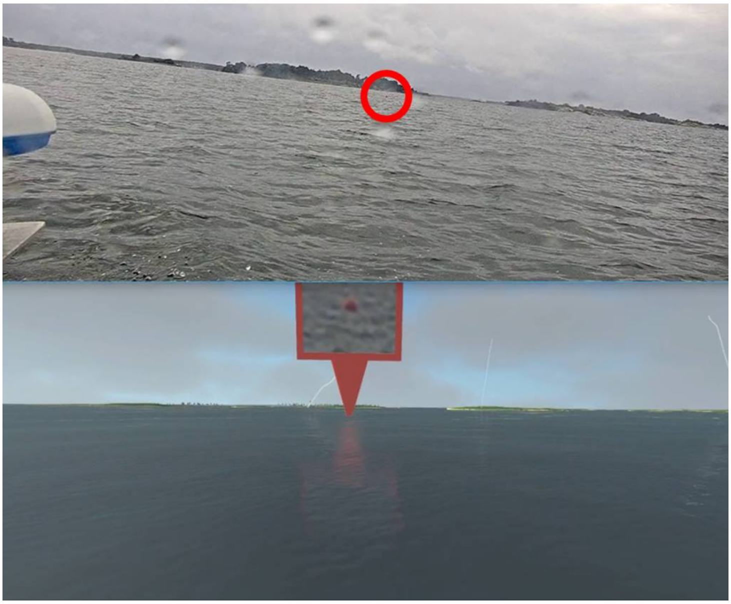

Figure 47: Above, an image from the sea-trials is shown. From this image, the buoy was detected. Below, the cropped image is presented in the VR GUI.

## 4.6 Usability Evaluation

The GUI has been evaluated by two experienced naval operators. They both found the cognitive load to be reduced by serving the operator with all available information, as the operator, e.g., does not need to mentally translate an AIS target to the sea chart, and then to the real world. Other functions that were mentioned to reduce the load were the enlarged sea marks, the NoGo-areas, the spheres and the

CEP-lines. The CEP-lines where pointed out to be able to serve the operator with valuable information, such as when passing the *Closest Point of Approach*. One of the operators was skeptical whether the colored compass rose would increase the orientation ability. More textual information from the AIS is also requested.

## 5 Discussion and Future Work

We have designed a GUI for remote control of a USV. Special attention has been given to reduce the cognitive load while maintaining safe navigation. It is important to have a good situational awareness, which is given by augmenting the surrounding ships and objects.

To be able to operate a USV remotely in a safe manner, it is important that the USV can detect all hazardous objects such as ships, and share this information with the GUI. By that, a function for automatic detection and classification of nearby objects would boost the functionality of the GUI.

In the near future, the GUI will be evaluated by experienced naval operators, in order to enhance the usability even further. New sea-trials will be conducted with new features to steer the USV directly from the GUI.

## ACKNOWLEDGMENT

This work was partially supported by the Wallenberg AI, Autonomous Systems and Software Program (WASP) [1] funded by Knut and Alice Wallenberg Foundation. The simulation environment provided by Saab Kockums AB is gratefully acknowledged.

# Paper III

# Paper III

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# Remote Supervision of an Autonomous Surface Vehicle using Virtual Reality

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## Abstract

We compared three different Graphical User Interfaces (GUI) that we have designed and implemented to enable human supervision of an Autonomous Surface Vehicle (ASV). Special attention has been paid to provide tools for a safe navigation and giving the user a good overall understanding of the surrounding world while keeping the cognitive load at a low level. Our findings indicate that a GUI in 3D, presented either on a screen or in a Virtual Reality (VR) setting provides several benefits compared to a *Baseline GUI* representing traditional tools.

Submitted to IAV 2019

# 1 Introduction

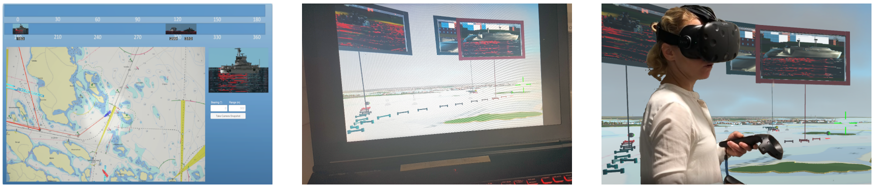
As the autonomous vehicles are becoming more intelligent, the human's role of being in constant control can be relaxed. In many cases, the semi-autonomous vehicle can plan and execute missions that meet the human needs, while the human can still take control by teleoperating the vehicle, which is useful, e.g., when some situation occurs that the vehicle has not yet been trained for. Many car manufacturers will equip their cars with teleoperation capability, and Levander [2] sees teleoperation of ships as a key technology in the transferring process towards autonomous ships.

In this study, we are focusing on a small Autonomous Surface Vehicle (ASV) that is being remotely supervised by a human user via a low bandwidth connection. Murphy [83] believes small ASVs like this are likely to play an important role during future Search and Rescue (SAR) operations at sea. The reason for adding the low bandwidth constraint that prohibits video streams and high-resolution images to be sent, is that we want the Graphical User Interface (GUI) to work on open sea. In these areas, ASVs need to rely on radio communication normally used by ships, as mobile communication has to insufficient coverage, and satellite communication is too costly and has too bulky antennas.

There are many benefits of using an ASV instead of a normal ship. An ASV can be constructed lighter and cheaper. An ASV can also be used when it would be dangerous for a human to operate, e.g., during bad weather at sea. Multiple ASV fleets can be placed in various locations, and during accidents, the closest fleet can be dispatched from a centralized location with teleoperating experts. ASVs and drones can typically be dispatched far more quickly than manned vehicles, as there is no need for waiting on the human crew. Compared to flying drones, ASVs have good endurance and can be on a mission for many hours, while drones are typically faster and can get a good overview of an area from their high altitude.

Although cars and airplanes are hard to teleoperate due to the constraints that the dynamic traffic situations set on time delays and jitter (see d'Orey et al. [84] and Neumeier et al. [59]), traffic at sea is often characterized by more available time for decision making, making it ideal for teleoperation.

During complex situations at sea on manned ships, Porathe [50] shows that it can be hard even for humans to interpret and match the surrounding environment with the information from the navigation equipment onboard. There are several occasions where the navigators, due to the high cognitive load, have mixed up sea marks, directions or landmarks, which in many cases have led to fatal accidents.



(a) Baseline 2D GUI (b) 3D GUI on a laptop (c) VR GUI

Figure 48: Three types of GUIs have been developed. (a) is a 2D GUI, that represents a traditional GUI. (b) and (c) are created in 3D, where (b) is presented on a laptop and (c) in VR.

This raises the question of how new types of GUIs can support remote supervision of an ASV with limited bandwidth. Of particular interest to us is to see how the user's *situational awareness* and *cognitive load* are affected when using such GUIs in comparison to using traditional ones. We use the term *situational awareness* to describe the ability of the user to assess the situation the vessel is in with respect to surrounding elements like other vessels, seamarks, or shallow areas.

To answer these questions, we propose a 3D-visualisation of the ship's surroundings either on a computer screen or in a Virtual Reality (VR) setup. We base this GUI on ideas from the available research regarding manned ships to increase the situational awareness while maintaining a low cognitive load.

We evaluated the two different versions of the GUI against a baseline GUI, see Figure 48, in a small study with 16 participants, showing that there are significant benefits regarding the mentioned factors.

This paper is organized as follows: In Section 2, an overview of related research is given followed by the GUI design in Section 3. Then the User Study is presented in Section 4, with related results and discussion in Section 5 and 6. Conclusion is given in Section 7.

## 2 Related Work

Teleoperation can be used for remote controlling vehicles and robots, e.g., cars (see Neumeier et al. [59]), drones (see Hedayati et al. [60]) or ships (see Nava-Balanzar et al. [62]). While teleoperating a vehicle, it is important to support the human's perception of what the vehicle's sensors detect of the surrounding world. Williams et al. [63] elaborate on how VR, Augmented Reality (AR) and Mixed Reality can strengthen visualization, and thereby the total communication between the machine and the human, and how various viewpoints, e.g., the ego-centric view can be used. Hedayati et al. [60] explore how AR can be used for augmenting a drone's field of view for a user collocated with the drone. When not collocated, VR is often a better presentation technique compared to AR. Hosseini and Lienkamp [58] and Shen et al. [57] show how VR can enhance the situation awareness when driving a remote car.

When navigating onboard a ship, the traditional way is to use either a paper sea chart or an electronic chart system, showing an abstracted map of, e.g., islands, groundings, depth measurements, and sea marks. Research has shown that it is difficult for humans to match what they see on the chart or radar to what they see in the real world outside the bridge of the ship. Instead, it is a better approach to visualize a 3D map oriented in a way that matches the user's view of the surrounding world (see Porathe [51] and Witt [53]). Our GUI is influenced by these results, as we place the user directly into the 3D world where the surrounding world easily can be matched with the sea chart. We call this ego-centric view *First Person View* (*FPV*).

Some research has also investigated how AR can reduce cognitive load when navigating. In these applications, Head Mounted Displays (HMD), normally with see-through technology, augment important information, such as sea lanes and other nearby ships directly in the real-world environment (see Morgere et al. [65]; Mollandsøy and Pedersen [66]; Hugues et al. [67] and Jaeyong et al. [68]). In our application, we augment the important information directly in the virtual environment.

## 3 Design

In our study, we focus on a GUI for remote supervision of a small ASV via a limited bandwidth connection which inhibits video or high-resolution images to be transferred. The ASV is expected to be highly autonomous in order to handle a SAR mission, but still assumed to need some human supervision with the ability to take measure if something unexpected happens.

The GUI is developed for a small ASV with a computer capacity and sensor suite comparable to an autonomous car. The postulated sensors and capabilities are:

- Global Positioning System (GPS), or a satellite independent positioning system (see Lager et al. [70]);

- Application for autonomous route steering;
- Camera with 360-degree coverage and zoom capability;
- Radio communication with a small antenna with a bandwidth of around 10 kbit/s;
- Application for image detection of ships; and
- Application for cropping and compressing images of ships, so that detected ship images can be transferred through the radio communication interface.

## 3.1 Architectural Overview

Figure 49 shows a summary of the communication interfaces to the GUI. To create the virtual surroundings and corresponding sea chart, the ASV transmits its position. When the camera onboard the ASV detects ships, it transmits all tracks of them every second, as well as a small cropped image every 10 seconds. Some, mainly larger, ships have an Automatic Identification System (AIS) transponder, that transmits, e.g., their identity, position and steering direction. This is also received by the GUI and presented to the user along with the tracks from the camera.

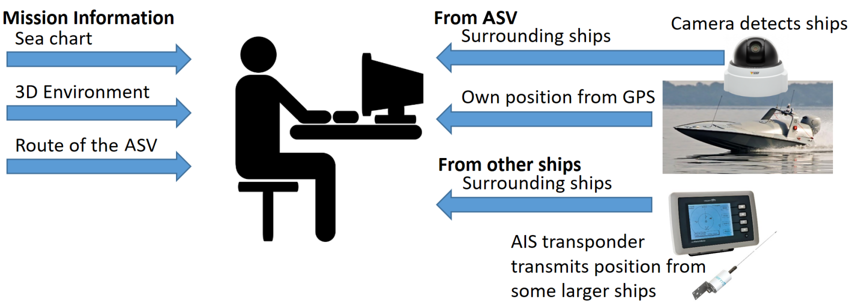



Figure 49: The GUI uses the position from the ASV's GPS to position the surrounding 3D world and the sea charts. The camera and AIS provide tracks to the GUI.

## 3.2 GUI Design

We have created two GUI versions in 3D to enhance situational awareness while maintaining a low cognitive load. In 3D, a virtual world is perceived in the same way as humans normally perceive the real world. By combining a virtual world with the navigation GUI, our intention has been to give the user a better understanding of the environment, instead of just letting the user look at an electronic chart system. In the virtual environment, objects such as sea marks, surrounding ships, sea lanes, and routes are augmented for the user. To enhance the immersive experience even further, one of those GUIs are using VR. VR is a technique that presents a fully computer-generated simulated environment for the user, and the user is thereby fully left out from the visual physical world. In Figure 48c, a user supervises the ASV during the user study by using a VR HMD called *HTC Vive*.

The design of the different parts of the GUI has been developed in an iterative approach. First, a prototype was created based on research by, e.g., Porathe [51] about how the cognitive load of the user can be reduced for navigators. After a brief evaluation by navigation experts, an improved version of the application was developed, which has now been tested by a larger user group.

The GUI is implemented in Unity 3D (see [71]), which is normally used for creating 2D and 3D games. We have used a simulation kernel, received from the shipyard Saab Kockums AB, that simulates own and other ships in a predefined mission. It also creates a 3D replica of the real world, which has been used as a foundation for the implementation of the GUI.

Three different GUIs have been developed; one *Baseline GUI*, representing traditional navigation tools, one 3D tool presented on a laptop, called *3D GUI*, and one 3D tool presented in VR, called *VR GUI*. All these GUI types are presented in Figure 48.

## 3.3 Baseline - Traditional GUI

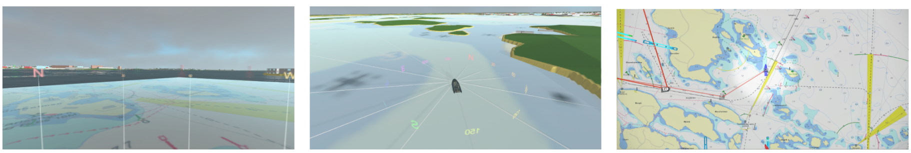
Navigators onboard manned ships use an electronic sea chart with north facing upwards. The own ship, positioned by the GPS, as well as other tracks of ships received by the AIS, are visualized directly on the chart. The *Baseline GUI*, see Figure 50 is created to mimic this design. A navigator normally needs to keep track of how the surrounding real world matches the sea chart, causing a large cognitive load. Because the ship in our application is controlled remotely, this matching is not needed, making it easier for the *Baseline GUI* users.

Optronic systems at sea often present a 360 view, split along two or four stripes with 180 degrees or 90 degrees each (see Maltese et al. [85]). As a compliment, normally an enlargement of one camera view can be seen. These features are also available in *Baseline GUI*. Because the received images have low resolution, we have been able to fit everything including the sea chart on one screen without


Figure 50: The *Baseline GUI* presents a 2D sea chart, as well as which images that the camera has photographed of the surroundings.

compromising too much with the size of the small images. When the camera on the ASV detects a ship, the large image in Figure 50 is shown at the same time as the image is placed in the correct location on the lower 180-degree stripe in the top of the GUI. At the same time, it indicates directly with a marker in the chart which area that has been photographed.

The users can manually take photos as well, by entering a bearing and a range. The camera onboard the ASV then takes a photo and transmits the compressed image when there is available bandwidth.



(a) First Person View (FPV) (b) Tethered View (TeV) (c) Ego-Centric View (ECV)

Figure 51: a) *FPV*: In the FPV the virtual user is placed onboard the ASV. b) *TeV*: The own ASV is situated in front of the virtual user, as the user was paragliding after the boat. c) *ECV:* This view provides a large sea chart for the user.

## 3.4 3D GUI and VR GUI

Our assumption is that we can create an easy-to-use GUI which provides a good situational awareness by:

- Creating the GUI in 3D, and present it in VR.
- Providing different views of the surrounding environment, optimized for various situations.
- Augment objects and information directly in the 3D world.

Our hypotheses are that a user operating a GUI built by these foundations will have a better overall understanding of the situation, and will observe potential dangerous situations earlier.

The GUIs seen in Figure 48b and 48c, named *3D GUI* and *VR GUI*, share most of the design and have three different views; *FPV*, *Tethered View* (TeV) and *Exo-Centric View* (ECV), see Figure 51. Each view has its own benefits so that the views complement each other.

#### First-Person View

The *FPV*, see Figure 52, visualizes the world from the ASV's (ego) perspective, hence it simulates what the surrounding environment looks like. A camera has good bearing accuracy but poor range accuracy. From the *FPV*, the range is of lower importance, hence information from passive sensors such as cameras is well visualized in this view. By capturing real-world images of landmarks and comparing the bearings to the sea chart, it will be obvious if the current GPS position diverges from the correct position, as the landmark bearings will not match the chart.

#### Tethered View

The TeV is created by a virtual camera hanging above the ASV, viewing the ASV from above, providing a bird's eye view of the ASV in its environment, see Figure 53.

#### Exo-Centric View

The ECV, see Figure 54, is used for presenting a north-up facing sea chart for the user where the own ship is located in the middle, much resembling the *Baseline*

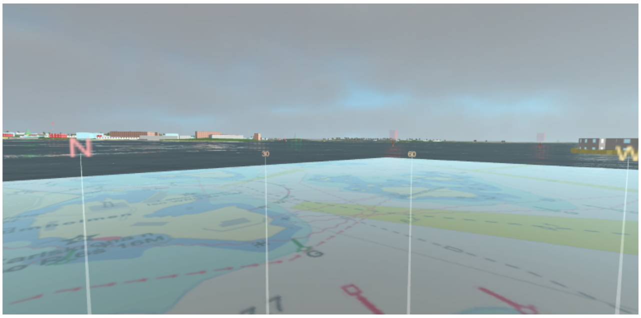



Figure 52: *FPV*: In the FPV the virtual user is placed onboard the ASV. The center of the sea chart is positioned in the user's location and is oriented to be consistent with the surrounding world.

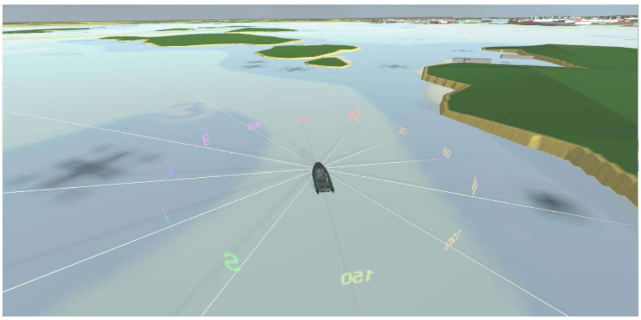



Figure 53: *TeV*: The own ASV is situated in front of the virtual user, as the user was paragliding after the boat. The dark blue in the sea chart indicates a dangerous area with a bottom depth less than 3m. In TeV, the user can easily get a feel for the own ASV's size compared to the passage between the shallow areas.

*GUI*. The ECV has been implemented as a room with a large sea chart in front of the user. In the *3D GUI*, the user can zoom in and out, and in the *VR GUI*, the user can walk around freely in the room and look at other parts of the sea chart. The strength of this view is that the user can get an overview of the situation and plan a long way ahead. It is also easy to get an understanding of if the own route is well positioned according to the sea chart so that it does not pass any groundings.

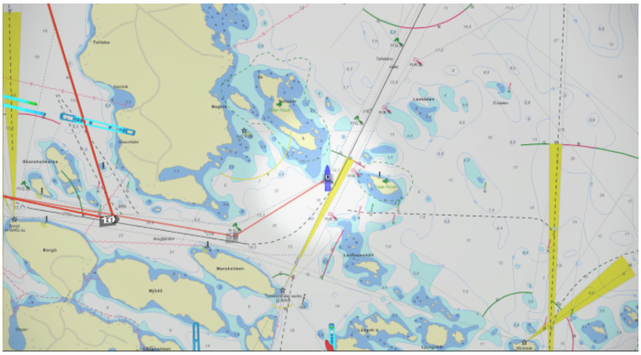


Figure 54: *ECV:* This view provides a large sea chart for the user, centered in the ASV's position.

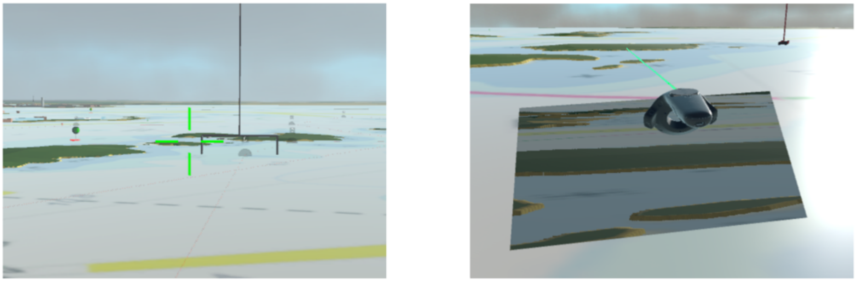
## 3.5 The differences between the 3D GUI and the VR GUI

The main difference between the *3D GUI* and the *VR GUI* is how to interact with the GUI, see Figure 55. In the *3D GUI*, the switching between the various views and the zooming is done with keyboard buttons, and photos are taken by pointing and clicking with the mouse. In the *VR GUI* on the other hand, the associated HTC Vive hand controllers are used for the same interaction.

## 3.6 Features to reduce the cognitive load

Several features have been implemented to support navigation and situational awareness, while still limiting the cognitive load:

- A correctly oriented sea chart surrounds the user in FPV, see Figure 52.
- A sea chart is presented instead of the water in TeV.
- A rainbow-colored compass is shown in FPV and TeV, to guide the user with directions.



(a) (b)

Figure 55: a) In the *3D GUI*, photos are taken with a mouse click while pointing the green hair cross. b) In the *VR GUI*, photos are taken by pointing the green ray from the hand controller and then pressing a button. The image also shows a zoom-window below the hand controller, which enlarges what the hand controller is pointing towards.

- Sea marks are augmented in FPV and TeV.
- Indications of surrounding ships are visualized in all views.
- Routes and waypoints are visualized in all views.

# 4 User Study

We evaluated our implementations with 16 participants, recruited mainly from Lund University and the shipyard Saab Kockums AB, in 50-minute long trial sessions (recorded on video) with the task and scenarios described below. We had the ethics board of our university check the study setup and were informed, that no supervision by the board or formal approval was needed to conduct the study. The participants were informed of the possibility to withdraw at any time and agreed upon the use of the recordings and other data for research purposes.

The user should, after an introduction phase based on written instructions and a slide show, use two different GUIs, either the *Baseline GUI* and the *3D GUI* (on screen), or the *Baseline GUI* and the*VR GUI* to supervise a ship that was passing through an archipelago on a predefined route in two different scenarios. The task was to observe potential dangerous situations and report them as soon as they were detected, and to keep track of the closest nearby ships. Also, they were asked to take pictures of surrounding islands when possible, assuming that we could measure their cognitive load by getting an idea of how much spare time (and mental capacity) they had to handle this secondary task. The participants were told that the safety tasks were most important, and the photo task was least important. A two minutes introduction to each GUI was given before each test.

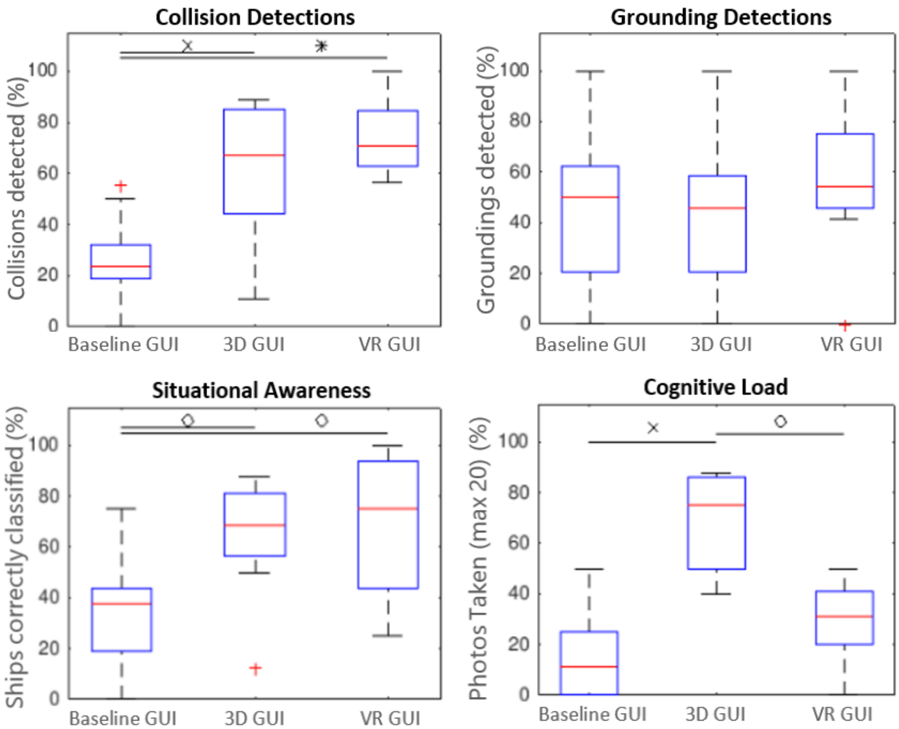



Figure 56: Objective results show that the situational awareness as well as the ability to detect collisions have been improved in both the *3D GUI* and the *VR GUI*. The users of the *3D GUI* have also managed to take more photos, which could indicate a lower cognitive load compared to the *Baseline GUI* and the *VR GUI*. (o), (x) and (*) denote comparisons with $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.

From analyzing the video recordings of the user study, four final score values were given for each run (objective results) for *Collision Observations*, *Grounding Observations*, *Situational Awareness* (closest ships correctly identified), and *Photos Taken* (Cognitive Load). The scores were computed as percentages of the respective possible values. After the experiments, the GUIs were evaluated subjectively by the participants by answering the following three questions for each GUI on a scale of 1-10 (10 was best):

1. Do you feel that you had a good overall picture of the situation? (Situational awareness rating)
2. Do you think that the GUI tool was easy to use?
3. If you had practiced 100 hours on this GUI, do you think it would be best for the task?

# 5 Results

The collected data from the user experiments have been summarized in the objective and subjective results below. The interpretation of the results is done in Section 6.

## 5.1 Objective Results

For the objective results from the user experiments, we found that both the *3D GUI* and the *VR GUI* gave significantly better results regarding the collision detection and situational awareness than the *Baseline GUI*, while there was no major difference regarding the detection of groundings. The *3D GUI* was significantly better than both the *Baseline GUI* and the *VR GUI* regarding the possibility to take photos, where the results for the *VR GUI* are somewhat inconclusive. Figure 56 summarizes the objective results, along with the p-values showing if there was a significant difference, computed in a series of one-tailed t-tests. The mean values are presented in Table 10. Even though it was a quite small user study, power tests (alfa=0.05, power>0.80) have shown that there were enough participants to support the significant results.

Table 10: Objective Results Summary

| | **Baseline** | **3D GUI** | **VR GUI** |
|---|---|---|---|
| Collision Detections | 26.8% | 61.5% | 74.0% |
| Grounding Detections | 42.2% | 43.8% | 56.3% |
| Situational Awareness | 33.6% | 64.1% | 68.8% |
| Photos Taken | 15.9% | 82.8% | 29.4% |

## 5.2 Subjective Results

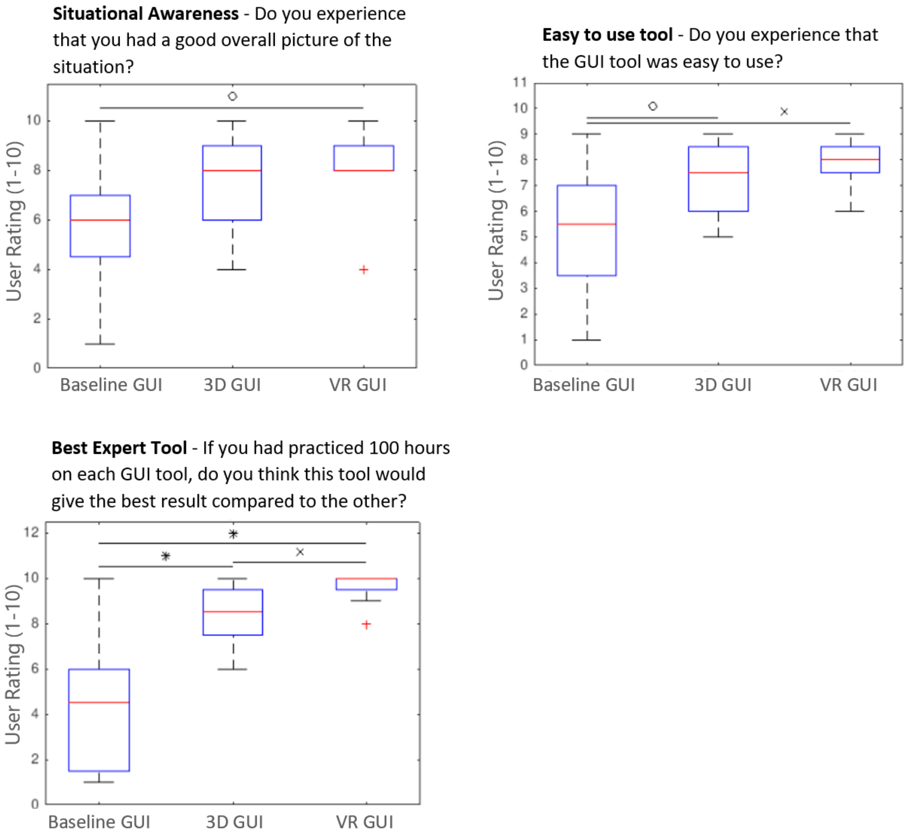



Figure 57: The evaluation score for *Situation Awareness*, *Easy to Use* and *Expert Tool* have been improved for the users of the *3D GUI*, and improved even more for the users of the *VR GUI*. (o), (x) and (*) denote comparisons with $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.

For the subjective results from the user evaluation, we found that the users experienced a significant benefit of the *VR GUI* compared to the *Baseline GUI*, regarding having a good *Situational Awareness*. The users also experienced that both the *VR GUI* and the *3D GUI* were more *Easy to Use*. The users expected the

*VR GUI* to be the best and the *3D GUI* to be the next best tool, for an expert user with many hours of training.

Figure 57 summarizes the subjective results, along with the p-values, computed in a series of one-tailed t-tests. The mean values are presented in Table 11. The power tests have shown that there were enough users to support the significant results with a p-value less than 0.01, but not the two results with a p-value between 0.01 and 0.05.

Table 11: Subjective Results Summary

| | **Baseline** | **3D GUI** | **VR GUI** |
|---|---|---|---|
| (1) Situational Awareness | 5.8 | 7.5 | 8.0 |
| (2) Ease of use | 5.3 | 7.3 | 7.9 |
| (3) Best tool | 4.3 | 8.4 | 9.6 |

# 6 Discussion

Our results show, that the users had better situational awareness when using 3D or VR, which can be seen in *Collision Detection* and (objective) *Situational Awareness*. They also said they experienced this in the question regarding the *Situational Awareness* and *Ease of Use* in the user evaluation. The *VR GUI* got a higher score than the *3D GUI* on all these four metrics, and the *3D GUI*, in turn, got a higher score on all these than the *Baseline GUI*, which is also reflected in the user ratings of the best tool for the task (given more training hours than they had experienced themselves). We think the good score for the *VR GUI* (and *3D GUI*) has to do with the fact that the perception in the GUI much resembles how a human normally perceives the world.

Regarding *Grounding Detections* and *Photos taken* (our assumed indicator for the cognitive load), our results are somewhat inconclusive, which we attribute to the relative unfamiliarity with the GUI as the users simply did not manage to switch into the optimal view (ECV) for this task reliably enough. We also observed a "fun factor" of taking photos of ships instead of islands in the VR setting, significantly reducing the scores for the *VR GUI* users.

Of the sixteen users in the user study, six persons considered themselves to be computer gamers (three used *3D GUI*, and three used *VR GUI*). These persons scored better in the experiments in general, indicating that the performance of the

GUIs is increased with training. Table 12 shows a summary for each of the GUI of how much better scores the gamers had compared to the persons that were not gamers. As can be seen, the gamers performed particularly well in the VR GUI. This finding goes in line with the user evaluation where the users suggested that the *VR GUI* and *3D GUI* would be a better expert tool after a long training.

Table 12: How much better gamers scored compared to non-gaming users.

| | **Baseline** | **3D GUI** | **VR GUI** |
|---|---|---|---|
| Collision Detection | 14.8% | 6.9% | 38.4% |
| Grounding Detection | 88.6% | 20.0% | 93.9% |
| Situational Awareness | -19.5% | 40.7% | 52.2% |

## 7 Conclusion

We investigated, how 3D and VR approaches could support the remote operation of an ASV with a low bandwidth connection, by comparing respective GUIs with a *Baseline GUI* following the currently applied interfaces in such contexts. Our findings show, that both the 3D and VR approaches outperform the traditional approach significantly. We found the *3D GUI* and *VR GUI* users to be better at reacting to potentially dangerous situations compared to the *Baseline GUI* users, and they could keep track of the surroundings more accurately. They also reported that they expected the *3D GUI*, and especially the *VR GUI*, to be the best tool of the three choices for an expert user with many hours of training.

As our investigations so far only have covered the supervision of a simulated ASV, we see the next step to be the integration of functionalities to control an actual ASV. This might potentially also mean looking at the integration of further information sources into the interfaces, which might entail new aspects for the user(s) to handle when interacting with the ASV.

## ACKNOWLEDGMENT

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# List of Acronyms

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## Abbreviations

**AI** Artificial Intelligence

**AIS** Automatic Identification System

**AR** Augmented Reality

**ASC** Autonomous Surface Craft

**ASV** Autonomous Surface Vessel

**AUV** Autonomous Underwater Vehicle

**CO2** Carbon Dioxide

**COLREG** Convention on the International Regulations for Preventing Collisions at Sea

**DARPA** Defense Advanced Research Projects Agency

**DGPS** Differential Global Navigation System

**ECDIS** Electronic Chart Display and Information System

**GMDSS** Global Maritime Distress and Safety System

**GNSS** Global Navigation Satellite System

**GPS** Global Navigation System

**GPU** Graphics Processing Unit

**GT** Gross Tonnage

**GUI** Graphical User Interface

**HMD** Head Mounted Display

**IMO** International Maritime Organization

**IMU** Inertial Measuring Unit

**INS** Inertial Navigation System

**IR** Infra Red

**Lidar** Light Detection and Ranging

**ML** Machine Learning

**NM** Nautical Mile

**NOx** A generic term for the mono-nitrogen oxides: Nitric oxide and Nitrogen dioxide

**PDF** Probability Density Function

**PF** Particle Filter

**Radar** Radio Detection and Ranging

**SAE** Society of Automative Engineers

**SAR** Search and Rescue

**SOLAS** Safety of Life at Sea

**STCW** International Convention on Standards of Training Certification and Watch-keeping for Seafarers

**USV** Unmanned Surface Vessel

**VE** Virtual Environment

**VHF** Very High Frequency

**VR** Virtual Reality

**WAM-V** Wave Adaptive Modular Vessel

# Appendix

# Appendix: Conference Posters

## Poster I: Digital Cognitive Companion for Marine Vessels

Presented during poster session on WASP Winter conference in Stockholm 2017.

## Poster II: Underwater Terrain Navigation Using Standard Sea Charts and Magnetic Field Maps

Presented during poster session on MFI in Daegu 2017.

## Poster III: Remote Operation of Unmanned Surface Vessel through Virtual Reality - a low cognitive load approach

Presented during poster session on WAM HRI Workshop in Chicago 2018.

# DIGITAL COGNITIVE COMPANION FOR MARINE VESSELS

Mårten Lager, Department of Computer Science at LTH

SAAB LUNDS UNIVERSITET

## Description

A naval ship that can process the OODA loop quicker than its opponent gains an advantage. The speed of the OODA loop is therefore of significant importance for measuring the performance of a naval ship.

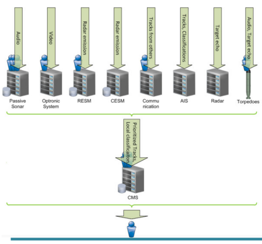
You improve your OODA loop by:
- Having better sensors
- Using your sensor data in a better way
- Collaborating with other platforms (low cost gives more platforms)

You worsen your opponent's OODA loop by:
- Having a low signature (you should hide, be small, be silent, and have stealth capability)


This research will show where and how human operators can be replaced or complemented by efficient algorithms, in order to remove bottle-necks in the operator work-flow. Sensor data will be used in a better way, the platforms will become smaller, and the cost will be reduced.

## Background & Motivation

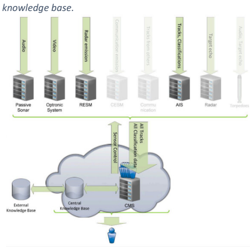
*A typical architecture of a naval ship, where each sensor operator is responsible for which data that should be forwarded to the fusion system CMS.*




The current trend is that naval ships are being equipped with an increasing number of increasingly complex sensor systems. Along with this evolution, the need for more operators to supervise the new sensor systems arises. The operators are often becoming the OODA loop's bottle-neck, because the operators need to process so much data.

## Research Goal & Questions

*The proposed architecture, where the operators work with the fusioned and processed information, and gain from previous experiences saved in the knowledge base.*




The main goal of this project is to develop a solution where operators can efficiently interact with the system on a more abstracted level, where new fusion algorithms replace some of the work that operators perform in present solutions.

## Methods & Preliminary Results

*Swedish submarine control room on-board HMS Södermanland.*

I will use the following research methods:

1. Literature survey to learn about state-of-the-art sensor fusion algorithms
2. Field-study, to get a better understanding of work-flow and bottlenecks on a naval vessel
3. Implementation of new algorithms
4. Feedback from end-users

## Roadmap & Milestones

The ultimate goal is to develop a complete architecture where all relevant information is fusioned, and where the operators and machines help each other interpreting the surrounding area. The following sub-projects will lead in the direction of that goal:

- **Positioning the naval vessel without GPS**, combining IMU-data, bottom depth and magnetic measurements
- **Classifying surrounding ships** using computer vision interpretation
- **Fusing abstracted information on a higher level**, such as pre-classification information from different sensors. The operators should then assist the system by confirming/rejecting classification suggestions

*The Swedish Visby class corvette.*


*The submarine A26.*

WASP WALLENBERG AUTONOMOUS SYSTEMS AND SOFTWARE PROGRAM

# Underwater Terrain Navigation Using Standard Sea Charts and Magnetic Field Maps

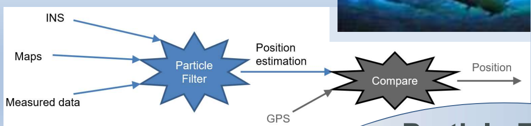
Mårten Lager, Elin Anna Topp, Jacek Malec

LUND UNIVERSITY

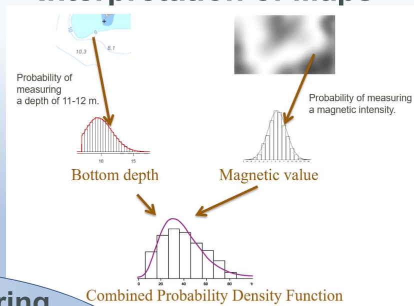
## Can we localize a ship by just comparing the measured depth with a normal sea chart? - Yes, it works fine!

## Background and Motivation

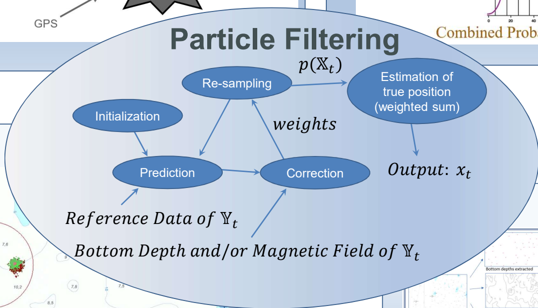
- Ships today rely on GPS
- GPS disadvantages:
  - dependent on external systems
  - Can be jammed
  - Can be spoofed
- Some ships and vehicles can not receive GPS transmission.



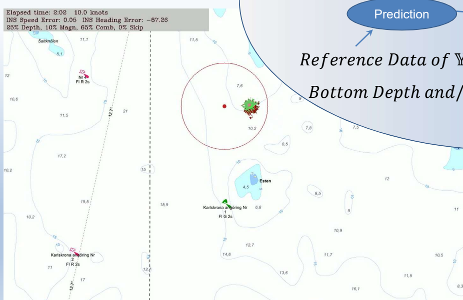

## Interpretation of Maps



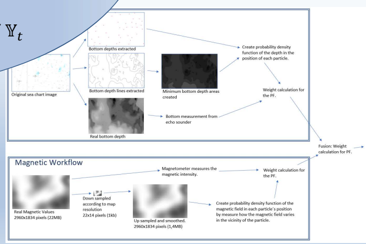

## Particle Filtering



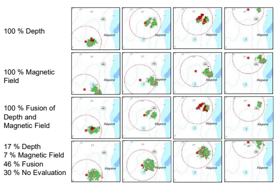

## Simulation




## Workflow



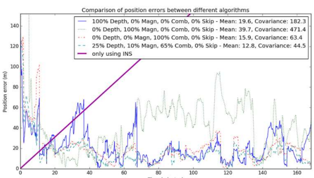

## Data Fusion in Correction Step




Various evaluation methods have been tested alone and in combination with others.

The simulation shows that a well balanced mix of different evaluation methods gives a robust and accurate solution.

## Results and Conclusion




- Good performance when comparing bottom depth with sea chart.
- Accuracy and robustness are increased when fusing bottom depth and magnetic field measurements.
- We only have simulation results. Actual sea tests are planned in the future.

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WASP WALLENBERG AUTONOMOUS SYSTEMS AND SOFTWARE PROGRAM

# Remote Operation of Unmanned Surface Vessel through Virtual Reality - a low cognitive load approach

Mårten Lager, Elin Anna Topp, Jacek Malec

SAAB · Lund University

## How can we design a GUI, so that we safely can control a USV remotely? What about cognitive load?

## Background and Motivation

Why Unmanned Surface Vessel (USV)?

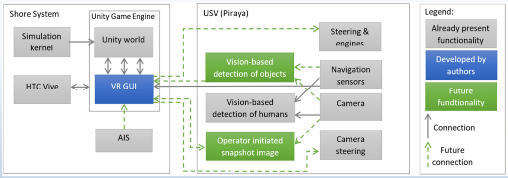
- Cost-effective
- Work-environment
- Safety
- Work in hazardous environments

Why remote-operation:

- Humans can handle complex dynamic environments

Why VR?

- Can provide a realistic environment comparable to what the operator is used to
- Can augment information and guide the operator

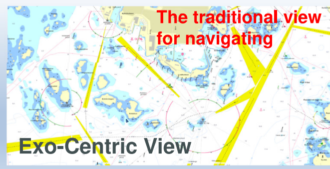



The Piraya USV

## Operational Views


First Person View


Tethered View



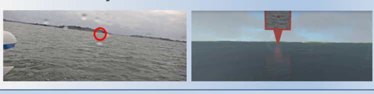
Exo-Centric View

## Features to reduce the cognitive load

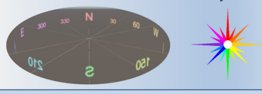
### Virtual groundings and seamarks

### AIS information

### Detected objects from real world



### Overlaid seachart and compass



## Results

- Naval operators found the cognitive load to be reduced, due to the operator was fed with valuable information.

## Future

- Add features for control.
- Add other features
- Start doing live sea trials.
- Evaluate GUI by unexperienced and experienced operators.

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