Petter Norgren

**Autonomous underwater vehicles in Arctic marine operations**

Arctic marine research and ice monitoring
Petter Norgren

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Thesis for the degree of Philosophiae Doctor

Trondheim, September 2018

Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology
To my family and my amazing girlfriend.
Abstract

This thesis considers autonomous underwater vehicles (AUVs) in Arctic marine operations. It focuses on their use as a sensor platform in ice monitoring operations and the use of AUVs for Arctic marine research. Arctic AUV operations pose several challenges compared to standard AUV operations, including the presence of drifting sea-ice and navigational challenges in the polar regions. These are some of the issues addressed in this thesis.

Chapter 2 introduces historic Arctic AUV operations, and it presents experiences and lessons learned through these campaigns. Challenges related to communication, navigation, fail-safes, and deployment and recovery, with a focus on Arctic operations are discussed. This chapter also motivates and assess the use of AUVs as a sensor platform for ice monitoring operations. A conceptual guidance and navigation system for Arctic AUVs is presented at the end of the chapter.

Field work and experiments are important to test theory, but also to build experience and acquire knowledge. Chapter 3 presents two Arctic AUV deployments using the NTNU REMUS 100 AUV and the experiences learned from these operations. Two experiments demonstrating the use of unmanned surface vehicles (USVs) as a support tool for AUVs in the Trondheimsfjord are also presented, along with a motivation for the use of such platforms in Arctic marine research.

Since Arctic AUV operations are considered as high risk, with significant costs associated, an Arctic AUV simulator environment has been developed, as presented in Chapter 4. The simulator consists of seven modules, where the modules defining the default guidance and control system, as well as the numerical AUV model, are similar to a regular AUV simulator. In addition, an ice drift model is provided to simulate drifting and rotating ice features. A multibeam echosounder (MBE) simulator is used to sense the ice topography, given as a digital elevation map (DEM). To achieve drift and rotation of the sensed terrain, the final module in the Arctic AUV simulator is a relative position and velocity module, which provides input to the MBE simulator.

A special consideration has been given to iceberg mapping using AUVs in this thesis, as the detailed topography of icebergs are important to develop iceberg trajectory models, as well as decision support in iceberg management operations (e.g., iceberg towing). Chapter 5 details a guidance system for determining the main particulars of an iceberg that relies on MBE measurements to determine the location of the edge of the iceberg. The guidance system is implemented as a state machine, starting in an iceberg detection mode. Once an iceberg is detected, an edge-detection algorithm is used to determine the location of the edge relative to
the AUV, and thereby to online generate a path along the iceberg edge. The line-of-sight (LOS) guidance scheme is used to follow the iceberg edge and circumnavigate the iceberg.

Motivated by the need to estimate the relative AUV-iceberg position in order to generate a consistent iceberg topography corrected for iceberg drift and rotation, an iceberg mapping navigation system has been proposed in Chapter 6. A simultaneous localization and mapping (SLAM) algorithm based on the bathymetric distributed particle filter SLAM (BPSLAM) is used to track the position and orientation of the iceberg in the global frame. The iceberg mapping navigation filter, implemented using an Extended Kalman filter (EKF) with the SLAM states as input, provides estimates of relative pose and velocity between the iceberg and the AUV. In addition, the velocity of the iceberg is estimated in the iceberg mapping filter. The iceberg SLAM algorithm provides a real-time estimate of the iceberg topography at a fixed resolution, which along with the iceberg drift velocity estimates are important parameters in an iceberg management operation.
Preface

This thesis is submitted in partial fulfilment of the requirements for the degree of philosophiae doctor (PhD) at the Norwegian University of Science and Technology (NTNU). The research has been conducted at the Department of Marine Technology in the period between March 2013 and April 2018. My main supervisor has been Professor Roger Skjetne and my co-supervisors have been Professor Martin Ludvigsen and Dr. Francesco Scibilia. This work was supported by the Faculty of Engineering Science at NTNU, the Research Council of Norway (RCN) through the Center for Research-based Innovation Sustainable Arctic Marine and Coastal Technology (SAMCoT), RCN-project 203471, and the Center of Excellence Autonomous Marine Operations and Systems (AMOS), RCN-project 223254. During my research, I have also had the opportunity of visiting the University Center in Svalbard (UNIS) on multiple occasions, through both course-work and field experiments.

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The AUR-lab team deserves a special thank you. I have had the pleasure of working with all of you on a multitude of projects, cruises, and workshops. I must say that it has been truly inspiring to work with so many hard working, dedicated, and skilled people. In particular, I would like to thank Frode Volden, Kay Arne Skarpnes, Pedro De La Torre, Stein Melvær Nornes, Øystein Sture, Trygve Olav
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Thanks to my fellow PhD students and postdocs for great and inspiring discussions over coffee and lunch. It has been a privilege working with so many great people.

I would like to give a big thank you to my family, for always being there for me, for believing in me, and for being proud of me. You are great! I would also like to thank my family-in-law, and a special thanks goes to Eli Aamot for help with feedback and proofreading in a stressful period.

And the biggest thank you goes to my amazing girlfriend, Inga. The best thing that has happened through my PhD studies is definitely meeting you. I would like to thank you for your patience, inspiration, motivational boost, for always believing in me, and for your love. Your support has kept me going, and I am eternally grateful. You are the best!

Petter Norgren
Trondheim, April 2018
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<th>Definition</th>
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<td>ABE</td>
<td>Autonomous Benthic Explorer</td>
</tr>
<tr>
<td>ACTV</td>
<td>Autonomous Conductivity Temperature Vehicles</td>
</tr>
<tr>
<td>ADCP</td>
<td>Acoustic Doppler current profiler</td>
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<tr>
<td>AGAVE</td>
<td>Arctic Gakkel Vents Expedition</td>
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<tr>
<td>ALTEX</td>
<td>Atlantic Layer Tracking Experiment</td>
</tr>
<tr>
<td>AMTV</td>
<td>Autonomous Microconductivity Temperature Vehicles</td>
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<tr>
<td>AUR-lab</td>
<td>Applied Underwater Robotics laboratory</td>
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<tr>
<td>AUV</td>
<td>Autonomous underwater vehicle</td>
</tr>
<tr>
<td>BPSLAM</td>
<td>Bathymetric distributed particle filter SLAM</td>
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<tr>
<td>CB</td>
<td>Center of buoyancy</td>
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<tr>
<td>CF</td>
<td>Center of floatation</td>
</tr>
<tr>
<td>CG</td>
<td>Center of gravity</td>
</tr>
<tr>
<td>CO</td>
<td>Center of origin</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial-of-the-shelf</td>
</tr>
<tr>
<td>CTD</td>
<td>Conductivity-temperature-depth</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital elevation map</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree-of-freedom</td>
</tr>
<tr>
<td>DP</td>
<td>Dynamic positioning</td>
</tr>
<tr>
<td>DPM</td>
<td>Distributed particle mapping</td>
</tr>
<tr>
<td>DPSLAM</td>
<td>Distributed particle filter SLAM</td>
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<tr>
<td>DT</td>
<td>Distance travelled</td>
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<tr>
<td>DVL</td>
<td>Doppler velocity log</td>
</tr>
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<td>DVM</td>
<td>Diel vertical migration</td>
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<tr>
<td>EKF</td>
<td>Extended Kalman filter</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>FFI</td>
<td>Norwegian Defence Research Establishment</td>
</tr>
<tr>
<td>FLS</td>
<td>Forward-looking sonar</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global navigation satellite system</td>
</tr>
<tr>
<td>GPS</td>
<td>Global positioning system</td>
</tr>
<tr>
<td>ICP</td>
<td>Iterative closest point</td>
</tr>
<tr>
<td>IM</td>
<td>Ice management</td>
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<tr>
<td>IMU</td>
<td>Inertial measurement unit</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial navigation system</td>
</tr>
<tr>
<td>ISE</td>
<td>International Submarine Engineering Research Ltd.</td>
</tr>
<tr>
<td>LBL</td>
<td>Long baseline</td>
</tr>
<tr>
<td>LeadEx</td>
<td>Lead Experiment</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-of-sight</td>
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<tr>
<td>MBE</td>
<td>Multibeam echosounder</td>
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<tr>
<td>MBR</td>
<td>Marine broadband radio</td>
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<tr>
<td>MCS</td>
<td>Monte Carlo simulations</td>
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<td>NED</td>
<td>North-east-down</td>
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<tr>
<td>NUI</td>
<td>Nereid Under Ice</td>
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<tr>
<td>OATRC</td>
<td>Oden Arctic Technology Research Cruise</td>
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<tr>
<td>PDF</td>
<td>Probability density function</td>
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<tr>
<td>PF</td>
<td>Particle filter</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional-integral-derivative</td>
</tr>
<tr>
<td>PII</td>
<td>Petermann Ice Island</td>
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<tr>
<td>RBPF</td>
<td>Rao-Blackwellized particle filter</td>
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<tr>
<td>REMUS</td>
<td>Remote Environmental Monitoring UnitS</td>
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<td>RMS</td>
<td>Root-mean-square</td>
</tr>
<tr>
<td>ROV</td>
<td>Remotely operated vehicle</td>
</tr>
<tr>
<td>RTK</td>
<td>Real-time kinematic</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic aperture radar</td>
</tr>
<tr>
<td>SAS</td>
<td>Synthetic aperture sonar</td>
</tr>
<tr>
<td>SBP</td>
<td>Sub-bottom-profiler</td>
</tr>
<tr>
<td>SEDNA</td>
<td>Sea-ice Experiment: Dynamic Nature of the Arctic</td>
</tr>
<tr>
<td>SHEBA</td>
<td>Surface Heat Balance of the Arctic Ocean</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
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<td>---------</td>
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<tr>
<td>SIR</td>
<td>Sampling importance resampling</td>
</tr>
<tr>
<td>SLAM</td>
<td>Simultaneous localization and mapping</td>
</tr>
<tr>
<td>SNAME</td>
<td>Society of Naval Architects and Marine Engineers</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>SPURV</td>
<td>Self Propelled Underwater Research Vehicle</td>
</tr>
<tr>
<td>SSS</td>
<td>Sidescan sonar</td>
</tr>
<tr>
<td>TAN</td>
<td>Terrain-aided navigation</td>
</tr>
<tr>
<td>TAPM</td>
<td>Thruster-assisted position mooring</td>
</tr>
<tr>
<td>UARS</td>
<td>Unmanned Arctic Research Submersible</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned aerial vehicles</td>
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<tr>
<td>UiT</td>
<td>Arctic University of Norway</td>
</tr>
<tr>
<td>UNIS</td>
<td>University Centre at Svalbard</td>
</tr>
<tr>
<td>USBL</td>
<td>Ultra-short baseline</td>
</tr>
<tr>
<td>USV</td>
<td>Unmanned surface vehicle</td>
</tr>
<tr>
<td>UUV</td>
<td>Unmanned underwater vehicle</td>
</tr>
<tr>
<td>VCS</td>
<td>Vehicle Control Station</td>
</tr>
<tr>
<td>VIP</td>
<td>Vehicle Interface Program</td>
</tr>
<tr>
<td>VNIR</td>
<td>Visual to near infrared</td>
</tr>
<tr>
<td>WHOI</td>
<td>Woods Hole Oceanographic Institution</td>
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Chapter 1

Introduction

The scope of this thesis is to assess the use of autonomous underwater vehicles (AUVs) as a mobile sensor platform for subsurface monitoring of sea-ice and icebergs. The use of AUVs as an Arctic marine research tool is also discussed. This chapter provides motivation for the problem, and creates a foundation for the research presented through the thesis. Furthermore, the research questions are formulated, and the outline of the rest of the thesis is presented.

1.1 Motivation

Recently there has been an increasing interest for Arctic marine operations. Better vessels and more knowledge on how to operate in such areas, together with the assessment by the United States Geological Survey concluding that about 30% of the world’s undiscovered gas and 13% of the world’s undiscovered oil may be found in the Arctic [71], have motivated research into Arctic marine technology and operations.

Hydrocarbons are not the only driver for increased Arctic marine activity. The Arctic region has had tourism since the nineteenth century, but the earliest tourists where small groups of explorers and adventurers. In the past few centuries, the technological advances in transport and the decline of the Arctic sea-ice have contributed to a great increase in polar tourism [159].

The sea-ice extent in the Arctic has been severely reduced in the last decades, with a record low in September 2012, and recorded sea-ice extent for the month of October shows a decline of 9.3% per decade [132]. In addition, it has also been reported that the mean Arctic sea-ice thickness has been reduced from 3.64 meters in 1980 to 1.89 meters in 2008 [56], and that the multi-year ice is decreasing at a higher rate than the younger, thinner ice. Transportation routes through Arctic waters may save transportation companies significant time and costs, and a significant increase in shipping through the Arctic Canadian waters was observed after the low sea-ice extent in 2007, and is expected to increase further [149].
The changing Arctic environment not only changes how the Arctic is used by humans, but it also impacts the Arctic ecosystem and marine life. The number of well-documented climate-related changes, however, are low, and require further research [175]. The sea-ice cover is an important factor controlling the phytoplankton bloom at Arctic latitudes [89, 148]. There is also a strong link between the polar cod and the ice algae, and the retreating ice cover may therefore influence the polar cod population, and further other marine life higher on the food chain [103]. Since processes like the under-ice algae and phytoplankton blooms are hard to detect using conventional means, like remote sensing, these are poorly understood processes [89] that suffer from under-sampling and emerging technologies may provide a way to bridge the knowledge gap.

Arctic marine operations pose new challenges due to low temperatures, lack of existing infrastructure, and the presence of sea-ice and icebergs. Especially, the loads caused by drifting sea-ice and icebergs are difficult to handle for commercially available dynamic positioning (DP) systems. DP of marine vessels in ice is discussed by Kjerstad [102], while Haugen et al. [78] present an ice observer system. For an accurate estimate of the movement of sea-ice and icebergs, several sensor platforms are needed. For above surface measurements, unmanned aerial vehicles (UAVs),
ships, and satellites can gather measurements, but the harsh weather conditions in the Arctic may render these sensor carriers useless for an extended period of time. The ice topography above the surface may in addition differ significantly from the ice topography seen from underwater. The AUV is a class of unmanned underwater vehicles (UUVs) that is especially interesting as sensor carriers in Arctic operations, since they are unaffected by the harsh weather conditions and they can gather spatially distributed information about the subsurface ice topography and other under-ice processes which otherwise can be hard to attain.

1.2 Background

This section presents a short history of AUVs, as well as some background on ice management and the Arctic marine environment.

1.2.1 A brief history of AUVs

The origin of AUVs can be linked to the development of torpedoes in the late 1800’s. Figure 1.1 shows a picture of the Whitehead Automobile “Fish” Torpedo, developed by Robert Whitehead in Austria. The vehicle was driven by compressed air, and could be considered as the first AUV if disregarding the fact that it carried an explosive payload [170].

The AUV that is considered as the first true AUV, is the Self Propelled Underwater Research Vehicle (SPURV), which came operational in the early 1960’s [170]. The vehicle supported research into internal wave modelling by collecting conductivity-temperature-depth (CTD) measurements. A second version of the SPURV was also developed, and in total, more than 400 SPURV deployments were conducted [170].

By 1987, there were six operational AUVs and additional 15 vehicles under development or in the prototype phase, but during the 1990’s, the interest in AUVs increased in academic research and several vehicles were developed (e.g., REMUS, HUGIN, Theseus, Odyssey, Autonomous Bentic Explorer (ABE), Autosub) [170].

Today, AUVs are commercially available with depth ratings of up to 6000 meters, and are highly modular with respect to payload sensors. Examples of geophysical instruments for AUVs are multibeam echosounders (MBE), sub-bottom profilers (SBP), sidescan sonar (SSS), and magnetometers. Sea-floor imaging (usually black-and-white, but color exist as well) is becoming more popular on AUVs, but requires the AUV to be close to the sea-bed and surveys must be conducted at lower speeds [180]. Common oceanographic instruments are CTD, fluorometer and optical backscatter, turbidity, and oxygen sensors.

1.2.2 Ice management

Figure 1.2 illustrates a possible future Arctic drilling operation. An Arctic drillship is keeping position by DP or thruster-assisted position mooring (TAPM), which means that the vessel is keeping its position using thrusters, and possibly moorings. This means that the amount of ice loads the vessel can withstand while still keeping position is limited, and thus, the presence of sea-ice and icebergs means that ice
1. Introduction

Figure 1.2: Illustration of a possible future Arctic marine operation: an Arctic drillship on DP or TAPM, aided by icebreakers and unmanned vehicles. Illustration: Bjarne Stenberg. Copyright: NTNU.

management (IM) is required. As illustrated in Figure 1.2, the vessel is assisted by icebreakers to reduce the incoming ice loads by breaking the ice into more manageable ice floes, and one or several unmanned vehicles are used to monitor the incoming ice. This constitutes a part of an IM system. Eik [46] gives the following definition of ice management:

**Definition 1.1.** Ice management is the sum of all activities where the objective is to reduce or avoid actions from any kind of ice features. This includes, but is not limited to:

- Detection, tracking, and forecasting of sea-ice, ice ridges and icebergs.
- Threat evaluation.
- Physical ice management such as ice breaking and iceberg towing.
- Procedures for disconnection of offshore structures applied in search for, or production, of hydrocarbons.

Detection and tracking of ice features have previously been performed by visual observations from ice observers, marine radars, ice drift buoys, airborne reconnaissance, and satellites, but most of these surveillance methods suffer from reduced quality in fog and bad weather [46] – a common occurrence in the Arctic. Visual to near infrared (VNIR) satellites also suffer from these drawbacks. Satellites
1.2. Background

Table 1.1: Sensor platforms for ice monitoring. Adapted from Haugen et al. [78].

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Satellite</th>
<th>UAV</th>
<th>Shipboard</th>
<th>Buoy</th>
<th>Underwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Laser altimeter/scanner</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Radiometer</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Synthetic aperture radar</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marine radar</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scatterometer</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radar altimeter</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sonar/acoustics</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meteorological suite</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oceanographic suite</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

operating at wavelengths > 0.9 cm (microwave) can penetrate clouds and polar darkness, but suffer from a tradeoff between spatial coverage and resolution, and online update rate [114]. Due to the high latitudes in the Arctic, satellites do not give sufficient temporal resolution. A sensor platform overview is given in Table 1.1. As can be seen from the overview, no platform covers the whole range of sensors, and multiple platforms must be combined to get the full picture.

Ice observation systems

Haugen et al. [78] describe the structure of an ice observer system, intended as an aid for decision making and risk assessment on IM operations, motivating the use of UAV for ice-monitoring. Eik and Loset [47] present specifications for a subsurface ice intelligence system and conclude that technology for mapping the underside of the ice, and for detecting and identifying icebergs and multi-year ice will contribute to increased operational safety. The use of unmanned underwater vehicles are discussed, and due to tether-ice interactions, the use of remotely operated vehicles (ROVs) are discouraged. Eik and Loset [47] discuss the use of UUVs, both for capturing details of ice features as a reaction to a detection by another platform, and for patrolling an area with multiple UUVs. Patrolling UUVs are considered as a less comprehensive alternative to using a fence of acoustic moorings.

1.2.3 The Arctic marine environment

Nearly two thirds of the Arctic region is ocean, which contains a large variety of environmental challenges not found in the rest of the ocean basin. For example, almost half of the Arctic Ocean is covered by an ice cap, with large seasonal variations to the ice extent [153]. Extremely low temperatures, marine icing, snow,
Table 1.2: Iceberg size classification. Adapted from McClintock et al. [121].

<table>
<thead>
<tr>
<th>Iceberg type</th>
<th>Mass [Ton]</th>
<th>Sail height [m]</th>
<th>Length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growler</td>
<td>500</td>
<td>&lt; 1</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Bergy bit</td>
<td>1,400</td>
<td>1 – 5</td>
<td>5 – 15</td>
</tr>
<tr>
<td>Small berg</td>
<td>100,000</td>
<td>5 – 15</td>
<td>15 – 50</td>
</tr>
<tr>
<td>Medium berg</td>
<td>750,000</td>
<td>15 – 50</td>
<td>50 – 100</td>
</tr>
<tr>
<td>Large berg</td>
<td>5,000,000</td>
<td>50 – 100</td>
<td>100 – 200</td>
</tr>
<tr>
<td>Very large berg</td>
<td>&gt; 5,000,000</td>
<td>&gt; 100</td>
<td>&gt; 200</td>
</tr>
</tbody>
</table>

polar lows, dark periods, and remoteness are other challenges that are typical in the Arctic.

Many areas in the Arctic are covered by a permanent ice cap; however, depending on operational area and time of year, the ice state may differ significantly, even in the same day. The type of ice may not even be the same. First-year ice is the term for ice that is not more than one winter’s growth old, with ice thickness between 0.3 and 2 meters [113]. Multi-year ice is the term for ice which have survived at least one summer’s melt, and is typically thicker, smoother, and harder than first year ice. The different classes of ice states that are typical in the Arctic marine environment are:

- Open water.
- Drifting sea-ice.
- Landfast sea-ice.

The drifting sea ice category covers all sea ice from a full ice cover, to pack ice with high ice concentration, to low ice concentrations with very open ice. Other types of ice features are rafted ice (ice fles that are overriding each other) and pressure ridges. Ridges consist of a sail, which is a wall of broken ice forced upwards by pressure, and a keel, which is the subsurface part of the ice ridge. Ridges with drafts between 5 and 29 meters are reported by Davis and Wadhams [39], while keels going as deep as 47 meters have been reported by Lyon [118]. The last category of ice features are icebergs.

Icebergs

An iceberg is a piece of ice that has calved from a glacier and into the ocean [113], but the size and shape of the iceberg can vary a lot. A classification of iceberg sizes can be found in Table 1.2, and examples of two different iceberg shapes can be seen in Figure 1.3.

Collection of 3D iceberg profiles can have multiple applications. Younan et al. [181] give an overview of an iceberg profiling program with primary interest in design of offshore structures by analysing iceberg contact area given an impact. Stuckey et al. [163] discuss the use of 3D iceberg models for improving existing iceberg impact models. Bruce et al. [29], on the other hand, state that 38% of iceberg towing attempts result in rope slippage events, and 10% result in iceberg roll events, and further discuss the use of 3D iceberg shapes to determine the best
1.3 Problem outline and research questions

The scientific goal of this thesis is to assess the use of AUVs as an ice monitoring sensor platform and Arctic marine research tool, and contribute with methods and ideas for performing ice mapping using AUVs. The problem is vast, and the thesis will mostly focus on the guidance and navigation problem for AUVs in the Arctic. Moreover, the following topics are covered in more detail:

- Using AUVs for Arctic marine operations is complex, with many new challenges compared to standard operations. The thesis will assess the use of AUVs as an ice

(a) A tabular iceberg. (b) An irregular iceberg.

Figure 1.3: Iceberg shapes of two different icebergs from the Oden Arctic Technology Research Cruise 2013.

towing direction, as well as net placement and development. King et al. [100] use 3D iceberg profiles to determine risk on subsea structures due to iceberg gouging.

To develop accurate iceberg drift models used for iceberg trajectory forecasting, detailed iceberg keel geometry is necessary. Kubat et al. [104] present an operational approach to estimate iceberg drift using an empirical model of the keel cross-sectional area depending on waterline height. Detailed iceberg surveys would improve the statistical foundation for the development of such empirical models [10]. Another modelling application that would greatly benefit from iceberg keel surveys is iceberg deterioration models, as stated by Murphy and Carrieres [130]. Such models would require repeated and systematic surveys of the same iceberg.

Younan et al. [181] acquired 29 3D profiles of icebergs using a combination of photogrammetry for the sail and ROV for the keel, and reported an average survey time in the range 3 – 4 hours. The datasets acquired on on this cruise, however, required several months of post-processing to attain the desired quality. To improve both iceberg survey speed and post-processing time, McGuire et al. [124] present a rapid profiling system for icebergs, using a boat with LIDAR and a side-mounted MBE. Iterative closest point (ICP) is used to correct the point cloud, and to estimate iceberg drift and rotation. The authors report that an iceberg with waterline length of 100 meters could be mapped in under 5 minutes. Since a small ship is used for the profiling, the iceberg must be floating in relatively open waters.
1. Introduction

monitoring sensor platform and Arctic research tool, as well as discuss necessary sensors, support systems, infrastructure, and failsafes. Field experiments will be used to verify the findings.

- To develop new methods and algorithms for Arctic AUV operations, an environment must be in place to test and verify the contributions. The thesis will therefore discuss the development of a simulator environment designed with focus on Arctic AUV operations.
- Autonomous mapping of icebergs would be useful to collect information about the iceberg topography and main particulars. This problem has been divided into two sub-problems, which are investigated through the thesis:
  - Guidance system for iceberg detection.
  - Navigation system for iceberg mapping.

The term iceberg detection is related to determining the iceberg’s main particulars, such as length, width, draft, and mass. Iceberg mapping, on the other hand, is related to complete coverage mapping and generation of a 3D topography map of the iceberg.

1.4 Notation

Matrices are written in capital letters, and vectors are written in small letters. The dimension of each variable will be defined. A variable in the Euclidean space with dimension $n$ is denoted $\mathbb{R}^n$, while matrices of dimension $n \times m$ are denoted $\mathbb{R}^{n \times m}$. Similarly, variables in the unit $n$-sphere are denoted $S^n$. $\operatorname{col}(a \ b)$ represents stacking of column vectors $a$ and $b$ into a larger column vector with size equal to the sum of the two column vectors. The total time derivative of a variable $x(t)$ is denoted $\dot{x}$. Superscript represents the reference frame to which a given vector is expressed. For example, $p^n$ is a position in the north-east-down (NED) frame. A rotation matrix $R_b^n \in \text{SO}(n)$ between reference frames use a subscript for the frame transformed from, and superscript for the frame transformed to. For example, rotating from BODY to NED is denoted $R^n_b$. For horizontal 3 degree-of-freedom (DOF) motion, with states $(x, y, \psi) \in \mathbb{R} \times \mathbb{R} \times S$, the simpler notation $R(\psi) = R_z, \psi \in \text{SO}(3)$ is used, representing a rotation of a reference frame about the $z$-axis by an angle $\psi$.

1.5 Thesis outline and contributions

The thesis is divided into five parts, considering different aspects of Arctic marine AUV operations. The content in each chapter is self-contained and can be read independently, but the order of the chapters are important for the red thread building up the thesis. Figure 1.4 gives an overview of the chapters and the papers with respect to the larger picture, which is an Arctic AUV guidance and navigation system. This figure is discussed in Chapter 2.

Chapter 2 presents historical Arctic AUV operations and challenges in these operations, and discusses how AUVs can be employed as an ice monitoring sensor platform. A structure of an Arctic AUV guidance and
Figure 1.4: Overview of an Arctic AUV guidance and navigation system. The figure serves as an overview of the thesis, with the topic of the different chapters and papers placed into the figure.
navigation system is proposed, as seen in Figure 1.4. The main contributions are:

1. Survey of Arctic AUV operations and challenges.
2. Discussion of AUV as an ice monitoring sensor platform.
3. Outline of a guidance and navigation system for an Arctic AUV.

Chapter 3 provides details on selected field work campaigns and cruises that have been conducted with the Applied Underwater Robotics laboratory (AUR-lab) and experiences learned. The main contributions are:

1. Discussion of the REMUS AUV navigation system for Arctic AUV operations.
2. Results related to Arctic marine research, such as ADCP measurements of zooplankton diel vertical migration.
3. Results and operational experiences during an under-ice REMUS AUV deployment.
4. Results from tracking and monitoring of AUVs using unmanned surface vehicles (USVs).

Chapter 4 details the development of an Arctic AUV simulator, used for design of the algorithms in the following chapters, and verification of the results. The main contributions are:

1. Implementation of a 6 degree-of-freedom AUV simulator with focus on Arctic operations.
2. Integration of a multibeam simulator with real iceberg topography.

Chapter 5 contains work on a guidance system for mapping of an iceberg’s main particulars utilizing measurements from a multibeam echosounder. Different strategies for performing iceberg detection using AUVs are also presented. The main contributions are:

1. Discussion of multiple iceberg detection strategies.
2. Design of a state machine guidance system for iceberg detection using AUVs.
3. Development of an edge-detection algorithm for following an iceberg edge.

Chapter 6 presents the development of a navigation system for iceberg mapping, including a simultaneous localization and mapping (SLAM) algorithm using multibeam measurements to determine the AUV’s location relative to an iceberg.

1. Development of an AUV/iceberg relative motion model.
2. Design of an online iceberg mapping filter estimating relative position and velocity between the iceberg and AUV.
3. Development of two new weighting algorithms for the bathymetric distributed particle filter SLAM (BPSLAM) algorithm.
4. Verification of the BPSLAM method and the new weighting algorithms on a real-world dataset collected with the HUGIN HUS AUV.
1.6 List of publications

In the period 2014-2018 a total of 10 papers have been published. In 7 of these, I have been the first author. The publications are listed below.

**Journal papers**


**Conference papers**


**Other papers**

Chapter 2

AUVs for Arctic marine operations

Through this chapter, experiences gained through different Arctic marine operations with AUVs are presented. Especially, challenges related to navigation, communication, deployment and recovery, and fail-safe principles, are highlighted. A motivation and assessment of AUVs as an ice monitoring sensor platform are also provided along with relevant sensor capabilities. At the end of the chapter, an outline of a guidance and navigation system for an Arctic AUV is proposed and discussed. Parts of the work presented in this chapter have been shown in [135, 140].

2.1 Introduction

Marine operations in the Arctic pose new challenges, due to extreme and rapidly changing weather conditions, limited accessibility, lack of infrastructure, and presence of sea-ice, and icebergs. In addition to operational and environmental challenges, the Arctic poses new technological challenges, with respect to for example navigation and communication. UUVs are especially interesting for Arctic marine operations, since they are protected from the potentially harsh surface weather conditions, and due to their unique position as mobile sensor platforms with a view of the underside of the ice. UUVs are also very interesting in this regard since they provide a way to obtain measurements in previously inaccessible areas (e.g., under icebergs, glaciers, and sea-ice). Different types of UUVs are suitable for different types of missions. ROVs are suited for missions where for example a live camera feed is required. Even though the tether-ice interaction may render ROVs as an infeasible option for some Arctic marine operations [47], they are essential in many application, for example in Arctic marine research. Gliders are a different type of UUV that typically have long endurance, and are generally used for gathering oceanographic measurements over large areas. In this thesis, the focus is on AUVs and how AUVs can be applied to Arctic marine operations.
2. AUVs for Arctic marine operations

![The Theseus AUV under the ice. Image courtesy of ISE Ltd.](image1)

![UBC-Gavia AUV under ice with tether attached. Image courtesy of Donnie Reid.](image2)

Figure 2.1: Under-ice AUV deployments.

2.2 Historical Arctic AUV operations

The first reported deployment of AUVs in the Arctic is presented by Francois and Nodland [67]. The Unmanned Arctic Research Submersible (UARS) was designed for a maximum operating depth of 450 meters and had 12 hours maximum endurance. The payload consisted of a three-beam profiling sonar, an obstacle avoidance sonar as well as an acoustic tracking and communication system. The UARS was tested in Lake Washington in February-March 1972, immediately followed by Arctic tests starting in the end of March 1972, at Fletcher’s Ice Island in Alaska. During the successful mission in the Arctic, about 1.4 km of ice topography data were acquired using the profiling sonar.

Other early players in this field are the Seashuttle AUVs and the Odyssey II AUV. Two Seashuttle AUVs, fitted with conductivity-temperature instruments and named Autonomous Conductivity Temperature vehicles (ACTV), were demonstrated in the Arctic in April 1989 [112], while Bellingham et al. [13, 14, 15] describe the development and testing of a small-size AUV, named the Odyssey II, with the objective to obtain measurements of the topography of the underside of the ice. The Odyssey II AUV was deployed in the Beaufort Sea in the Arctic in 1994, and several tests were performed to evaluate the vehicle’s performance and to assess requirements for the next stage of development. A mini-ROV was also used to scout the deployment site and to document the deployment procedure. An ACTV AUV was also deployed in the Beaufort Sea in 1992 [128] through the winter Lead Experiment (LeadEx), and a version of the Remote Environmental Monitoring Units (REMUS) AUV, the autonomous microconductivity temperature vehicle (AMTV) was deployed in the same area through the Surface Heat Balance of the Arctic Ocean (SHEBA) program in 1998 [79].

One of the pioneering AUVs in complex Arctic operations is the Theseus AUV. Ferguson [57], Thorleifson et al. [167] and Ferguson et al. [61] report two successful missions using the Theseus AUV, co-developed by the International Submarine Engineering Research Ltd. (ISE) and the Esquimalt Defense Research Detachment of the Defense Research Establishment Atlantic. After successful trials in the shal-
low ice-covered waters near Ellesmere Island in Canada in April 1995 and at a test range in the Georgia Strait in January 1996, the Theseus AUV was used for pipe-laying in ice-covered waters, and in April 1996 a fiber-optical cable was laid from Jolliffe Bay to Ice Camp Knossos near Ellesmere Island under a 2.7 meter thick ice-cover. A picture of the Theseus AUV under-ice is shown in Figure 2.1(a).

Wadhams et al. [173] report the use of a Maridan Martin 150 AUV to obtain the first under-ice sidescan sonar imagery from an AUV. This mission took place in the winter marginal ice zone of the East Greenland Current in February 2002, and from the data collected it was possible to identify first-year, multi-year, brash, and frazil ice. In 2004, the Autosub-II AUV operated off north-east Greenland and successfully obtained the first multibeam sonar data of the underside of the ice [174]. During the survey, 458 km of high quality multibeam sonar data were acquired, providing a new view of the underside of the ice, as these images were of much higher quality than what were previously gathered. The Autosub-II AUV was also deployed later in 2005 under the Fimbul Ice Shelf in Antarctica [133].

The climate changes taking place in the Arctic are affected by the inflow of warm Atlantic water through the Fram Strait, as well as the current from the Barents Sea. The intention of the Atlantic Layer Tracking Experiment (ALTEX) was to understand the effect of the Atlantic water in the Arctic Ocean on the global climate, by taking measurements in the water column using an AUV. Due to the large spatial scale and the deep waters in the area, special considerations had to be made with respect to endurance and depth rating, and the development of the ALTEX AUV is presented by Bellingham et al. [16]. The ALTEX AUV was designed with a range between 1500 km and 3000 km (depending on payload) and had a depth rating of 4500 meters. The first tests reported from the use of the ALTEX vehicle can be found in [17]. During this expedition, which took place in the waters north of Svalbard in October 2001, the ALTEX AUV was operated under ice on latitudes as high as 82° north, and CTD data were acquired for the Atlantic layer north of Svalbard. As the vehicle was equipped with an ice profiler [165], measurements of ice thickness were also gathered during the missions.

The Gavia class AUV is a modular, small size AUV developed by Teledyne Gavia. Forrest et al. [63] present the results from the deployment of the UBC-Gavia, a Gavia AUV owned by the University of British Columbia, in the ice-covered Pavilion Lake in Canada in February 2007, with the objective to investigate under-ice thermal structure (see Figure 2.1(b)). Operational and technical experience from the aforementioned mission, as well as three new missions, can be found in the papers by Doble et al. [40, 41]. One of these missions where a part of the Sea-ice Experiment: Dynamic Nature of the Arctic (SEDNA) and involved several deployments in the Beaufort Sea in April 2007 [172]. The AUV was equipped with an interferometric sonar, and by running the AUV inverted, the team was able to obtain a three-dimensional digital terrain map of the underside of the sea ice. Due to the small size, and light weight of the AUV, it was possible to deploy the AUV from a hole in the ice. Another deployment was performed in the Pavilion Lake in February 2008, followed by a deployment at Ellesmere Island in May 2008, close to the area where the Theseus AUV had been deployed [64].

2. AUVs for Arctic marine operations

(a) Timeline of historic Arctic AUV deployments.

(b) Timeline of AUR-lab’s Arctic AUV deployments.

Figure 2.2: Timeline of Arctic AUV deployments.
due to its location under a permanent ice cap, and during the AGAVE campaign, the Jaguar AUV was used in an attempt to map hydrothermal vents [86]. The survey was conducted at water depths of around 4000 meters, and strict demands were placed on navigational accuracy, and therefore, a long-baseline (LBL) acoustic system was used to aid the navigation system. The LBL transponders were placed by dropping them from the ship, or from the ice, and the locations were verified by hovering over the water with a helicopter and ranging the transponders. A second AUV was also deployed during the AGAVE project, namely the Puma AUV. This vehicle was used for plume tracking and other water-column surveys [107, 108].

Driven by a deadline to expand Canada’s border under the United Nations Convention on the Law of the Sea (UNCLOS) in 2013, the National Resources Canada launched an under-ice bathymetric survey mission near Borden island in the Arctic Ocean. The Explorer AUV was developed by ISE, which has had a proven track record of developing and using AUVs for under-ice operations. The experiences gained during the Theseus project [58, 59], both technological and operational, have greatly contributed to the success of the ISE Explorer mission. Details of the Arctic ISE Explorer and the results of this mission, conducted in April 2010, are presented by Crees et al. [36], Kaminski et al. [93], and Ferguson [60]. Charging and data download were performed while the vehicle was in the water, through a small hole in the ice. During the mission, 1000 km of sonar data under ice were captured without removing the vehicle from water, and depths of more than 3000 meters were achieved.

During the last decade, the interest for Arctic AUVs operations has increased and some recent operations include the use of a REMUS 100 AUV offshore Barrow in Alaska in March 2010 [105, 150], and an Iver2 AUV deployment in Ny-Ålesund at Svalbard to verify an ice detection algorithm [120]. Forrest et al. [65] present the use of the UBC-Gavia AUV for mapping of Petermann Ice Island fragments in the Canadian Arctic in 2011.

It is worth mentioning that the first under-ice AUV operation using commercial-of-the-shelf (COTS) equipment without alterations, was conducted in January 2017, using the Kongsberg Maritime MUNIN AUV [80]. The project used single-transponder navigation and was able to deliver sea-bed survey data according to the International Hydrography Organization standards with less than 2 meters uncertainty. The survey was conducted in a frozen lake in North America.

More recently, Hybrid ROVs have also become popular. These vehicles combine the advantages of AUVs and ROVs, and have the capability of standing still in the water column, which opens the possibility for close inspection and intervention tasks. McFarland et al. [123] present Arctic deployments using the Nereid Under Ice (NUI), a hybrid ROV with optional light tether, for studying ice-physics, marine biology, and Arctic navigation. A survey on underwater robotic vehicle design for under-ice operations is presented by Barker and Whitcomb [11], discussing the design of AUVs, ROVs, Gliders, as well as hybrid ROVs.

### 2.2.1 Arctic AUV operations with NTNU AUR-lab

NTNU AUR-lab has, in collaboration with the Arctic University of Norway (UiT) and the University Center at Svalbard (UNIS), been involved in multidisciplinary
Arctic research since 2010. The first Arctic AUV deployments involving AUR-lab were performed in collaboration with the University of Delaware, using their REMUS 100 AUV. The REMUS AUV was deployed under drifting sea-ice to examine under-ice phytoplankton bloom in the ice marginal zone north of Svalbard in May 2010 [89]. The same AUV was also used to investigate diel vertical migration (DVM) of zooplankton during the Arctic polar night in Ny-Ålesund at Svalbard in January 2011 [18].

In 2013, the NTNU AUR-lab acquired its first AUV, and has since conducted multiple Arctic AUV operations. Figure 2.2(b) shows all of NTNU AUR-lab Arctic AUV operations, and the author has been one of the leading field engineers on all cruises marked in red in this figure. The scientific objectives include investigation of DVM in the Arctic polar night, archaeological surveys, oceanographic research, as well as under-ice measurements. A significant amount of experience have been acquired, and selected field work results and experiences are presented in Chapter 3, while experiences related to Arctic marine research from the literature is presented in the following section.

2.3 Operational challenges for Arctic AUV research

Performing Arctic research with AUVs often involve deployments from an ice-station, or from ships in areas with drifting sea-ice. The following section presents some special considerations that must be taken when performing Arctic research with AUVs.

2.3.1 Deployment and recovery of vehicles

The remote location of operations in the Arctic makes resupply time-consuming and costly. Therefore, all necessary equipment, including spare parts, must be brought to the ice. Doble et al. [41], Ferguson [58], and Kaminski et al. [93] all discuss the challenges of logistics for operating an AUV from a remote location on the ice. Kukulya et al. [105] present an operation where the team had to break camp about an hour after deployment at a seemingly ideal ice floe, due to the ice breaking up. This illustrates the rapidly changing conditions in the Arctic. Due to the dark period in the Arctic, and the spring/summer melt which makes it dangerous to perform long operations on an ice floe, there may be a limited operational window when it is possible to fly out to a remote area. Another point worth considering is that the rapidly changing weather might preclude an attempt to evacuate due to ice melt or any other reason, so contingency plans must be in place.

When deploying an AUV from the ice, one needs access to the water. Using a small vehicle gives the possibility to deploy from the ice edge, but this is risky due to uncertain ice conditions at the ice edge. To reduce the risk, a hole in the ice must be made. Depending on the size of the vehicle and the thickness of the ice, this could be a complicated process. Figure 2.3 shows the deployment of the NTNU REMUS AUV before an under-ice mission in Svea at Svalbard in 2017 through a hole in the ice. Doble et al. [41], Ferguson [57], and Kaminski et al. [93] all use hot water drills for the cutting of ice, while Kukulya et al. [105] cut the ice by hand.
2.3. Operational challenges for Arctic AUV research

Figure 2.3: Deployment of the NTNU REMUS AUV in Svea, Svalbard.

(only 20 cm ice thickness). In addition to the cutting of the ice, the blocks need to be removed from the hole, requiring a crane or a snowmobile if the ice is thick. To reduce the logistical challenges involved in a complex operation on ice, Kaminski et al. [93] deploy their 7.4 meter long AUV from a main camp just outside Borden Island. At the remote camp, on an ice floe about 300 km from the main camp, they cut a small hole to allow charging and data download. The vehicle navigated from the main camp to the remote camp and was kept in the water for the whole mission, lasting for 12 days in total.

In an open water operation, an AUV would drive around in the surface, getting satellite position updates and attempting to dive. This may require a significant area of open water. When deploying the AUV from a hole in the ice, this is not an option. Different solutions have been proposed by Doble et al. [41], Kaminski et al. [93], Kukulya et al. [105], and Hegrenæs et al. [80]. The simplest method is to just pitch the vehicle such that the nose is pointing into the water, start the propeller and release the vehicle. This way, the vehicle will have enough thrust downwards to avoid hitting the ice if the ice is sufficiently thin. Another simple method is to push the vehicle down to a given depth, and start the mission. Note that these methods leave room for human error, and the margin for error may be small. If the vehicle hits the underside of the ice, the fins may not be able to produce enough moment to dive [80]. If the ice is too thick, or if it is suspected that a ridge with a deep keel is nearby, a more complex method can be used. A weight-release system (either automatic or manual) is a method that can be used for obtaining a desired depth before a mission is started. If the vehicle has a variable ballast system (as presented by Ferguson [57] and Kaminski et al. [93]) this would provide an easy way of implementing a variant of the automatic weight-release system.
Another difference between operations from the ice and in open water is the recovery of the vehicle. In open water, it generally does not matter if the vehicle has drifted a few meters from the actual surfacing position for recovery purposes. When deploying from a small hole in the ice, on the contrary, the vehicle must return to the exact same location. One attempted solution in the Arctic, is to use a net to capture the AUV \cite{41,105}. Another feasible solution is to recover the AUV by an ROV that attaches a tether to the AUV (after parking the AUV under the ice close to the recovery site). An ROV was used for recovery of the AUV in \cite{57} and for connecting power and data cables to the AUV in \cite{93}. A more complex method in this context is the AUV dock presented by King et al. \cite{99}.

For the operation of AUVs from a ship, it is important to remember that the weather can change rapidly in the Arctic. If an open-water area is ice-free when the AUV is deployed, this does not mean that it will stay ice free for the next few hours. If this is not taken into consideration, the AUV might try to surface but ends up stuck under some ice floe. A possible solution to this issue, as presented by Kunz et al. \cite{107}, is to let the AUV loiter at a specified depth, and not to surface before a command is given. This way, it is possible to either wait for the area to clear, or to somehow clear the area before the AUV surfaces.

For deployment and recovery of unmanned vehicles from a ship, cranes are mostly used. Bellingham et al. \cite{17} use a small boat in addition, for towing the AUV away from the ship and for recovery. The reason they towed it away was to give the vehicle some space for maneuvering and avoid crashing with the ship before it reached a safe depth. Dowdeswell et al. \cite{43}, on the other hand, use a sink weight-release system on the AUV to reach a desired starting depth. Such a system is beneficial when deploying the AUV close to the ice edge, or in an area with high concentrations of ice, due to the lack of space to maneuver at the surface. Bellingham et al. \cite{17} mention that operations including a small boat can be complicated by icing on the boat, and by very cold weather since the work will be conducted outdoors. It is also worth mentioning that working with a small boat requires the area to be relatively ice free, and that this is associated with a higher risk than work conducted from the deck of a ship. Other aspects related to recovery is, for instance, reported by Kunz et al. \cite{107} who use a helicopter for recovery of the AUV when the recovery location was far away.

### 2.3.2 Failure cases and fail-safe principles

It should be noted that operations of unmanned vehicles in the Arctic have a higher risk of failure than normal operations. The risk is also perceived as higher, as Ferguson \cite{58} experienced when trying to insure equipment used in the Arctic, after many years of successful operations in more traditional environments; the insurance company claimed that the Arctic is incomparable to open water operations and the rate for replacement of equipment used in an Arctic operation was 100%. The high risk comes partly from the fact that the usual fail-safe for underwater vehicles has been to float to the surface for recovery, but in the Arctic this could lead to the vehicle being stuck under the ice. Several teams have reduced the risk by attaching a tether to the AUV \cite{41,65}, as seen in Figure 2.1(b). Kukulya et al. \cite{105} report that the tether got cut by a propeller, and the AUV became stuck
2.4 AUV as an ice monitoring sensor platform

under the ice anyway. The stuck AUV was located by using an avalanche beacon which had been mounted inside the vehicle, and the AUV was eventually recovered. Instead of having a fail-safe of floating to the surface, some report that a better fail-safe is to park the vehicle on the bottom and wait for external commands [58]. Kaminski et al. [93] implement fault tolerant control, that would try to guide the vehicle back to a safe location. A risk analysis tool for AUV operations in extreme environments is presented by Brito et al. [26]. Applying the method to the probability of AutoSub-III's survival during both operations in sea-ice, as well as operations under ice shelves, showed significant reduced probability of survival when compared to open water and coastal AUV operations [26]. The risk was also shown to be even higher for operations under an ice shelf, than operations under sea-ice.

An additional challenge that arises when operating in arctic environments is low temperatures. This will cause a harsh working environment for the people involved in the operation, and the large temperature gradients during deployment might cause problems if the equipment is not properly stored. This is due to the fact that even if the air temperature in the Arctic may drop below -50 °C, the temperature in the water will be close to 0 °C. Ferguson [58] states that a potential outcome of too large temperature gradients can be cracked seals and consequent leakages in the vehicle. Kaminski et al. [93] report a broken CTD sensor due to a fresh water rinse that froze inside the instrument. Another potential consequence of the cold temperature is ice formation on the vehicle. Bellingham et al. [17] state that the AUV was unable to obtain GPS fixes, possibly due to thin ice layers on the antenna. Additionally, the autonomous nature of the AUV require that the vehicle use a portable power source. Conventional lithium-ion batteries, which are often used in these kind of vehicles, will have a significant capacity reduction at low temperatures [4], especially noticeable for temperatures below -20 °C. Moreover, storing the battery at low temperatures, could result in damage or permanent performance degradation of the battery.

Another aspect which could cause huge problems for AUVs in the Arctic, is the large water-density gradients that can arise from the melt of glacier ice. Dowdeswell et al. [43] report a density difference of 4 kg/m³ between the surface and 6 meters depth, which for their vehicle resulted in a 10 kg increase in buoyancy. The consequence of these layers could either be an unstable depth controller, or that a vehicle could get stuck in a water layer – unable to surface.

Despite the relatively high risk associated with operating unmanned vehicles in arctic environments, not many vehicles have been reported lost. The Autosub-II vehicle was, however, lost during a mission beneath the Fimbul Ice Shelf in Antarctica in 2005 [43]. After a thorough investigation, Strutt [162] concluded that the most likely reason for the loss of the AUV was either due to loss of power (as a result of open circuit hardware failure) or due to an abort command (resulting from a network failure).

2.4 AUV as an ice monitoring sensor platform

As offshore activities move into Arctic waters, where sea-ice and icebergs may threaten installations and structures, IM becomes an important part of the offshore
2. AUVs for Arctic marine operations

An essential part of an IM system is the detection, tracking, and drift forecasting of ice features [46]. Eik and Løset [47] discuss an ice observation system. They motivate the use of untethered UUVs for tracking of icebergs detected by stationary platforms and for continuous monitoring of an area upstream a protected installation or vessel. AUVs are often highly modular, and thus, the sensor suite can be configured to the desired application. Depending on configuration, AUVs can reach water depths of several thousand meters, and the endurance varies from hours to a few days. Synthetic aperture radar (SAR) satellites can estimate sea-ice thickness from measurements of the ice freeboard\(^1\), and by using estimates of the sea-ice density [110]. Uncertainties like snow loading, and uncertain ice density, will contaminate the ice thickness estimates. Also, the estimate will only provide an average sea-ice thickness, thus, erasing features like ridge keels. Similarly, marine radars have problems with detecting ice features accurately in large sea states [143]. Large sea states are not a problem when operating around a continuous ice cover, but the retreat of sea-ice also affect the wave heights. Thomson and Rogers [166] report that the increased open water area in the Beaufort sea during the summer of 2012 allowed waves to evolve into swells, and that these results suggest that larger waves in the Arctic are to be expected in the future.

Sea-ice features are much more dominant on the underside of the ice, than above. For example, the ridge keel depth to sail height ratio is reported to have a mean value of 4.4 [169]. This motivates the use of an underwater sensor platform for monitoring of sea-ice, and AUVs have a large spatial and temporal scale, while still maintaining a high spatial and temporal resolution compared to other platforms as can be seen from Figure 2.4. A further motivation for the use of AUVs are provided by Table 2.1, indicating different sensor platform’s ice monitoring capabilities regarding operational conditions and ability to detect different ice features. As seen from Table 2.1(a), the only ambient condition causing problems for AUVs is large currents. For operations taking place far from land, the currents are not expected to often exceed the design limit of AUVs, which is typically around 1 m/s. Table 2.1(b) shows that AUVs are capable of detecting all ice features, except the sail of ridges and icebergs. Therefore, an ice monitoring system should consist of multiple sensor platforms, which will provide complementary properties and redundancy. For example, the use of AUVs, UAVs, and satellites would provide a system with both good spatial coverage and resolution, and the system would be able to detect and map all ice features in all ambient conditions, with some redundancy.

This section will detail the capabilities of AUVs with respect to ice-monitoring, and present challenges and technological barriers that must be managed before AUVs can be used for this purpose.

2.4.1 Sensor capabilities for ice-monitoring

Due to high attenuation of shortwave electromagnetic (EM) radiation in water, acoustics are widely used in different sensor technology in underwater vehicles, both for data collection (e.g., sonars), and for navigation and communication. An acoustic wave is a pressure wave that propagate through a medium. It is charac-

\(^1\)Surface elevation of the sea-ice above the water surface.
2.4. AUV as an ice monitoring sensor platform

Table 2.1: Sensor platform capabilities for ice monitoring.

(a) Sensor platform ability to operate in different ambient conditions

<table>
<thead>
<tr>
<th>Ambient conditions</th>
<th>VNIR sat.</th>
<th>Microwave sat.</th>
<th>UAV</th>
<th>Shipboard</th>
<th>Buoy</th>
<th>ROV</th>
<th>AUV</th>
</tr>
</thead>
<tbody>
<tr>
<td>High winds</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High waves</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High currents</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Precipitation</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fog</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Polar lows</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Low ice concentrations</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>High ice concentrations</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

(b) Sensor platform ability to detect different ice features

<table>
<thead>
<tr>
<th>Ice feature</th>
<th>Satellites</th>
<th>UAV</th>
<th>Shipboard</th>
<th>Buoy</th>
<th>ROV</th>
<th>AUV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iceberg detection</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Iceberg size</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Iceberg sail topography</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Iceberg keel topography</td>
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<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Iceberg drift</td>
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<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Sea-ice thickness</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Sea-ice drift</td>
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<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Floe size/distribution</td>
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<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ridge detection</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ridge sail topography</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Ridge keel topography</td>
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<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
2. AUVs for Arctic marine operations

Figure 2.4: Spatial and temporal coverage and resolution of different sensor platforms. Image courtesy of Nilssen et al. [134]. Left/lower part of a box illustrate resolution, while the right/upper part of a box show the coverage.

The SSS is characterized by its intensity, its frequency, and the length of the pulse [21, Chapter 1]. In the following, several acoustic sensors relevant for ice-monitoring will be presented. Figure 2.5 illustrates an AUV with MBE, SSS, and acoustic Doppler current profiler (ADCP)/Doppler velocity log (DVL).

**Sidescan sonar**

The SSS is mounted on the sides of the AUV, and transmits one fan-shaped acoustic beam to each side of the vehicle, see illustration in Figure 2.5. To cover as large range as possible, the beams are wide across-track the vehicle path, and narrow along-track. Most of the acoustic wave transmitted from the sonar (at an elevation angle) will be reflected off the sea bottom, at the same angle as the incoming wave (the reflection angle), and only a fraction of the wave will propagate back to the sonar [21, Chapter 1]. The amplitude of the backscattered sound received by the SSS are used to create an acoustic image of the environment, where objects that reflect differently than the sea bottom can be identified. SSS, on the contrary to multibeam sonars, have only one receiver per transducer.

The first SSS images of the underside of the ice was captured from the British nuclear submarine HMS Sovereign beneath the Arctic ocean in October 1976 [171].
Sear and Wadhams [158] present an analysis of sidescan sonar imagery from 140 km of under ice transit, collected with another British submarine in 1987. From the SSS imagery, ridges and multi-year ice was classified, but the authors state that first-year ice was hard to classify, and several ridges were not identified.

The first SSS imagery from the underside of the ice collected with an AUV was presented by Wadhams et al. [173]. From this data, the authors are able to calculate the ice draft directly above the two transducers, and to identify smooth surfaced first-year ice, as well as multi-year ice with depressions and bulges. In addition, brash and frazil ice, and open water were classified from the imagery.

Forrest et al. [65] present the use of the UBC-Gavia AUV to map fragments of the Petermann Ice Island (PII) in the Canadian High Arctic. An interferometric sidescan sonar was used for collecting a terrain map of the underside of the PII-B fragment using the AUV, and the side of the PII-B, PII-Ba and Berghaus fragments were mapped using a ship-mounted multibeam echosounder. By combining the multibeam measurements and the sidescan measurements, a digital 3D model of a part of the PII-B fragment was constructed.

**Multibeam echosounder**

MBEs have generally been used for creating bathymetric maps of the sea floor. Echosounders operate by transmitting an acoustic pulse and listening for the received echo. By measuring the time from the ping was transmitted to the echo was received, the range to the sea floor (or other targets) can be estimated. A multibeam sonar consist of groups of projector arrays and hydrophone arrays [109]. A projector array is isotropic sources\(^2\) placed in such a manner that the beams that are formed are narrow and directed, rather than an isotropic expansion of the pressure wave [109]. Hydrophone arrays are used to receive sound waves, and one hydrophone array is only sensitive to soundwaves originating from a specific direction. This process, producing narrow transmit and receive beams, is called beam forming [109]. Since the narrow beams only ensonifies a small area, many beams can be used to create a high resolution 3D map of the target being mapped, see Figure 2.5 for an illustration.

Multibeam surveys under ice are presented by Jakuba et al. [86], Kaminski et al. [93] and Hegrenæs et al. [80]. All the aforementioned surveys are conventional bathymetric surveys using AUVs equipped with MBE, but with the added complexities of under-ice AUV operations. Williams et al. [179] show detailed under-ice topography of drifting sea-ice collected by an AUV with an upwards-looking MBE, which also includes additional complexities due to the moving terrain that is mapped. Kim et al. [94] also discuss an AUV used for mapping of the under-ice topography of sea-ice and icebergs.

Sonar-based iceberg-relative AUV navigation by using MBE measurements are discussed by Kimball and Rock [95, 96, 97, 98] and Hammond and Rock [76, 77], where the authors present methods using a sidemounted MBE to map drifting and rotating icebergs.

\(^2\)Isotropic sources create pressure waves with isotropic expansion, which is the circular pattern created by e.g. throwing a stone into water.
2. AUVs for Arctic marine operations

![Figure 2.5: An AUV using MBE, SSS, and ADCP. MBE: blue beams, SSS: Green waves, and ADCP: yellow beams. Image courtesy of Fugro © 2018.](image)

**Acoustic Doppler current profiler**

An ADCP is an acoustic instrument that transmits sound at a fixed frequency, and uses the Doppler shift in the received backscatter to estimate relative velocity between the instrument and the scatterers [164]. By assuming that the scatterers in the water column (typically Euphasiid, Pteropod, and Copepod) float in the ocean with the same average speed as the current, ADCPs can be used for estimating the ocean current [164]. Bottom-tracking is an application of DVL\(^3\) that is used for navigation, since it measures the relative velocity between the instrument and the sea floor. Only radial motion causes Doppler shift, that is changes in distance between instrument and scatterers [164]. This means that only translational velocity can be measured from ADCPs, not angular velocities.

For ice-monitoring applications, an ADCP can be used for measurements of ice-instrument relative velocity [122]. With knowledge of the vehicle velocity, the absolute velocity of the ice can be estimated, but due to limited range of ADCPs and the deep waters common in the Arctic, bottom-tracking capability when performing ice-monitoring with AUVs can not be assumed. Ice-relative navigation with AUVs is discussed by e.g., McEwen et al. [122] and Forrest et al. [64].

### 2.4.2 Communication

As stated by Eik and Løset [47], an important part of an ice intelligence system is the ability to transfer a sufficient amount of data from the sensors, to a central ice

---

\(^3\)An ADCP can be employed as a DVL.
management team, typically onboard the drilling vessel, or an icebreaker. Communication from an AUV is usually performed by means of acoustics, and the Arctic causes an especially challenging acoustic environment due to multipath formation by the sound waves’ repeated interactions with the ice cover [144]. In addition to these challenges, the available bandwidth in underwater acoustic communication is limited by transmission losses, and these losses increase with both increased frequency and increased range [160].

At lower frequencies, the ice cover in the Arctic will have less effect on the acoustic waves, but at very low frequencies, the sound is not trapped effectively in the ocean and interactions with the sea bottom can cause high losses [144]. Freitag et al. [68] report tests of under ice communications, and of the four tested frequencies (12, 24, 48 and 96 Hz), the 12 Hz bandwidth was the most reliable, with the highest signal-to-noise ratio (SNR) over the whole range (20 - 75 km). Johnson et al. [90] present testing of an acoustic communications network of six nodes, and communication with the Odyssey AUV moving through the network. The network was deployed over an area of 15 square km in an ice covered lake, and over an area of 22 square km in the Beaufort Sea, and communicated with a host PC over radio Ethernet. During the tests, a frequency of 15 kHz was used, and a data rate of 5 kilobits per second (kbits/s) was typical. The network proved reliable in the lake, but too much ambient noise caused connectivity issues in the Arctic. The 15 kHz frequency used by Johnson et al. [90] allow a higher communication rate than the low frequencies reported by Freitag et al. [68], but reduces the range (tested range was 75 km in [68] versus 1.8 km in [90]). During a US Navy Exercise in the Beaufort Sea in March 2016, an AUV with a towed hydrophone array was deployed below the ice cover [157]. A phenomenon called the Beaufort Lens was observed, which is when a layer of warm Pacific water enters the Arctic through the Bering Strait. The effect of the Beaufort Lens was shown to drastically deteriorate both long and short range acoustic communication and navigation. Schmidt and Schneider [157] state that the only viable option for maintaining communication with the AUV is to have the platform adapt its depth depending on the environmental conditions and the current acoustic configuration. To achieve this, an acoustic model must be run online on the AUV.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Data update rate</th>
<th>Channel baud rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellites</td>
<td>Daily/hourly</td>
<td>Medium</td>
</tr>
<tr>
<td>UAVs</td>
<td>Real-time</td>
<td>High</td>
</tr>
<tr>
<td>Shipboard</td>
<td>Real-time</td>
<td>Very high</td>
</tr>
<tr>
<td>Buoys</td>
<td>Hourly/online</td>
<td>Low</td>
</tr>
<tr>
<td>ROV</td>
<td>Real-time</td>
<td>Very high</td>
</tr>
<tr>
<td>AUV</td>
<td>Online</td>
<td>Low</td>
</tr>
</tbody>
</table>
Communication requirements for online monitoring applications

A possible acoustic communication system for continuous ice-monitoring, using AUVs, includes the deployment of an acoustic network at the area where the ice is being monitored. As IM operations will seldom be conducted without surface vessel assistance (e.g., icebreakers), these can be used as communication relays – transmitting data over radio frequency to a centralized IM decision center. An example of an under-ice acoustic communication network for AUVs can be seen in Figure 2.6. A comparison of communication capabilities of different sensor platforms is given in Table 2.2.

The limited bandwidth of the acoustic communication network requires the AUVs to autonomously decide what data to transmit. For example, the Imagenex DeltaT MBE, operating at a frequency of 260 kHz with 480 beams, will acquire 5 megabytes (MB) of data per minute (or approximately 680 kbits/s) [85]. In addition to the MBE data, other data acquired by the AUV will also be relevant for IM decisions support (e.g., ADCP data for ice drift and current estimates, and navigation data from the AUV). This results in a considerable amount of data if a typical data transfer rate of 5 kbits/s is assumed (reported by Johnson et al. [90]).

Due to the large amount of data relevant for IM decision support, alternative ways of representing data, to reduce the amount of data to be transferred, are attractive. An example highly relevant to ice-monitoring in this context, is the ice
2.4. AUV as an ice monitoring sensor platform

2.4.3 Navigation

Two types of navigational systems are common in an AUV. Inertial navigation systems (INS) relying solely on internal vehicle sensors, and acoustic systems which use external infrastructure.

Acoustic navigation

Since EM waves do not propagate far under water, it is impossible to use global navigation satellite systems (GNSS) for underwater vehicles, except at the surface. As with communication, acoustics are often used for navigation of AUVs. Two acoustic systems that are widely used for navigation of underwater vehicles are LBL and ultra-short baseline (USBL) [101].

With LBL, a transducer placed on the vehicle communicates with at least three transponders to obtain an unique north-east position through trilateration\(^4\), or with at least four transponders (at least one in a different plane than the others) for an unique north-east-down position trough quadlateration\(^4\). Note that quadlateration is seldom used for underwater vehicles, since the pressure sensor usually provide

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\(^4\)Lateration – Position determination through distance measurements.
a more reliable depth measurement. Only two transponders are usually used for lateration, but since this gives two possible solutions for the horizontal position, the vehicle must be able to determine the correct solution. Figure 2.7 shows an example of the REMUS AUV navigation aids, which uses two LBL transponders. A 12 kHz LBL system can operate at a maximum range of 5-10 km, with a range precision of 0.1 - 10 m, and an update rate of 0.1 - 1 Hz [101]. Higher frequency of the acoustic signal will give higher precision and higher update rate, but the range is reduced. Accurate single transponder navigation has also been demonstrated for under-ice AUV operations by Hegrenæs et al. [80].

USBL, on the other hand, measures range and bearing between a transducer and a transponder (e.g., placed on a ships hull, or on a sub-sea station). In under-ice applications, USBL can be used to give the underwater vehicle homing capability, so it can return to for example a hole in the ice. Bellingham et al. [14] report an example of this application, where the vehicle typically returned to within 30 cm of the homing transponder. Note that both LBL and USBL navigation systems only provide a relative navigation reference. For absolute positioning, the total navigation error is limited to the precision of the placement of the transponders, often recorded with GNSS. To achieve improved accuracy of transponder placement, real-time kinematics (RTK) GNSS can be used. To utilize RTK GNSS, the transponders would have to be mounted on rigid poles with integrated IMU, since tether movement will contribute to the error way more than the RTK GNSS error. For more details on underwater acoustic positioning systems, the reader is referred to Milne [126].

**Inertial navigation**

Inertial navigation systems rely on measurements from inertial measurement units (IMU), that is, gyroscopes and accelerometers, to provide a continuous estimate of position, attitude, and linear and angular velocities. A good reference on INS is provided by Britting [27]. The heading of the vehicle is determined either by a magnetic compass, or by using measurements from gyroscopes in the IMU (and gyrocompassing if the gyroscopes are accurate enough). At Arctic latitudes, the magnetic compass will become unreliable due to the near vertical magnetic field [122]. North-seeking gyrocompasses utilize the rotation of the earth and the earth’s gravitational field [101], and at Arctic latitudes the horizontal component of the earth’s rotation will become too small. The uncertainty of gyrocompasses can be shown to be proportional to $1/\cos(\text{latitude})$, with the accuracy of a typical marine gyrocompass in the order of $0.1^\circ/\cos(\text{latitude})$ [70]. Therefore, neither magnetic compasses, nor gyrocompasses are suitable for Arctic navigation alone [122]. McEwen et al. [122] chose an integrated gyro-based INS/DVL/GPS solution as the primary navigation sensor, and used setpoint navigation (using the heading estimate-setpoint error directly to guide the vehicle) as opposed to waypoint navigation to avoid the large error growth in an INS that calculates position estimates.

An INS is often coupled with position estimates from GNSS, acoustic positioning systems, and with velocity measurements from a DVL. Figure 2.7 illustrates an AUV that utilizes GPS when it is in the surface, ADCP/DVL when in range of the sea-bottom, an acoustic positioning system when within range, and possibly
2.4. AUV as an ice monitoring sensor platform

Inertial navigation when no other position references are available. INS aided by velocity measurements can obtain very low navigation errors over relatively long duration [101]. For underwater vehicles, position updates from GNSS only occur at the surface, and the rate of acoustic position systems can be low, making inertial navigation an important part of an underwater vehicle’s navigation suite.

According to Jalving et al. [87], the main contributors to position drift in a DVL aided INS is error in the body-fixed velocity, and error in heading. The velocity errors are mainly determined by the accuracy of the DVL itself (0.2% of distance traveled (DT) for a 1200 kHz DVL according to Jalving et al. [87]). Heading error will be a function of gyro drift (in the range 0.005-1°/h for AUV navigation systems), and for a gyrocompass the heading error will also be a function of latitude. For example, for a gyrocompass with a drift of about 0.005°/h, the across-track error will be about 0.05% at 45° latitude, and 0.2% DT at 80° latitude [87]. Gade [70] also states that uncertainty of the vehicle velocity will reduce the heading accuracy. Therefore, in long missions, or missions without accurate velocity measurements, some sort of position measurements should be made, to correct the unbounded error that is an inherent problem of pure inertial navigation.

2.4.4 Technology demands for continuous ice-monitoring applications

For extended underwater operations, like a continuous monitoring application, several factors may limit the duration of the operation. Most AUVs depend on battery power, and have limited endurance before charging is required. As discussed in Section 2.4.3, underwater navigation is a challenge, and some sort of means for eliminating the unbounded error of inertial navigation must be present for extended AUV operations. Furthermore, it may be undesirable to have a human operator controlling high-level decisions, like where to monitor, or when to return for charging – introducing a higher demand for autonomy. The technological challenges related to continuous underwater monitoring application will be discussed subsequently.

Docking stations

An ice-mounted system for underwater charging and data downloading is presented by King et al. [99]. This docking system was designed for the Explorer AUV, to limit the logistical demands (e.g., drilling of larger hole in the ice, and cranes for lifting) of deployment and recovery of the AUV from the ice. The docking station had the ability to rotate the AUV while held, for INS calibration purposes and for aligning the AUV with the current while docked. Capture of the vehicle was performed by the means of a small size ROV, which attached a tether to the AUV. A refined version of the docking system was demonstrated successfully in the Arctic by Kaminski et al. [93].

As offshore exploration will be performed in a given area for an extended period of time, deploying sub-sea infrastructure may be justified economically. Hobson et al. [81] provide a short summary of previous work on docking stations for AUVs, and discusses the development and testing of a sub-sea docking station, which may
be more relevant for ice-monitoring. The docking station provides inductive power transfer, and wireless data transfer – limiting the need for maintenance demanding moving parts. A USBL homing system provides a navigation reference for the navigation system, and capture and release can be performed autonomously.

Navigation networks

In addition to docking stations, a network of sub-sea acoustic navigation sensors, placed at known positions, is essential for navigating over a long period of time in deep water. With a network of sensors, redundancy can be used to provide enhanced accuracy, to detect and reject erroneous measurements, or to increase reliability of the network in case of malfunctions. For the 2D case, where depth is measured from a pressure sensor, at least four transponders are necessary for redundancy checks [126]. A problem with acoustic networks emerges when multiple AUVs are utilized in the same area, since regular acoustic networks send one interrogation-response cycle per vehicle, and the time delays will grow with the number of vehicles in the network. Eustice et al. [52] present a solution using one-way travel time pseudo ranges to overcome this problem, and attempt to scale the navigation network to accommodate multiple vehicles.

As an alternative to sub-sea infrastructure for acoustic navigation, Santos et al. [156] present a solution for relative navigation using moving transponders, placed on surface vessels. In this scheme, the AUV does not know its global position, but moves in a pattern relative to the moving transponders. By re-organizing the transponder locations, external control of the AUV trajectory can be achieved. Another solution that limits the need for sub-sea infrastructure, is a communication and navigation network where AUVs are utilized as mobile sensor nodes, see e.g., Rice [152].

Autonomy

In the majority of the reported AUV missions up to today, the AUV operate with a pre-programmed mission plan, defining the entire mission. Figure 2.8 shows a control system architecture for UUVs illustrating layers of autonomy as presented by Ludvigsen and Sørensen [115], which discusses autonomy aspects for mapping and monitoring aspects on the sea-bed and in the ocean. Hagen et al. [75] define two conceptual classes of decision autonomy: the ability to handle malfunctions, and the ability to react to external events. The former class of autonomy is a key component for operations in extreme environments, like the Arctic (see e.g., Ferguson [57] and Kunz et al. [108]), while the latter is important for optimizing resource usage. Examples of applications of AUVs basing decisions on sensor readings are given by Cruz and Matos [37] and Wiig et al. [177].

For ice-monitoring applications, autonomy will be vital due to communication constraints and reliability requirements. The AUV must detect, classify, and track identified ice features, based on measurements, and autonomously decide what information to relay to the IM decision center. The AUV must also handle malfunctions in an appropriate, fail-safe manner, without intervention from an operator.
2.5 Guidance and navigation system for Arctic AUVs

Motivated by the challenges presented up to this point, a conceptual guidance and navigation system for Arctic AUVs will be proposed. A block diagram is shown in Figure 2.9, showing the main elements. The figure is indented as an illustration of a guidance and navigation concept, rather than a detailed schematic.

2.5.1 Relative navigation

The navigation filter block of Figure 2.9 contains both the global position and a local position (and estimates of the transition between these frames). The idea is that due to the nature of the ice, which is drifting and rotating, it makes sense to keep track of both a relative state and a global state, possibly also with corresponding uncertainty estimates. This can be useful when an acoustic navigation system is drifting with the ice and provides relative position updates, but not necessarily global fixes. The proposed structure can also utilize the fact that the AUV may have measurements of the relative velocity between the vehicle and the ice, but not necessarily earth relative velocity.

Keeping a local frame that is fixed to the moving ice will also ease the assignment of measurements from upwards-looking MBE and helps construct a consistent map, unaffected by the moving ice. Relative navigation and SLAM for iceberg...
2. AUVs for Arctic marine operations

Figure 2.9: Overview of a conceptual Arctic AUV guidance and navigation system.

mapping is presented in Chapter 6.

2.5.2 Guidance system

The guidance system group in Figure 2.9 shows four different blocks. The global guidance block may be a standard waypoint-based method, or a more sophisticated method, but it steers the vehicle based on its global position and corresponding uncertainty. The local guidance scheme performs guidance in the local frame, which may be translating and rotating relative to the global frame, using the local position estimate. As for the global guidance scheme, the implementation may be waypoint guidance (using local waypoint coordinates), as well as more complex schemes.

The obstacle avoidance block should utilize for example a forward-looking sonar (FLS) to avoid the sea-bottom and any features on the sea-bed, and in addition, detect ice features like pressure ridges and icebergs to avoid collisions. The obstacle avoidance method should also keep track of the clearance between the sea-ice and

34
the sea-bed, to avoid a situation where the vehicle is stuck. Collision avoidance and clearance between sea-ice and sea-floor are also discussed by Jalving et al. [88].

The sensor-based guidance block refers to the use of payload sensor data directly to guide the vehicle. Note that the measurements may require corrections using navigation sensors (e.g., IMU and depth sensor), but the position estimates of the vehicle are not used. A method using MBE measurements to guide an AUV around a drifting and rotating iceberg is presented in Chapter 5.

### 2.5.3 External support platforms

External support systems are often necessary in AUV operations due to two main reasons: communication and navigation. Networks of communication and navigation systems were discussed in the previous section, and an envisioned under-ice communication system for AUVs is presented in Figure 2.6. This system uses both drifting and anchored buoys, and may or may not provide navigation updates along with data.

The standard method of providing AUV support in geological surveys has been to use a support ship with USBL. A more cost efficient method is to use USVs that can autonomously track and provide navigation fixes to the AUV. Reduced range in an acoustic communication channel allows higher speed, and USVs can therefore also be used as data mules that collect payload data from AUVs and relays the data to an operator center. Using USVs for AUV support is even more interesting in the Arctic, due to associated risks of getting close to icebergs and glaciers because of ice calving. Field work demonstrating USVs for tracking and monitoring of AUVs, as well as for establishing a communication network with multiple vehicles, are presented in Chapter 3. It should be noted that the use of small and medium sized USVs must be limited to open water Arctic operations.

### 2.6 Summary

As ice features are more dominant on the underside of the ice, IM systems will need subsurface ice-information to gain an accurate picture of the ice loads in an area. AUVs have the ability to monitor the subsurface ice features, and can cover relatively large spatial and temporal scales, regardless of weather conditions – making AUVs a suitable platform for ice-monitoring. Communication rate constraints and endurance limitations, make continuous monitoring a challenge. Due to these challenges, sub-sea infrastructure (docking stations, acoustic communication and navigation networks) are recommended if AUVs are employed for ice-monitoring applications. Increased autonomy will also be a criterion for ice-monitoring using AUVs – the AUV must be able to detect, track, and report relevant ice features automatically and reliably. In addition, autonomous supervisory systems, and decision support systems are necessary when applying AUVs for ice-monitoring.

It is further believed that a custom guidance and navigation system for Arctic AUV operations would be beneficial, to take the drifting ice features into account. Proposals for the building blocks of this guidance and navigation system are presented in the following chapters.
Finally, it is worth remembering that an AUV which fails during a mission in open water has a very good chance of failing during the same mission under ice. It is imperative that time be allocated to run the planned Arctic mission in open water, and to repeat it as often as is necessary to gain confidence that the Arctic operation will be a success.

James Ferguson
Chapter 3

Field work and AUR-lab cruises

This chapter presents field work and results from cruises conducted with the NTNU Applied Underwater Robotics laboratory. Two operations with the NTNU REMUS AUV in the Arctic are presented, highlighting both under-ice deployments as well as open water operations. In addition, field work from two projects aiming at using USVs as an AUV support tool are reported. Parts of the work presented in this chapter, have been shown in [35, 117, 135, 141].

3.1 Introduction

The Applied Underwater Robotics laboratory is a infrastructure laboratory, and is run by the Department of Marine Technology on behalf of several departments at NTNU. The main responsibilities are developing and maintaining the underwater robotics platforms at NTNU, and to provide operational expertise in research activities. Relevant AUR-lab vehicles for the work presented in this thesis can be found in Appendix A. AUR-lab is involved in a variety of interdisciplinary research, ranging from marine biology and archeology, to marine cybernetics.

Performing field work is a crucial part of marine research. It is important for testing of developed technology and methods, but also to build knowledge and learn from accumulated experience in marine operations. In the following section, some of the field work that have contributed to the knowledge contained in this thesis is presented. The author has served as one of the leading field engineers in all mentioned cruises as a part of teaching and laboratory assistant duties at NTNU.

3.2 The REMUS AUV in the Arctic polar night

In the 9 day period between January 16th and January 24th in 2014, a field campaign was conducted at the research settlement in Ny-Ålesund at Svalbard in Norway. The field campaign was a part of a course at UNIS, called “Underwater robotics in the Arctic polar night”. A REMUS AUV was used throughout the
3. Field work and AUR-lab cruises

campaign, for seafloor mapping and mapping of spatial and temporal distribution of oceanographic variables. In addition to AUV data, several other platforms were used to investigate the Arctic polar night, including ROVs, stationary subsea camera platforms, and CTD point measurements. One research question that was studied was if the ambient light levels in the Arctic polar night is sufficient to influence the vertical migration of zooplankton, as presented by Cohen et al. [35].

Figure 3.1 illustrates the planned paths for the AUV missions conducted in Ny-Ålesund. The blue line in Figure 3.1 shows a mission that was repeated four times with the objective of mapping spatial and temporal variability of zooplankton in the water column, and the pink line shows a mission crossing the Kings Bay outside Ny-Ålesund to gather measurements of oceanographic parameters across the fjord. Due to deep water, the missions were run without bottom-tracking, i.e., without AUV velocity measurements from the DVL. Running without bottom-tracking for extended periods of time caused the INS uncertainty to grow too large, and

Figure 3.1: Planned AUV surveys for the Arctic polar night campaign. **Blue line**: Zooplankton survey (transect A-B). **Pink line**: Cross-fjord survey (WP 1-6).
3.2. The REMUS AUV in the Arctic polar night

the AUV reverted to using the onboard magnetic compass and propeller RPM for dead-reckoning. In addition, the acoustic LBL positioning system was used when available. A position drift due to uncertainties in the magnetic compass was expected when the AUV was outside the range of the LBL network (the estimated LBL coverage area is illustrated by the green box in Figure 3.1). Therefore, surface and GPS-fix objectives were added at intervals to correct accumulated errors. The depth controller reference for the cross-fjord mission was an undulating pattern with a depth rate setpoint of 15 meters/min, varying between a minimum depth of 5 meters and a maximum depth of 80 meters. The depth controller for the zooplankton survey was a periodic pattern, where the transect A – B (see Figure 3.1) was transited using undulating depth controller (with slightly different settings between missions, but similar to the controller used for the cross-fjord survey), and
3. Field work and AUR-lab cruises

Table 3.1: REMUS in Ny-Ålesund mission statistics. Mission duration, distance travelled, and percentage good LBL fixes reported by the REMUS VIP. Standard deviations calculated by the NavLab software [69]. INS data were not available for the cross-fjord survey mission (mission conducted on 2014-01-24).

<table>
<thead>
<tr>
<th>Mission start [date/time UTC]</th>
<th>Duration [h:mm:ss]</th>
<th>Distance traveled [m]</th>
<th>Accepted LBL fixes [%]</th>
<th>Measured position STD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x [m]</td>
</tr>
<tr>
<td>2014-01-21 10:02:31</td>
<td>2:53:24</td>
<td>13964</td>
<td>37.73</td>
<td>1.3078</td>
</tr>
<tr>
<td>2014-01-21 20:59:10</td>
<td>3:18:45</td>
<td>17828</td>
<td>47.88</td>
<td>1.0636</td>
</tr>
<tr>
<td>2014-01-23 09:53:45</td>
<td>4:55:56</td>
<td>27426</td>
<td>45.72</td>
<td>1.9790</td>
</tr>
<tr>
<td>2014-01-24 09:37:39</td>
<td>2:49:38</td>
<td>15504</td>
<td>7.96</td>
<td>N/A</td>
</tr>
</tbody>
</table>

then the transect was run three times at constant depth, where the depth set-points was 15, 35, and 75 meters, respectively. The pattern was repeated a number of times (different for each mission). A summary of the conducted surveys can be found in Table 3.1. In the mission conducted on the 23rd of January, the transect was transited solely with the undulating pattern, and the mission performed on 24th of January was the cross-fjord survey.

Figure 3.2 shows a plot of the calculated AUV trajectory for the cross-fjord survey mission, as well as good and bad LBL position fixes. The corrected trajectory was estimated with Hydroid’s REMUS Vehicle Interface Program (VIP) software. The first run across the fjord was performed successfully. But due to a limited amount of good LBL fixes, the AUV drifted a significant distance from the intended survey line, even inside the area with LBL coverage. Outside the LBL network coverage area, the cross-track error at surfacing on the first dead-reckoning transect (between WP3 and WP4) was about 250 meters, which was more than anticipated (more than 20% of the distance travelled). The return transect was transited with significantly less cross-track error, and good LBL fixes were obtained within the coverage area. A GPS fix was acquired after the AUV surfaced at WP2, and the AUV transited to WP1 before heading north again. The AUV drifted to the west, and attempted to correct its course after a few good LBL fixes. An incorrect heading estimate caused the AUV to continue on a wrong course, heading east. During the off-course track, multiple LBL fixes were received along the track. However, all the LBL fixes were rejected by the navigation system. After a surface objective and a position error of approximately 1400 meters, the AUV corrected its course again. The compass bias terms were altered, but they were still not correct. The AUV was recovered after automatically aborting its mission on the other side of the fjord, since it was unable to reach its intended destination.

An investigation of the fault log exported from the vehicle, revealed 32 warnings related to large compass bias, where the bias changed between 18.6 and -55.3 degrees. The compass bias error turned out to be calculated by the REMUS navigation system based on bad LBL measurements, which caused the vehicle to diverge from its intended path. The bias problem alone did not cause the navigation system to fail, but in conjunction with the poor LBL system performance, it had dire con-
3.2. The REMUS AUV in the Arctic polar night

Figure 3.3: ADCP data collected by REMUS to assess zooplankton DVM.

sequences. As seen from Table 3.1, only 7.96% of the LBL fixes were accepted by the navigation system. The reason for the bad LBL network performance remains unknown. CTD measurements showed a quite homogeneous water mass, so effects caused by temperature and salinity layers (like the Beaufort Lens [157]) are not likely to be the cause. As the AUV was recovered, several large pieces of floating ice was observed in the fjord. It was not considered likely that an ice floe with a large enough draft had shadowed the transponders. However, the ice pieces could cause a challenging acoustic environment due to reflections from the ice.

3.2.1 Mapping of zooplankton DVM using AUVs

The light regime is an ecologically important factor in pelagic habitats, influencing a range of biological processes. Above the polar circle, the period when the sun is below the horizon for a 24-hour period or more is called the polar night. The duration of the polar night and the corresponding irradiance in this period increase with latitude from south to north [91]. Due to the sun’s angle below the horizon, moonlight, and aurora, the polar night is not a homogeneous dark period [19]. At 78°N 55' in Kongsfjorden, Svalbard, the polar night lasts for 129 days each year, thus playing a significant role in the area’s light regime. Although this period was once thought to be void of biological activity, recent research (see [19] for a review) challenges this assumption by presenting evidence of DVM throughout the polar night. However, despite evidence that DVM is usually considered to be tuned to an exogenous light cue [12, 34], there is no direct evidence that marine zooplankton would be sensitive enough to supposed extreme low light levels that characterize the high Arctic polar night.

To assess if ambient light is sufficient to act as a visual cue for zooplankton
DVM, a range of sensors were used to collect data in the polar night, including an AUV, a light sensor, and an all-sky camera. In addition, zooplankton samples were collected using plankton nets. Figure 3.3 shows the ADCP data collected from the AUV during the survey on the 23rd of January 2014. This figure indicates that there is a heightened concentration of biomass in the watercolumn at a depth of around 8 - 12 meters during the survey. The data shown in Figure 3.3 have been averaged over approximately 2 hours, while the full survey lasted for almost 5 hours (see Table 3.1). To get a better picture of DVM from AUV data, a survey of about 24 hours should have been conducted. Due to limited battery power, this was not possible. Another way to improve the data is to adapt the sampling based on the measured data, since the AUV is spending much time mapping areas with limited information.

The remaining datasets are discussed in Cohen et al. [35], which is the first study to conclude that zooplankton DVM is affected by ambient light in the polar night.

3.2.2 Experiences from the Arctic polar night

While the main objective of the surveys conducted at Svalbard was related to marine biological research, several aspects that are relevant to ice-monitoring and other Arctic marine research activities using AUVs were present. This includes the presence of drifting ice, severely limited visibility throughout the campaign, navigation at Arctic latitudes, and communication constraints.

The presence of drifting sea-ice does not pose a treat for the AUV while performing its mission underwater, unless deep drafted ice features are present. However, several surface objectives with subsequent GPS fixes were performed in the fjord. The REMUS AUV has no knowledge of what is above it, and a collision with one of the ice pieces could have resulted in dramatic consequences (e.g., breaking of the GPS antenna, or hull damage). For continuous ice-monitoring applications, the AUV should not rely on GPS fixes for performing its mission, but sooner or later a surface may be necessary. A solution where the AUV returns to a moonpool in a vessel by a homing system could be an option, or the AUV could search for an area of open water (within a certain area) autonomously. In areas with deep drafted ice features like ridges or icebergs, collision avoidance should be employed.

AUVs require a high accuracy and robust INS to perform dead-reckoning. However, as demonstrated from this case study, accurate dead-reckoning is still a problem without velocity measurements. For ice monitoring applications, an acoustic network could be used, but this requires subsea infrastructure. Another solution is terrain-aided navigation (TAN), using a bathymetric map of the area [33]. A drawback with this solution is that the AUV must be within MBE range if the sea floor, while also observing the ice (requires both upwards- and downwards-looking MBEs). This motivates the use of SLAM when observing the ice, using only an upwards-looking MBE.

Limited visibility is not a problem for the AUV under operation, but it does complicate human factors involved in deployment and recovery operations. Deployment and recovery with limited visibility must be taken into account, since the
3.3 The REMUS AUV under ice in Van Mijenfjorden

Polar night lasts for months in large parts of the Arctic. An advantage with the darkness is that if lights are mounted on the AUV, the AUV is very easy to spot. Communication is an integral part of an ice-monitoring application. For an offshore operation extending over a long period, it may be economically viable to place a permanent acoustic positioning and communication grid, perhaps even with underwater docking stations – limiting the need for deployment and recovery of AUVs drastically. For Arctic marine research with AUVs, or for operations lasting for a relatively short period of time, this is not an option. Unmanned surface vehicles could be used both to provide position updates, and to act as a communication relay without the need for a large vessel in a potentially dangerous area.

3.3 The REMUS AUV under ice in Van Mijenfjorden

An important first step towards AUV operations under drifting sea-ice is under-ice deployments from land-fast ice. Svalbard provides a location with high probability of land-fast ice of sufficient thickness while keeping the logistical complexities at a reasonable level for a test deployment. The field campaign was coordinated with the Future Arctic Algae Bloom (FAABulous), Research in Svalbard (RiS) project 10383, studying the role of the decreasing ice thickness and the increasing water temperature on Arctic algae bloom. The motivation for the joint field campaign was to lower the logistical costs and complexities, by sharing equipment and personnel, but also to share collected data.

Van Mijenfjorden, outside Svea in Svalbard, was chosen as location for the field campaign that took place between 19th of April and 2nd of May in 2017. The AUV

![Figure 3.4: Screenshot of AUV mission with launch site and LBL transponders.](image-url)
3. Field work and AUR-lab cruises

(a) REMUS AUV ready for deployment.  
(b) Under-ice AUV launch.  
(c) REMUS AUV and Blueye ROV.  
(d) Deployment of recovery frame.

Figure 3.5: NTNU REMUS under-ice deployment in Svea, Svalbard.

deployment site was chosen to achieve as good navigation system performance as possible, since the AUV requires bottom-lock with the DVL during launch and recovery. The DVL used on REMUS has a maximum typical range of 30 meters, meaning that the deployment site (and the immediate vicinity) must have a water depth of less than 30 meters. The REMUS AUV also has an upwards-looking ADCP, but the ice-lock feature was not implemented into the navigation system, and could not be used. Furthermore, the deployment/recovery area needed to be within range of the LBL transponders to ensure good navigation during recovery. Figure 3.4 shows one of the under-ice missions conducted. It illustrates the deployment and recovery area about 5 km outside Svea City.

A short test mission was planned on the 26th of April to verify the behavior of the vehicle and the under-ice configuration. During launch, the vehicle was too positively buoyant, causing the vehicle to drift to the surface before achieving a large enough velocity to drive itself down. This caused a crash with the ice-edge, which resulted in the AUV being unable to dive. The AUV drove for a few hundred meters just below the ice, before the AUV mission was aborted and the vehicle altered course towards the deployment/recovery site. REMUS was unable to get a good LBL fix close to the ice (believed to stem from multipaths and reflections from the ice). This caused position drift in the navigation system, and the vehicle eventually stopped under the ice, about 35 meters away from the hole. The AUV
The REMUS AUV under ice in Van Mijenfjorden

Figure 3.6: Plot of water column parameters captured by the REMUS AUV.

was located by an acoustic pinger mounted on the AUV, and a Blueye ROV was used to recover the AUV.

The following days, longer missions were planned and executed successfully. However, some issues were identified. Firstly, the launch procedure was not optimal. REMUS was set up to acquire a GPS fix, before a deployment tool was used to push the vehicle to the desired depth. Due to the size of the hole, and varying visibility in the water caused by ice slush, the method proved to be prone to human error, and multiple attempts had to be taken to perform a successful launch. Secondly, due to a fault in the DVL, the range was severely reduced (the range when the vehicle lost bottom-lock was about 10 - 12 meters, compared to the typical 30 meter range). This caused bad performance of the navigation system due to large parts of the mission being conducted without bottom-lock. The LBL performance was good during most of the mission, but during the critical recovery phase the AUV only got a few good LBL fixes. The recovery phase was performed at two meters depth, and multipath effects from the ice may have caused the bad LBL reception. Due to these problems, the AUV was unable to return to the recovery hole, and the Blueye ROV was used to recover the AUV on all missions.

3.3.1 FAABulous relevant data

Water column data is of interest for studying the Arctic algae bloom, but the spatial distribution of collected measurements has typically been sparse. Figure 3.6 shows a plot of the salinity, and temperature profiles, as well as oxygen and chlorophyll-a depth profiles collected by the AUV during one of the missions. From the plots we
3. Field work and AUR-lab cruises

(a) FAABulous equipment under the ice.  
(b) Algae patchiness under the ice.

Figure 3.7: Under-ice images captured with the Blueye ROV.

see that in addition to a trend in the depth profile, there are some spatial differences. In addition to the AUV missions, ROV sampling missions were performed to complement the FAABulous dataset. The collected data consisted of spatially distributed images of the patchiness of the algae bloom on the underside of the ice, as well as under-ice video inspection of the scientific equipment frozen into the ice. Two images from the Blueeye sampling missions are shown in Figure 3.7.

### 3.3.2 Experience from under-ice deployments

The main learning outcome from the under-ice deployment when looking towards AUV deployments under drifting ice, is the need for a robust navigation system, customized for Arctic AUV operations. Being able to use the upwards-looking DVL to obtain ice-lock, as well as a homing system for recovery would have contributed

Figure 3.8: Experimental launch platform for Arctic AUV research.
3.4. USV as a support tool for AUV operations

to a safer and easier operation. Moreover, the accuracy of the GPS sensor on the REMUS AUV is 15 meters, which will cause problems if attempting to return to a hole in the ice of 3 by 3 meters. If the navigation system had an option of using a relative coordinate frame, the LBL transponders could be placed relative to the base (e.g., by using RTK GNSS with centimeter precision), which would separate the uncertainty in the global frame from the guidance problem.

Furthermore, fault detection and fail safe actions would have been beneficial to detect problems early and reduce the impact of the error. For example, by returning immediately when an error is detected, the chance of returning to the correct recovery location is increased.

Deployment and recovery of AUVs in Arctic research is also an area that would benefit from further development. It would be desirable to have methods that would be less influenced by a human operator. A suggested solution could be a deployment ramp launching the AUV at an angle, as illustrated in Figure 3.8.

3.4 USV as a support tool for AUV operations

One of the most challenging tasks in underwater operations is communication. Especially establishing a continuous communication link with an AUV is demanding. Moreover, the communication bandwidth is typically low, and decreases as the distance between the sender and receiver increases. For many applications, the communication constraints, along with the need to provide position updates to the AUV, have led to a dependency on a support vessel for AUV operations [116].

As the support vessel is required to stay close to the AUV, the operational expenses of an AUV deployment are significantly increased. Many areas, especially in the Arctic, may in addition pose dangers that restrict the proximity of vessels (e.g., icebergs and ridges). To reduce the dependency of a mother ship, and to limit the risk involved in extreme environments, the ship can be replaced with an USV with acoustic navigation and communication systems [1, 51, 55, 125]. The following section presents two experiments with USV and AUV in the Trondheimsfjord.

3.4.1 AUV tracking and monitoring

The first experiment was conducted as a demonstration of autonomous tracking of a REMUS 100 AUV with an USV, to extend and improve the acoustic link between operator and vehicle. Due to the lack of USBL on the REMUS AUV, position updates could not be provided by the USV in this experiment, and an LBL network was deployed prior to the experiment.

The USV Telemetron was used in the demonstration, which is a custom made Polarcirkel 845 Sport, and is owned and operated by Maritime Robotics. Through the Maritime Robotics’ in-house control and monitoring software Vehicle Control Station (VCS), the USV could be monitored and operated from a remote location. For the AUV tracking application, an extension to the VCS was implemented which also allowed monitoring of the AUV through the VCS (see Figure 3.10).
3. Field work and AUR-lab cruises

Communication setup

To be able to communicate with the AUV, a Woods Hole Oceanographic Institution (WHOI) micromodem was mounted in the moonpool of the USV and interfaced with the onboard control computer. Using an ICE-modem, the USV relayed all acoustic modem messages from the AUV to both the VCS and VIP. A state message was sent from the AUV every minute, containing timestamp, position, speed, heading, depth, and destination waypoint [161]. The modem messages were displayed in VIP and used to monitor the status and health of the AUV, while the data were decoded and used to estimate the position of the AUV by the VCS software. An overview of the communication setup is shown in Figure 3.9.

Tracking algorithm

Based on the information received in the acoustic modem telemetry, the USV predicted the current position of the AUV. To do this, the speed and bearing of the AUV were considered to be constant between modem messages, while the depth of the AUV was disregarded. Due to potential long periods without modem messages being received, the mission plan of the AUV was used as a backup in the estimator. If the AUV arrived at a waypoint, the estimator would switch to the next waypoint automatically without having to wait for the next modem message with a new target position. When a new modem message was received, the position of the AUV was updated. The estimator on the USV assumed that the AUV had perfect knowledge of its position, and the AUV position in the estimator was set to the received position (adjusted for time-delay). A snapshot of the VCS, showing the position of the USV, the estimated AUV position, and the last known AUV position, is presented in Figure 3.10.

The USV used the constant bearing (CB) guidance scheme for tracking the estimated AUV position. This means that the USV will align the relative interceptor-
3.4. USV as a support tool for AUV operations

The experiment was conducted on the 7th of May in 2015 in the Trondheimsfjord. The experiment was performed as a demonstration in conjunction with the NTNU Ocean Week, and the objective was to monitor the progress of the operation live from a remote location. All communication with the AUV was performed using the USV as a relay.

The experiment demonstrated the USV’s ability to track the REMUS AUV, with an acoustic link of varying quality. Throughout the operation, 63% of the modem messages were successfully received by the USV, and the longest period between telemetry updates was 6 minutes. The modem was mounted in a moonpool of the USV close to the hull, and some high-frequency vibrations were observed.

target velocity vector along the line-of-sight vector between the interceptor and the target [25]. The CB guidance scheme is particularly useful for underactuated vehicles, like the Telemetron USV, since an overshoot would only decrease the velocity of the interceptor to slower than the target, rather than changing the heading.

AUV tracking results

The experiment was conducted on the 7th of May in 2015 in the Trondheimsfjord. The experiment was performed as a demonstration in conjunction with the NTNU Ocean Week, and the objective was to monitor the progress of the operation live from a remote location. All communication with the AUV was performed using the USV as a relay.

The experiment demonstrated the USV’s ability to track the REMUS AUV, with an acoustic link of varying quality. Throughout the operation, 63% of the modem messages were successfully received by the USV, and the longest period between telemetry updates was 6 minutes. The modem was mounted in a moonpool of the USV close to the hull, and some high-frequency vibrations were observed.
3. Field work and AUR-lab cruises

Figure 3.11: Trajectory of the AUV and the USV during the experiment.

during the experiment. Improved transducer placement may therefore increase the quality of the acoustic link further.

Figure 3.11 shows the trajectory of the AUV and the USV, as well as the desired trajectory of the USV. The USV track was offset 75 meters to the starboard side of the AUV, at an angle of 45 degrees. This was believed to improve the acoustic channel as the placement of the acoustic transducer on the REMUS is on the underside of the vehicle. The trajectory shows that the USV was able to track the vehicle during most of the mission, but remote operator intervention was required a few times (e.g., due to marine traffic in the operating area).

3.4.2 Network of heterogeneous autonomous vehicles

The second experiment was set up using the NTNU research vessel Gunnerus [142] as base of operations 30 nautical miles outside Trondheim, close to an area called Nord-Leksa. The vehicles used in this experiment were the USV Telemetron, the HUGIN HUS AUV, as well as an X8 UAV. To further extend the range of the communication system, an aerostat balloon called Ocean Eye was launched from Gunnerus.
3.4. USV as a support tool for AUV operations

Figure 3.12: Vehicles and communication links in the Nord-Leksa experiment.

The objective of this experiment was to demonstrate a network of collaborating vehicles with the ability to communicate and relay data. All the vehicles were equipped with a Kongsberg Seatex Marine Broadband Radio (MBR), configured with a maximum bandwidth of 15 MBps. An overview of the communication network is shown in Figure 3.12.

During the AUV operation, the high-speed radio link was not available when the AUV was underwater. Instead, an acoustic transducer was mounted on the USV, and this was used to send AUV position estimates to the USV. The USV used a formation path following controller with the AUV as leader. The relative position offset between the AUV and the USV was determined from the operating depth and the transponder beam pattern. The progress and state of the AUV were monitored from the ship through the MBR link to the USV and further through the acoustic link. AUV commands were also relayed through the USV.

Several speed tests were performed to assess the performance of the MBR network. As an example, while Telemetron was travelling away from Gunnerus, reaching a maximum distance of 10 km, the average downlink speed was 3.14 Mbps and 1.79 MBps for uplink. At 22 km distance, the average downlink and uplink speed were 2.98 and 1.81 Mbps, respectively. Communication speed for the HUGIN AUV was lower, probably due to the low antenna elevation height above the water, with downlink/uplink speed of 2.57/1.33 Mbps. These bandwidths provide the ability to relay significant amount of data over a large distance, which may have several interesting applications.

3.4.3 Experiences from USV experiments

The experiences from two experiments with a USV as a support platform for an AUV show that the concept has great potential. However, it requires research and
3. Field work and AUR-lab cruises

development to get to a stage where it can be used in a normal operation. Especially when moving USVs to the Arctic, the control systems should be robust and include both path following and collision avoidance. Furthermore, both subsea and topside communication systems should be able to handle and recover from faults without operator intervention. It is believed that USVs will become an important tool in marine research, also in Arctic operations, in the future.
Chapter 4

Arctic AUV simulator for design and verification

This chapter presents a simulator developed for design and verification of Arctic AUV guidance, navigation, and control algorithms. The simulator consists of seven modules, including a numerical AUV model, loads acting on the AUV, and a guidance and control system. In addition, a multibeam simulator sensing ice topography, an ice drift model, and a relative AUV-ice model, are also a part of the simulator. Parts of the work in this chapter have been presented in [137, 139].

4.1 Introduction

The previous chapters have illustrated that performing AUV operations in the Arctic is challenging, due to the presence of sea-ice and ice features, as well as demanding logistics. In addition, it is expensive and time consuming. This makes developing algorithms and methods for Arctic AUV operations especially arduous, since testing the methods in a real environment requires so much resources. In addition, the risk is much higher in the Arctic.

This has motivated the development of a simulator, specialized towards Arctic AUV operations. The simulator should capture the essential dynamics related to vehicle rigid body dynamics, hydrodynamics, hydrostatics, thruster and control surface forces, environmental loads and objects, as well as applicable sensor dynamics and properties. The following sections detail these topics.

4.2 Simulator structure

An overview of the complete Arctic AUV simulator is shown in Figure 4.1. The numerical AUV model, as well as the guidance and control system, are similar to an normal AUV simulator. For completeness, a description of all the components
of the AUV simulator is presented in this chapter. Since the main difference between Arctic AUV operations and open water operations is the presence of ice features, this is a key component in the simulator. The terrain is represented as a digital elevation map (DEM), which allows the use of real ice data if available. The terrain used for simulating an iceberg in Chapter 6 is taken from the PERD iceberg sightings database [168]. The iceberg used in these simulations is shown in Figure 4.3.

The multibeam block in Figure 4.1 is used to sense the terrain, and it has the option to use both bathymetric terrain, as well as ice feature topography. An ice drift model is used to simulate drift and rotation of the terrain, and is used as input in the relative model. The relative model block represents the relative position and velocity between the AUV and the terrain. The relative velocity can be used to simulate measurements from an upwards-looking DVL, while the relative position is used as input to the multibeam sensor to emulate the movement of the sensed terrain. The contributions presented through this chapter lies in the overall simulator structure, in addition to the sensing of the drifting and rotating terrain.

4.3 Kinematics

The study of dynamics can be divided into kinetics and kinematics. Kinematics treat the geometrical aspects only, while kinetics is the analysis of how forces affect the motion [66]. The following section presents the kinematics for the 6 DOF AUV
4.3. Kinematics

Table 4.1: SNAME notation for marine vessels.

<table>
<thead>
<tr>
<th>DOF</th>
<th>Forces and moments</th>
<th>Linear and angular velocities</th>
<th>Positions and Euler angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Motion in the x direction</td>
<td>X</td>
<td>u</td>
<td>x</td>
</tr>
<tr>
<td>2 Motion in the y direction</td>
<td>Y</td>
<td>v</td>
<td>y</td>
</tr>
<tr>
<td>3 Motion in the z direction</td>
<td>Z</td>
<td>w</td>
<td>z</td>
</tr>
<tr>
<td>4 Rotation about the x axis</td>
<td>K</td>
<td>p</td>
<td>ϕ</td>
</tr>
<tr>
<td>5 Rotation about the y axis</td>
<td>M</td>
<td>q</td>
<td>θ</td>
</tr>
<tr>
<td>6 Rotation about the z axis</td>
<td>N</td>
<td>r</td>
<td>ψ</td>
</tr>
</tbody>
</table>

The six DOFs are named according to the Society of Naval Architects and Marine Engineers (SNAME) notation [66], see Table 4.1.

4.3.1 Fossen’s robot-like vectorial model for marine crafts

Fossen [66] represents the vectorial form of the general 6 DOF equations of motion of a marine craft as

\[
\dot{\eta} = J_{\Theta}(\eta)\nu,
\]

\[
M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau,
\]

where \( \eta = \text{col}(p_{\text{AUV}}^n\Theta_{\text{nb}}) \) is the position and orientation vector of the AUV. \( p_{\text{AUV}}^n = [x\ y\ z]^T \in \mathbb{R}^3 \) denote the position of the AUV in the \( n \)-frame, while \( \Theta_{\text{nb}} = [\phi\ \theta\ \psi]^T \in S^3 \) is a vector of Euler angles. \( \nu = \text{col}(v_{\text{AUV}}^b\omega_{\text{AUV}}^b) = [u\ v\ w\ p\ q\ r]^T \in \mathbb{R}^6 \) is the linear and angular velocities of the AUV, expressed in the \( b \)-frame, and \( \tau \in \mathbb{R}^6 \) is the forces and moments acting on the AUV in the body-fixed frame from the thruster, control surfaces, and the environmental loads. The relative velocity is \( \nu_r = \nu - \nu_c \in \mathbb{R}^6 \), where \( \nu_c \) is the velocity vector of the ocean currents. The transformation matrix of (4.1) is presented in Section 4.3.3, while the system matrices of (4.2) are detailed in Section 4.4.

4.3.2 Reference frames

It is convenient to define several coordinate frames to describe motion and to reference measurements [66]. The coordinate frames used are

- **NED** (\( n \)): The North-East-Down (NED) reference frame is defined relative to the Earth’s reference ellipsoid. For local area navigation, this reference frame can be assumed to be inertial.
- **BODY** (\( b \)): The body-fixed reference frame is moving with the body of the marine craft and is non-inertial. The origin of this coordinate system is called center of origin (CO). Other body-fixed reference points are the center of buoyancy (CB), the center of gravity (CG), and the center of floatation (CF).
- **ICE** (\( i \)): A coordinate system fixed to the drifting and rotating ice.
- **BEAM** (\( bm \)): A coordinate system fixed to the AUV, but corrected for roll and pitch angles. The origin of the coordinate system is the CO.
4. Arctic AUV simulator for design and verification

- **MEAS** \((m)\): A reference frame moving and rotating with the AUV that is specialized for the instrument used.

For the work presented through this thesis, the NED frame is assumed to be inertial, and the earth-centered reference frames have not been used. The AUV body frame and the inertial frame are shown in Figure 4.2.

### 4.3.3 Transformations

To transform vectors between reference frames, Euler angle transformation will be used [66]. The linear velocity transformation can be described by three principal rotations about the \(z\), \(y\), and \(x\) axes by

\[
R_{\text{b}}^n(\Theta_{\text{nb}}) = R_{z,\psi} R_{y,\theta} R_{x,\phi},
\]

with

\[
R_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi) & \cos(\phi) \end{bmatrix}, \quad R_{y,\theta} = \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix}, \quad R_{z,\psi} = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix},
\]

(4.3)

where \(c \cdot = \cos(\cdot)\) and \(s \cdot = \sin(\cdot)\).

Similarly, the angular velocity transformation is given by

\[
\dot{\Theta}_{\text{nb}} = T_{\Theta}(\Theta_{\text{nb}}) \omega^b_{\text{auv}},
\]

with

\[
T_{\Theta}(\Theta_{\text{nb}}) = \begin{bmatrix} 1 & \sin(\theta) & \cos(\phi) \sin(\theta) \\ 0 & \cos(\theta) & -\sin(\theta) \cos(\phi) \\ \sin(\phi) / \cos(\theta) & \cos(\phi) / \cos(\theta) & \end{bmatrix},
\]

(4.6)
where $t \cdot = \tan(\cdot)$. Note that $T_{\Theta}(\Theta_{nb})$ is singular for $\theta = 90^\circ$. This singularity can be avoided by using quaternion representation, but this problem has been disregarded. The 6 DOF kinematic transformation can now be expressed as

$$\dot{\eta} = \begin{bmatrix} R_{b}^a(\Theta_{nb}) & 0_{3\times3} \\ 0_{3\times3} & T_{\Theta}(\Theta_{nb}) \end{bmatrix} \nu.$$  

(4.7)

4.4 Kinetics

The developed simulator uses a 6 DOF AUV model. All six degrees of freedom were included since for example the MBE sensor head is fixed to the AUV body, which causes the measurements from the MBE to be greatly affected by AUV motions, like rolling and pitching. The targeted AUV during the simulator development is the REMUS 100 AUV; see Appendix A.1. The model parameters have been taken from a REMUS 100 model by Prestero [151].

Equation (4.2) defines the kinetics of a 6 DOF marine craft. $M = M_{RB} + M_{A} \in \mathbb{R}^{6\times6}$ is the rigid-body inertia and added mass of the AUV, while the centripetal and Coriolis rigid-body and added mass are denoted $C(\nu_{r}) = C_{RB}(\nu) + C_{A}(\nu_{r}) \in \mathbb{R}^{6\times6}$. $D(\nu_{r}) \in \mathbb{R}^{6\times6}$ represents hydrodynamic damping, and restoring forces are given by $g(\eta) \in \mathbb{R}^{6}$. The structure of the matrices of (4.2) are given below, while all parameters are given in Appendix A.1.

4.4.1 Rigid body dynamics

The rigid body mass matrix is expressed as

$$M_{RB} = \begin{bmatrix} mI_{3\times3} & -mS(r_{g}^{b}) \\ mS(r_{g}^{b}) & I_{b} \end{bmatrix},$$  

(4.8)

where $S(r_{g}^{b}) = -S^{\top}(r_{g}^{b}) \in \mathbb{R}^{3\times3}$ is a skew-symmetric matrix with input $r_{g}^{b} = \begin{bmatrix} x_{g} & y_{g} & z_{g} \end{bmatrix}^{\top}$ which represents the location of the CG with respect to the CO. $I_{b}$ represents the inertia tensor.

The Coriolis-centripetal matrix is

$$C_{RB} = \begin{bmatrix} 0_{3\times3} & -mS(v_{auv}) - mS(\omega_{auv})S(r_{g}^{b}) \\ -mS(v_{auv}) + mS(r_{g}^{b})S(\omega_{auv}) & -S(I_{b}\omega_{auv}) \end{bmatrix},$$  

(4.9)

expressed in the CO. For more details, the reader is referred to Fossen [66].

4.4.2 Hydrodynamics

The hydrodynamic added mass matrix is given by

$$M_{A} = \begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} & X_{\dot{p}} & X_{\dot{q}} & X_{\dot{r}} \\ Y_{\dot{u}} & Y_{\dot{v}} & Y_{\dot{w}} & Y_{\dot{p}} & Y_{\dot{q}} & Y_{\dot{r}} \\ Z_{\dot{u}} & Z_{\dot{v}} & Z_{\dot{w}} & Z_{\dot{p}} & Z_{\dot{q}} & Z_{\dot{r}} \\ K_{\dot{u}} & K_{\dot{v}} & K_{\dot{w}} & K_{\dot{p}} & K_{\dot{q}} & K_{\dot{r}} \\ M_{\dot{u}} & M_{\dot{v}} & M_{\dot{w}} & M_{\dot{p}} & M_{\dot{q}} & M_{\dot{r}} \\ N_{\dot{u}} & N_{\dot{v}} & N_{\dot{w}} & N_{\dot{p}} & N_{\dot{q}} & N_{\dot{r}} \end{bmatrix}.$$  

(4.10)
where for example the coefficient \( X_\ddot{u} \) is added mass in x-direction due to acceleration in surge. Due to body top-bottom and port-starboard symmetry for a torpedo-shaped vehicle, the added mass matrix for the REMUS 100 AUV reduces to [151]

\[
M_A = \begin{bmatrix}
X_\ddot{u} & 0 & 0 & 0 & 0 \\
0 & Y_\ddot{v} & 0 & 0 & Y_\ddot{r} \\
0 & 0 & Z_\ddot{w} & 0 & Z_\ddot{q} \\
0 & 0 & 0 & K_\ddot{p} & 0 \\
0 & 0 & M_\ddot{\psi} & 0 & M_\ddot{\theta} \\
0 & 0 & 0 & 0 & N_\ddot{\phi}
\end{bmatrix}.
\] (4.11)

Given the hydrodynamic added mass matrix, the added Coriolis-centripetal matrix can be found from [66]

\[
C_A = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
-S(A_{11}v_{\text{auv}} + A_{12}\omega_{\text{auv}}) & -S(A_{21}v_{\text{auv}} + A_{22}\omega_{\text{auv}}) & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix},
\] (4.12)

with \( A_{ij} \in \mathbb{R}^{3 \times 3} \) given by

\[
M_A = \begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}.
\] (4.13)

Using the hydrodynamic damping model presented by Prestero [151], where nonlinear damping is assumed to dominate, the damping matrix can be expressed as

\[
D(\nu) = -\begin{bmatrix}
X_{[u][u]}|u_r| & 0 & 0 & 0 & 0 \\
0 & Y_{[v][v]}|v_r| & 0 & 0 & Y_{[v][r]}|r| \\
0 & 0 & Z_{[w][w]}|w_r| & 0 & Z_{[q][q]}|q| \\
0 & 0 & 0 & K_{[p][p]}|p| & 0 \\
0 & 0 & M_{[w][w]}|w_r| & 0 & M_{[q][q]}|q| \\
0 & 0 & 0 & 0 & N_{[e][e]}|e|
\end{bmatrix}.
\] (4.14)

The damping model in (4.14) also assume top/bottom and port/starboard symmetry. The model presented by Prestero [151] neglects linear damping terms, and also ignores damping terms greater than second-order. Effects of damping for underwater vehicles moving at high speeds are highly nonlinear, but linear effects may be important if the speed is low, or in control system design [38] (especially for states that will reach steady state in normal operations like heave and pitch). Hydrodynamic modeling has been considered outside the scope of this thesis, and the model is therefore used without linear damping.

### 4.4.3 Hydrostatics

Floating and submerged vehicles have restoring forces acting from the displaced water volume. The vector of restoring forces for an AUV in the body-frame is defined
4.5 Generalized forces

by [66]

\[
g(\eta) = \begin{bmatrix}
(W - B) \sin(\theta) \\
-(W - B) \cos(\theta) \sin(\phi) \\
-(W - B) \cos(\theta) \cos(\phi) \\
-(y_g W - y_b B) \cos(\theta) \cos(\phi) + (z_g W - z_b B) \cos(\theta) \sin(\phi) \\
(z_g W - z_b B) \sin(\theta) + (x_g W - x_b B) \cos(\theta) \cos(\phi) \\
-(x_g W - x_b B) \cos(\theta) \sin(\phi) - (y_g W - y_b B) \sin(\theta)
\end{bmatrix},
\]

where \( W \) and \( B \) are the weight and buoyancy force, respectively. The vector \( \mathbf{r}_b^b = [x_b \ y_b \ z_b]^T \) represents the location of the CB with respect to the CO. AUVs are typically balanced such that they are slightly positively buoyant, which will result in the vehicle drifting to the surface upon failure.

4.5 Generalized forces

The main external forces acting on an underwater vehicle are the ocean current, the thruster forces, and the control surface forces. The hydrodynamic forces depend on the relative vehicle-fluid velocity through the added mass, added Coriolis and centripetal loads, and the damping loads. The ocean current is incorporated into this model through the relative velocity formulation as seen in (4.2). The model for the thrust forces and control surfaces is given in the following section, along with the model for the ocean current velocity.

4.5.1 Environmental forces

Since an AUV is generally submerged for most of the mission, neither wind nor waves have been considered. The only environmental load is the ocean current, which is considered constant and irrotational. It is also assumed that there is no vertical component from the ocean current. The resulting ocean current velocity vector, expressed in the \( b \)-frame, is

\[
\nu_c = \begin{bmatrix}
u_c & 0 & 0 & 0 & 0
\end{bmatrix}^T = \begin{bmatrix} V_c \cos(\psi_c) & V_c \sin(\psi_c) & 0 & 0 & 0 \end{bmatrix}^T,
\]

where \( \psi_c = \beta_c + \psi \), and \( \beta_c \) is the ocean current direction relative to the \( b \)-frame, also called sideslip angle. \( V_c \) denotes the speed of the ocean current, that is \( V_c = \sqrt{u_c^2 + v_c^2} \).

4.5.2 Thruster forces

The propeller model of Prestero [151] was designed for small deviations from a given forward speed. Since the control system of the REMUS vehicle outputs a desired propeller shaft speed, the propeller shaft model was altered by adopting the model of Carlton [32]

\[
X_p = K_T \rho D_{prop}^4 |n|, \quad (4.17)
\]
\[
K_p = K_Q \rho D_{prop}^5 |n|, \quad (4.18)
\]
where $K_T$ and $K_Q$ are the strictly positive thrust and torque coefficients, $D_{prop}$ is the propeller diameter, and $n$ is the shaft speed given in revolutions-per-second. $K_T$ and $K_Q$ have been calculated from the REMUS propeller characteristics by Allen et al. [2], and are given in Appendix A.1.

### 4.5.3 Control surfaces

The pitch of the REMUS AUV is controlled by two horizontal fins, and similarly, the heading of the AUV is controlled by two vertical fins. Both the stern planes and the rudder planes are moving together; that is, the two horizontal fins cannot be controlled individually, and neither can the vertical fins. Prestero [151] derives the following expressions for the forces and moments from the rudder and pitch fins

\[
Y_r = \frac{1}{2} \rho c_{L,\alpha} S_{\text{fin}} [u^2 \delta_r - uv - x_{\text{fin}}(ur)], \quad (4.19)
\]

\[
Z_s = -\frac{1}{2} \rho c_{L,\alpha} S_{\text{fin}} [u^2 \delta_s + uw - x_{\text{fin}}(uq)], \quad (4.20)
\]

\[
M_s = \frac{1}{2} \rho c_{L,\alpha} S_{\text{fin}} x_{\text{fin}} [u^2 \delta_s + uw - x_{\text{fin}}(uq)], \quad (4.21)
\]

\[
N_r = \frac{1}{2} \rho c_{L,\alpha} S_{\text{fin}} x_{\text{fin}} [u^2 \delta_r - uv - x_{\text{fin}}(ur)], \quad (4.22)
\]

where $\rho$ is the density of water, $S_{\text{fin}}$ is the fin area, $x_{\text{fin}}$ is the x-coordinate of the fin placement (with respect to the CO), and $c_{L,\alpha}$ is the fin lift coefficient estimated from an empirical formula taking the angle of attack, $\alpha$, as argument. The remaining variables of (4.19)-(4.22) are the linear and angular velocities of the AUV, and $\delta_s$ and $\delta_r$ are the stern and rudder angles, respectively, relative to the body x-axis. The coefficients are found in Appendix A.1. From the last two sections we see that the input to the AUV model can be described by $\xi = [n \quad \delta_s \quad \delta_r]^\top$, giving one control parameter for speed, one for pitch, and one for heading. Setting $\tau = [X_p \quad Y_r \quad Z_s \quad K_p \quad M_s \quad N_r]^\top$ concludes the 6 DOF AUV model.

### 4.6 Arctic simulator models

The Arctic simulator models in Figure 4.1 consist of the ice drift model, as well as the relative motion model, and a short description is provided in the following section. The ice drift and relative model are used to represent movement of the ice terrain, which is represented by a gridded DEM, with north, east, and depth data. An example of a ice topography that is used in the simulator is shown in Figure 4.3 which illustrates an iceberg from the PERD iceberg sightings database.

#### 4.6.1 Ice drift model

The ice drift model is similar to the ocean current model presented in Section 4.5.1, using a constant ice drift speed, $V_{\text{ice}}$ and a constant ice drift course angle, $\beta_{\text{ice}}$. The
4.7. Multibeam simulator

Figure 4.3: Iceberg R11i01 from the PERD iceberg sightings database.

3 DOF iceberg velocity model is given by

\[
\dot{\eta}_\text{ice}^n = R(\psi_\text{ice}) \nu_\text{ice}^i, \\
\nu_\text{ice}^i = [V_\text{ice} \cos(\beta_\text{ice}) \ V_\text{ice} \sin(\beta_\text{ice}) \ 0]^\top. 
\]

Because of the modular structure of the simulator, this block can easily be replaced by real ice drift data if desired.

4.6.2 Relative motion model

The relative AUV-ice position is used in the MBE simulator to get correct MBE measurements of the drifting ice topography. The relative velocity can also be used to simulate velocity measurements with a upwards-looking DVL. The relative model is given by

\[
\eta_\text{rel}^i = R^\top(\psi_\text{ice}) (\eta_\text{auv}^n - \eta_\text{ice}^n), \\
\nu_\text{rel}^b = \nu_\text{auv}^b - \nu_\text{ice}^b = \nu_\text{auv}^b - R^\top(\psi_\text{rel}) \nu_\text{ice}^i, 
\]

where \( \psi_\text{rel} = \psi_\text{auv} - \psi_\text{ice} \). The 3 DOF model can be extended into 6 DOF by setting

\[
\eta_{\text{rel,6DOF}} = \text{col} \begin{pmatrix} p_\text{rel}^i & \Theta_\text{rel} \end{pmatrix} = \begin{bmatrix} x_\text{rel}^i & y_\text{rel}^i & z_\text{auv}^i & \phi_\text{auv} & \theta_\text{auv} & \psi_\text{rel} \end{bmatrix}^\top. 
\]

4.7 Multibeam simulator

The beam range simulator used in conjunction with the AUV dynamics has been developed through a master’s project by Holsen [83] and extended by the author.
to support drifting and rotating terrain, and a description of the MBE simulator will be given in the following.

The objective of the multibeam simulator is to provide \( N \) beam range and angle measurements of a terrain represented by a DEM. The beams are assumed to be evenly spaced over a certain sector (e.g., 120° for a DeltaT MBE), and therefore, the angle measurements will be constant for a given configuration. The range measurements, however, must be calculated at each iteration and depend on the state of the AUV relative to the environment that is mapped. The input to the MBE simulator is therefore the relative state of the AUV, which will emulate that the terrain is moving according to the ice drift model presented in Section 4.6.2.

Given a range measurement, \( r_m \), the beam hit position can be calculated from

\[
E^i = R^T(\psi_{\text{ice}})p_{\text{rel}}^i + R^b_{\text{rel}}(\Theta_{\text{rel}})R^b_{\text{m}}(\Theta_{\text{beam}})\vec{k}r_m.
\]  

(4.28)

where \( \Theta_{\text{MBE},i} = [\alpha_{m,i} \beta_{m,i} 0]^T \in S^3 \). \( \alpha_{m,i} \) and \( \beta_{m,i} \) are the cross-track and along-track angles of the \( i \)th beam, respectively. \( \vec{k} \) is the unit vector in the direction of the \( z \)-axis, and the sign of \( \vec{k} \) is positive if the MBE is mounted downwards, and negative if mounted upwards.

Calculating the range of each beam is an iterative process, since a DEM is used to represent the terrain. Let \( e_i \) be the current estimate of the \( i \)th beam range (with initial value determined by some minimum allowed range). Inserting \( e_i \) as the range measurement in (4.28) provides an estimated beam end position, \( \hat{E}_i = [\hat{x}_{\text{mbe},i} \hat{y}_{\text{mbe},i} \hat{z}_{\text{mbe},i}]^T \). To get the actual depth at a given position, bilinear interpolation between the four nearest neighbours is used, resulting in a depth at a given position, \( Z_{\text{surface}}(x, y) \). The error between the estimated beam-end position and the actual terrain is

\[
\tilde{e} = \hat{z}_{\text{mbe},i} - Z_{\text{surface}}(\hat{x}_{\text{mbe},i}, \hat{y}_{\text{mbe},i}).
\]  

(4.29)

If the error, \( \tilde{e} \), is positive, the beam range is too small, while a negative error tells us that the beam range is too large. The beam range is increased by an increment until the error becomes negative, then binary search is used to reduce the error to a sufficient accuracy. Binary search could have been used for the whole search; however, this has shown to cause the beams to hit the wrong surface (beams hitting the water surface when they should have been hitting the ice) under some conditions.

### 4.8 AUV control system

The implemented control system in the simulator consists of two parts: a path planner using waypoints for determining the path of the vehicle, and a low level control system taking set-points as input and converting it to control signals.

#### 4.8.1 Low level control system

To implement a guidance algorithm, a control system is necessary for the AUV to be able to follow the commands given. In Section 4.5.2-4.5.3 we saw that the
input to the AUV model could be described as three signals: one for speed, one for pitch, and one for heading. Therefore, the control system is divided into three independent controllers: speed control, depth control, and heading control. This is the structure of the REMUS 100 AUV control system, and the simulated control system was designed to be similar to the real AUV.

The depth is changed by altering the pitch of the AUV, but the setpoints are given as desired depth. Therefore, the depth control is divided into two loops. The first loop is a proportional-integral (PI) controller on the depth error that generates a pitch setpoint, while the second loop is a proportional-integral-derivative (PID) controller that controls the stern planes of the AUV. The heading controller is a PID controller that controls the rudder fins of the AUV. All setpoints passed to the controllers are passed through reference models to avoid excessive changes in control commands.

### 4.8.2 Default guidance system

A typical way of programming AUV missions is through waypoints, and for many cases this sufficient. Using a list of 3D waypoints, \( WP_k = [x_k, y_k, z_k]^\top \), to be visited, the heading setpoint for the vehicle can be generated using line-of-sight (LOS) [66]. The LOS guidance scheme allows the vehicle not only to follow a path course, but it also forces the vehicle to converge to the path. This is achieved by defining an intersection point on the path, some lookahead distance \( \Delta \) ahead of the vehicle (see Figure 4.4 for an illustration of the LOS guidance scheme). By assigning the desired course angle, \( \chi_d \), to a sum of the path-tangential angle, \( \chi_p \) and the path-relative angle, \( \chi_r \), the LOS course angle can be expressed as

![Figure 4.4: LOS guidance principle where the desired course angle points toward a LOS intersection point.](image-url)
\[ \chi_d(e) = \chi_p + \chi_r(e). \] (4.30)

The path-tangential angle is given by

\[ \chi_p = \alpha_k = \text{atan2} \left( y_{k+1} - y_k, x_{k+1} - x_k \right), \] (4.31)

where \((x_k, y_k)\) and \((x_{k+1}, y_{k+1})\) represent the last and next waypoint, respectively.

\(e\) is the cross-track error from the current position, \((x(t), y(t))\), to the path, given by

\[ e(t) = -[x(t) - x_k] \sin(\alpha_k) + [y(t) - y_k] \cos(\alpha_k). \] (4.32)

Using the cross-track error, a steering law that ensures that the vehicle converges to the path is given by

\[ \chi_r(e) = \text{arctan} \left( -K_p e - K_i \int_0^t e(\tau) d\tau \right). \] (4.33)

\(K_p\) and \(K_i\) are tuning parameters for the control law, similar to tuning parameters for a PI-controller. \(K_p\) will influence the lookahead distance, shown in Figure 4.4. Integral action is especially useful for path-following for underactuated vehicles, like AUVs, in presence of ocean-currents, but care must be taken to avoid overshoot and anti-windup effects [66]. The depth setpoint is given by the current active waypoint, and the speed setpoint is constant for the duration of the simulation (but could easily be changed).

An important part of a guidance algorithm dealing with piecewise linear paths, is the switching of waypoints. A simple method is to define a circle of acceptance \(R_{acc}\) and switch waypoint when the vehicle enters this circle. That is, if the position of the vehicle satisfy

\[ (x_{k+1} - x(t))^2 + (y_{k+1} - y(t))^2 \leq R_{acc}^2, \] (4.34)

then the next waypoint should be selected. The circle of acceptance should not be chosen to small, since this the vehicle may not hit the waypoint exactly, and this may cause an unstable guidance scheme. For more details on the LOS guidance algorithm, the reader is referred to Fossen [66].

### 4.9 Summary

An Arctic AUV simulator has been presented, which includes a 6 DOF AUV model, a control and guidance system, as well as generalized forces. An ice drift and relative motion model are used to simulate a drifting terrain. The terrain, represented by a DEM, is sensed by a MBE simulator, capable of measuring both bathymetric terrain, as well as ice features. The presented simulator will be used in the results given in the following chapters of the thesis.
Chapter 5

AUV guidance system for iceberg detection

Autonomous underwater vehicles equipped with multibeam echosounders are suitable for obtaining measurements of the underwater geometry of icebergs, but advances in autonomy are needed to map drifting icebergs reliably. This chapter details a guidance algorithm for detecting and circumnavigating an iceberg by following the iceberg edge. The guidance scheme is implemented as a state machine, starting in an iceberg detection-mode. Once an iceberg is detected, the AUV will enter a circumnavigating-mode. An edge detection algorithm will determine the position of the edge, and a line-of-sight (LOS) approach will be used for edge-following. The work in this chapter is presented in [136, 137].

5.1 Introduction

An experiment aiming at mapping icebergs with AUVs is presented by Forrest et al. [65], which state that one of the biggest challenges encountered was the ability to plan missions for a drifting reference frame, indicating the need for an autonomous mapping scheme. It is possible to measure the relative velocity between the AUV and the iceberg using an upwards-looking DVL, while the AUV is directly below the iceberg. The rotational velocity, however, remains unknown, so a guidance system intending to map the ice must be able to account for this unmeasured disturbance.

Kimball and Rock [98] present a method to estimate the AUV trajectory in an iceberg-fixed reference frame (non-inertial frame, translating and rotating with the iceberg), and mapping of MBE measurements into this reference frame to construct a 3D map of the keel of an iceberg. The presented algorithm utilize relative velocity information between the iceberg and the AUV, captured from a side-mounted DVL, and is able to estimate the position and heading of the iceberg, through post-processing. An extension of the algorithm presented by Kimball and
Rock [98] is detailed by Hammond and Rock [77], where the inertial position of the vehicle is removed from the algorithm. This way, the map is constructed solely in iceberg-relative terms, removing potential AUV position errors from the geometry estimation. A limitation in this extension is that the position of the iceberg can not be estimated. However, it may not be necessary for all applications.

Zhou et al. [184] present an algorithm for profiling an iceberg by performing a downward spiral movement around the iceberg, using an AUV with a side-mounted scanning sonar. The algorithm assumes that the waterline profile of the iceberg is known at the commencement of the survey, and a new segment of the spiral is generated at each circumnavigation based on the iceberg profile from the last round.

5.1.1 Determining the main particulars of an iceberg

To be able to develop an autonomous guidance algorithm for monitoring of icebergs, we must first determine an appropriate mapping scheme. Through this section, three different methods for determining the main particulars (i.e., length, width, draft, and mass) of an iceberg are discussed, which can be divided into two main categories: mapping from the side of the iceberg, and mapping from below.

Scanning of the iceberg keel side

An illustration of an AUV mapping the side of an iceberg keel can be seen in Figure 5.2. A requirement for this mapping scheme is that the AUV performing the mapping has a side-mounted MBE, and preferably a side-mounted DVL to be able to measure relative velocity between the AUV and the iceberg. This could be a drawback, since most AUVs are designed with the DVL looking down (and many also have an upwards-looking DVL), and changing the configuration of the DVL could be time-consuming, since the DVL is often integrated with the INS.
An advantage with the mapping scheme shown in Figure 5.2 is that designing a guidance algorithm for circumnavigating the iceberg can be done using existing control algorithms, once the iceberg has been detected. Since the iceberg can be seen as a surface, and the AUV is flying at an “altitude” above this surface (the cross-track distance between the iceberg and the AUV), an altitude controller can be used for maintaining a constant cross-track distance between the iceberg and the AUV. The altitude controller can be implemented by utilizing sonar ranges, or by using the DVL range measurements, as presented by Dukan and Sørensen [44].

It is possible that the AUV might still hit the iceberg using this altitude control scheme if the iceberg shape is non-convex, and has a sharp edge. This will be similar to ordinary altitude control where the AUV runs into a near vertical wall – it does not have time to react to the change in altitude before hitting the bottom. To avoid this, a forward-looking obstacle avoidance sonar could be utilized. A forward-looking sonar would also be beneficial when the location of the iceberg is unknown and the iceberg must be detected.

Figure 5.2: AUV mapping the side of an iceberg. MBE and DVL footprint shown on iceberg. Picture courtesy of Kimball and Rock [98].
5. AUV guidance system for iceberg detection

Figure 5.3: Determining main particulars of an iceberg by moving between edges.

Mapping of the underside of the iceberg

Mapping of the underside of the iceberg is preferable for an IM operation, since we are able to utilize the same AUV sensor suite for mapping the underside of the sea-ice, and other ice features. Also, several AUVs come with upwards-looking DVL (e.g., the Gavia, Iver2, and REMUS AUVs), which will complement the dataset with iceberg-AUV relative velocity and ease post-processing of data. Two different methods that aim to map the general outline of an iceberg, while treating the iceberg drift as an unknown disturbance are discussed in the following section.

Figure 5.3 illustrates a possible strategy for determining the main particulars of an iceberg. The AUV detects an iceberg (by analyzing the MBE measurements), and keeps the same heading until it cannot detect the iceberg any longer. Now the AUV changes its heading by some angle (e.g., 120 degrees) towards the iceberg. The AUV detect the iceberg when passing the edge, and continues until the next edge is located, and so on. Following this strategy, a boundary box of the iceberg can be calculated (by storing the locations of the edges, as seen in Figure 5.3). To achieve full coverage mapping, a lawn-mover pattern could be performed after a sufficient number of edge-points have been detected. It must be noted that for this strategy to work, the translation and rotation of the iceberg must be estimated online. The detected edge-points must be fixed to the moving iceberg frame, and any planned paths (e.g., lawn-mover pattern) must also be fixed to this frame. In the work conducted by Kimball and Rock [98] and Hammond and Rock [77], the
translantions and rotations of the iceberg are estimated offline, and require the path to be self-intersecting. Thus, estimating these parameters online is not a trivial task. A method for estimating these variables is presented in Chapter 6, but for now they will be treated as unknowns.

An Arctic iceberg is a piece of a glacier, which has calved into the ocean, and it comes in many sizes and shapes [113]. A second strategy for determining an iceberg’s main particulars is to follow the iceberg edge around the iceberg. This chapter will focus on this strategy, which assumes that the submerged part of the edge of the iceberg has a relatively steep edge (Figure 5.1 shows an iceberg with steep sail). The proposed strategy is to use MBE measurements to detect a large gradient in the range measurements present when measuring along the edge. Since it is desired to map as much of the iceberg as possible, and to ensure that relative velocity measurements with the DVL are available, the AUV should travel parallel to the edge, but offset a distance towards the iceberg’s center.

Since the AUV is detecting and following the edge of the iceberg, it is not necessary to estimate the iceberg translation and rotation for guidance purposes, and the strategy will not be affected by iceberg drift. Complete coverage of the iceberg cannot be guaranteed using this mapping scheme, since the size of the iceberg may be larger than the area the MBE swath can cover with one circumnavigation, but the main particulars of the iceberg may be extracted from this data. Additionally, the guidance algorithm will not be affected by a potential degradation of the AUVs navigation system, since the objective is to follow a path constructed online from MBE measurements.

5.2 Iceberg detection guidance system

Consider an AUV patrolling a given area, by some guidance scheme (e.g. pre-programmed waypoints). The area may contain icebergs, and the objective is to acquire the main particulars of the icebergs in the area. The obtained parameters may be used for example in iceberg trajectory forecasting applications. The AUV is assumed to have a robust and accurate orientation sensor, capable of measuring the attitude of the AUV at a high rate. Moreover, the AUV is assumed to be equipped with an upwards-looking MBE, which will be used as the primary sensor for mapping and decision-making.

No prior information about the iceberg position is assumed available, but the iceberg geometry is assumed to be convex in the horizontal plane, and the edge of the iceberg is assumed to be steep, and the bottom relatively flat (i.e., approximately constant draft). The drift direction and speed of the iceberg are assumed unknown and constant. The iceberg can also rotate at a constant rate, independent of the ocean current.

The guidance system presented in this chapter does not consider forward-looking collision avoidance sonars. For practical implementations this will be an important part of the guidance system, to avoid potential impact with a deep drafted iceberg or entrapment between the sea-bottom and the ice.

The iceberg detection guidance system is implemented as a state machine, as illustrated in Figure 5.4. The outer layer of the state machine consists of two states,
iceberg detected and iceberg not detected. Detection in the context of the state machine refers to the transitional conditions placed on the start of the iceberg detection guidance algorithm. The iceberg edge-detection and following algorithms are implemented in the iceberg detected-state, which consist of three substates. All states are presented in the following section.

### 5.2.1 Iceberg detection

To transition to the iceberg detected-state, the guidance system must determine when an iceberg has been detected. Icebergs often have large drafts, but draft
alone may not be enough to distinguish an iceberg from a ridge. Ridges with drafts between 5 meters and 29 meters are reported by Davis and Wadhams [39], while drafts as deep as 47 meters have been reported by Lyon [118]. The method presented in this chapter only considers icebergs with principal length larger than 75 meters (medium berg and larger), resulting in a draft larger than 50 meters [121]. Using this assumption, an iceberg can be considered detected when the ice draft exceeds 50 meters. A different threshold can be specified depending on the expected iceberg draft, and the expected draft of other ice features. Since acoustic measurements may be noisy, at least $N_{\text{detection}} \geq 2$ beams should exceed the specified threshold before an iceberg is considered detected. This is to avoid false detections and, subsequently, to avoid searching for an iceberg that does not exist.

The MBE provides range measurements, $r_m$, between the sonar head and the ensonified object. To extract a point cloud from these measurements (such that e.g. the ice draft is easily identifiable), the measurements are transformed to the beam-frame (see Figure 5.5) by correcting for the AUV’s roll and pitch angles.

Let $R_{\mathbf{b}m}^b : \mathbb{S}^3 \rightarrow SO(3)$ denote the rotation matrix with argument $\Theta_{rp} = \begin{bmatrix} \phi & \theta & 0 \end{bmatrix}^T$, corresponding to the transformation between the body-frame and the beam-frame (i.e. roll and pitch corrections). Similarly, let $R_{\mathbf{m}b}^b : \mathbb{S}^3 \rightarrow SO(3)$ denote the rotation matrix between the measurements and the body-frame parameterized by $\Theta_{\text{beam}} = \begin{bmatrix} \alpha_m & \beta_m & 0 \end{bmatrix}^T$.

By assuming that the CO is placed at the MBE sonar head (to simplify the equations), the ranges can be converted to a point in the beam-frame by

$$p_{\text{mbe}}^b = \begin{bmatrix} 0 \\ 0 \\ z_{\text{auv}} \end{bmatrix} + R_{\mathbf{b}m}^b(\Theta_{rp})R_{\mathbf{m}b}^b(\Theta_{\text{beam}})k_r r_m,$$

where $p_{\text{mbe}}^b = [a_m b_m c_m]^T$ is the point derived from the range measurement in the beam-frame, where $a_{\text{mbe}}$ and $c_{\text{mbe}}$ represent along-track and cross-track distance, respectively. $z_{\text{mbe}}$ is measured draft, $z_{\text{auv}}$ is the depth of the AUV assumed measured with a pressure sensor, and $\phi$ and $\theta$ are the roll and pitch angles of the AUV, respectively. $\alpha_m$ and $\beta_m$ are the beam across-track and along-track angle. The AUV roll and pitch angles can be measured accurately from high performance IMU, typically part the AUV’s navigation system, while the MBE angles can be fixed or variable, depending on the MBE used. $k_r$ is the unit vector in the direction of the z-axis, and this is negative if the MBE is mounted upwards (and positive otherwise).

### 5.2.2 Iceberg edge detection

Once an iceberg candidate has been detected, a circumnavigation of the iceberg must be performed. This is a challenging task, due to the fact that an iceberg will both drift and rotate while the AUV conducts its mapping. By using an upwards-looking DVL, the relative velocity between the iceberg and the AUV can be measured. However, since rotation does not induce a Doppler shift, the iceberg rotation cannot be measured the same way. The guidance scheme proposed in this chapter aims at circumnavigating the iceberg, by following the iceberg edge. This requires
the edge of the iceberg to be identified in real-time using the available measurements.

Assume that the AUV is located near the edge of the iceberg, traversing parallel to the edge. If the walls of the iceberg are near vertical, and the bottom of the draft of the iceberg can be approximated as constant, the range measurements from the MBE will have three clearly identifiable sections; one where the beams reflect off the surface or sea-ice, one where the beams are hitting the near vertical wall, and one where the beams are hitting the bottom of the iceberg. This situation is illustrated in Figure 5.5.

From Figure 5.5, the cross-track distance to the edge is clearly identifiable. To effectively extract the cross-track distance to the edge (also in the presence of noise), a simple detection algorithm using piecewise linear regression on all MBE measurements is proposed (for more on piecewise linear regression, see [119]). The idea is to detect three distinct line segments from the MBE measurements, as seen in Figure 5.5. Let \( c_1 \) and \( c_2 \) be the cross-track distance to the break-points between the line segments. The piecewise linear function describing draft as a function of the cross-track distance, \( x \), can be expressed as

\[
F(x, \theta_0) = \begin{cases} 
    f_1(x) = a_1 + b_1 x, & x \leq c_1, \\
    f_2(x) = a_2 + b_2 x, & c_1 < x \leq c_2, \\
    f_3(x) = a_3 + b_3 x, & x > c_2,
\end{cases} \tag{5.2}
\]

where \( b_n \) is the slope of line segment \( n \), and \( a_n \) is the value where line \( n \) crosses the \( y \)-axis. \( \theta_0 \) is a column vector containing all the parameters of (5.2), i.e., all \( a_n \), \( b_n \), and the breakpoints. To be able to include the unknown breakpoints into the
5.2. Iceberg detection guidance system

regression, (5.2) can be rewritten to

\[
F(x, \theta) = \begin{cases} 
  f_1(x) = a_1 + b_1 x, & x \leq c_1, \\
  f_2(x) = a_1 + c_1 (b_1 - b_2) + b_2 x, & c_1 < x \leq c_2, \\
  f_3(x) = a_1 + c_1 (b_1 - b_2) + c_2 (b_2 - b_3) + b_3 x, & x > c_2. 
\end{cases} \tag{5.3}
\]

Since the water surface (or sea-ice) can be approximated as flat, then \(b_3 = 0\). If the bottom of the iceberg is also assumed to have approximately constant draft, then \(b_1 = 0\), and (5.3) reduces to

\[
F(x, \theta) = \begin{cases} 
  f_1(x) = a_1, & x \leq c_1, \\
  f_2(x) = a_1 - c_1 b_2 + b_2 x, & c_1 < x \leq c_2, \\
  f_3(x) = a_1 - c_1 b_2 + c_2 b_2, & x > c_2, 
\end{cases} \tag{5.4}
\]

with \(\theta = [a_1 \ b_2 \ c_1 \ c_2]\). Equation (5.4) can be solved using nonlinear least squares to find the best fit. The constraint \(c_2 > c_1\) must be enforced, since \(c_1 \geq c_2\) may cause numerical issues for the nonlinear least squares solver. If we look at (5.4) and Figure 5.5, it can be seen that \(a_1\) will be equal to 80, and \(a_3 = a_1 - c_1 b_2 + c_2 b_2\) will be equal to 0. The algorithm will also handle the case where the iceberg is on the other side of the AUV, and which will give \(a_1 = 0\) and \(a_3 = 80\).

The nonlinear optimization problem can now be formulated as

\[
\min_{\theta} J(x, \theta) = |Z(x) - F(x, \theta)|^2, \quad \text{s.t.} \quad c_2 > c_1, \tag{5.5}
\]

where \(x, Z(x) \in \mathbb{R}^k, k = 1, \ldots, \text{Nbeams}\) are the cross-track distance and the depth of each beam, respectively. The line between the breakpoints will mark the transition

---

Figure 5.6: Piecewise linear regression on a set of noisy MBE measurements.
between the iceberg bottom and the surface. By inserting \( x = c_1 \) and \( x = c_2 \) into the second equation in (5.4), and choosing the breakpoint corresponding to the minimum draft, that is, \( z_e = \min(F_{\text{fit}}(c_1), F_{\text{fit}}(c_2)) \), the cross-track distance, \( c_e \), to the edge of the iceberg for the piecewise linear function \( F_{\text{fit}}(x) \) can be found.

To avoid false detections, an edge is only deemed detected if the resulting fit has an root-mean-squared (RMS) error less than some margin (depending on the expected noise and shape deviations from the assumed ideal iceberg). Thus, all edge-points with RMS error above the threshold are discarded, and counted as a lost edge-point. Figure 5.6 illustrates a piecewise linear regression result using a set of noisy MBE points.

Having found the cross-track distance and the draft of the iceberg relative to the AUVs position, the edge-point, \( p_e^n = \begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix}^\top \), can be transformed to the \( n \)-frame using

\[
p_e^n = \begin{bmatrix} x_{\text{auv}}^n \\ y_{\text{auv}}^n \\ 0 \end{bmatrix} + R_z(\psi) \begin{bmatrix} a_e \\ c_e \\ z_e \end{bmatrix}
\]

(5.6)

where \( x_{\text{auv}}^n \) and \( y_{\text{auv}}^n \) are the position coordinates of the AUV in the horizontal plane expressed in the \( n \)-frame, and \( \psi \) is the heading of the AUV. \( R_z(\psi) \) is the principal rotation matrix about the \( z \)-axis by an angle \( \psi \). \( a_e \) is the along-track distance to the swath, which can be calculated from the average of all the along track distances in (5.1).

### 5.2.3 Iceberg edge following

After an iceberg is found, and the edge has been detected, the AUV must be able to follow the edge. The AUV is only able to measure the cross-track distance to the edge, and no information about the iceberg topography in front of the AUV is available. It is also not given that the AUV is able to detect an edge once an iceberg has been detected (for example if the AUV has a heading perpendicular to the iceberg edge). A simple method to search for the iceberg edge is to employ an outward spiral search. If no edge is detected after a certain amount of time, the iceberg is deemed lost, and the AUV continues its survey. In relation to the state machine in Figure 5.4, an edge is detected once \( N_{\text{edgeDetected}} \geq 2 \) number of edge-points are successfully detected. The reason multiple edge-points are required is to be able to calculate the edge bearing.

#### Calculating the edge bearing

Since the AUV does not have any information about what is in front of it, the bearing of the iceberg edge is calculated based on the history. This means that all detected edge-points are transformed into the \( n \)-frame, and stored in a queue. The queue has a fixed size. When this is full, each new measurement will cause the oldest measurement to be removed from the queue. The algorithm must be robust with regards to false edge detections and outliers; therefore, the bearing of the edge is calculated by using linear regression. Given a queue with \( q \)-elements of
edge-points, \([x_{e,j}^n, y_{e,j}^n]\), \(j = 1, ..., q\), we define

\[
S_{XX} = \sum_{j=1}^{q} (x_{e,j} - \bar{x}_e)^2, \tag{5.7}
\]

\[
S_{YY} = \sum_{j=1}^{q} (y_{e,j} - \bar{y}_e)^2, \tag{5.8}
\]

\[
S_{XY} = \sum_{j=1}^{q} (x_{e,j} - \bar{x}_e)(y_{e,j} - \bar{y}_e), \tag{5.9}
\]

where \(\bar{x}_e\) and \(\bar{y}_e\) represent the average values, that is, \(\bar{x}_e = \frac{1}{q} \sum x_{e,j}\) and \(\bar{y}_e = \frac{1}{q} \sum y_{e,j}\). Given the general line equation, \(y = \beta_0 + \beta_1 x\), the least squares estimates of \(\beta_0\) and \(\beta_1\) can be found from the following assignment [176, Chapter 2]

\[
\hat{\beta}_1 = \begin{cases} 
\frac{S_{XY}}{S_{XX}} & \text{if } S_{XX} \geq S_{YY}, \\
\frac{S_{XY}}{S_{YY}} & \text{otherwise,} 
\end{cases} \tag{5.10}
\]

\[
\hat{\beta}_0 = \begin{cases} 
\bar{y}_e - \hat{\beta}_1 \bar{x}_e & \text{if } S_{XX} \geq S_{YY}, \\
\bar{x}_e - \hat{\beta}_1 \bar{y}_e & \text{otherwise.} 
\end{cases} \tag{5.11}
\]

The reason for the two cases in (5.10) and (5.11) is that the general line equation does not handle vertical lines (\(S_{XX}\) or \(S_{YY} \rightarrow 0\)). Note that for the second case, the line equation becomes \(x = \beta_0 + \beta_1 y\). Now that an estimate of the line for the iceberg edge has been found, the four-quadrant angle for the iceberg edge bearing is

\[
\alpha = \arctan2(y_2 - y_1, x_2 - x_1), \tag{5.12}
\]

where the coordinates \(x_1, x_2, y_1,\) and \(y_2\) are found by setting two arbitrary x-coordinates if \(S_{XX} \geq S_{YY}\), or by setting two arbitrary y-coordinates otherwise, and inserting them into the corresponding line equation.

**Line-of-sight guidance for edge-following**

To follow the calculated bearing angle, the LOS guidance scheme [66, Chapter 10] will be used. This scheme allows the AUV to converge to and follow a path parallel to the iceberg edge. For a lookahead-based steering scheme, the course angle assignment is divided into two parts,

\[
\chi_d(e) = \chi_p + \chi_v(e), \tag{5.13}
\]

where \(\chi_p\) is the path-tangential angle, given by the edge bearing \(\chi_p = \alpha\). The velocity-path relative angle, \(\chi_v(e)\), depends on the cross-track error \(e\) to the desired path, which is calculated by

\[
e = -(c_e + s_e), \tag{5.14}
\]
where $\epsilon$ is used to offset the AUVs trajectory towards the estimated center of the iceberg, and $s \in [-1, 1]$ shifts the offset, depending on if the iceberg is to the left ($s = -1$) or to the right ($s = 1$) of the AUV. $c_e$ is the cross-track distance to the edge of the iceberg that was found in Section 5.2.2. This will not only ensure that the AUV maps as much of the iceberg as possible, but it will also provide measurements of the AUV-iceberg relative velocity using the DVL. Since the swath-width of the MBE will vary with the distance from the AUV to the iceberg, the offset should ideally have been calculated from this distance.

The velocity-path relative angle can now be found from the ordinary lookahead-based steering law [66]

$$
\chi_r(e) = \arctan \left( -K_p e - K_i \int_0^t e(\tau) d\tau \right),
$$

(5.15)

with proportional and integral gains given by $K_p$ and $K_i$, respectively. The integral effect in (5.15) is necessary to guarantee convergence to the desired path in the presence of disturbances, like ocean currents [31]. The full guidance law can be written as

$$
\chi_d(e) = \alpha + \arctan \left( -K_p e - K_i \int_0^t e(\tau) d\tau \right).
$$

(5.16)

**Relocating a lost edge**

The guidance scheme shown in (5.16) will only work as long as it is possible to detect the edge of the iceberg. If a corner of the iceberg causes the edge to change with close to 90 degrees, then the AUV will not be able to detect the iceberg edge any longer. Overshoot in the AUV’s path-following control function, e.g., due to a sharp corner, may also result in edge detection failure. Thus, the guidance system must be able to handle the scenario where an edge is lost.

The edge is deemed lost if the algorithm shown in Section 5.2.2 is unable to detect an edge for a given number of iterations. A counter is used to count the number of edges not detected, and if this counter reaches a given threshold ($N_{\text{lostEdge}}$), the state machine switches to the *relocate edge*-state. If this happens, the queue containing all the detected edge-points will be cleared. By assuming that the iceberg is approximately convex and that the AUV has followed the desired track, we know that the AUV cannot have passed in under the iceberg. Therefore, to relocate the edge, the AUV will initiate a turn in the direction the iceberg was detected until the edge is reacquired. Once the edge is found, the edge-following algorithm takes over.

One could argue that a more sophisticated commencement of the edge-following algorithm could be employed. For example, once the edge has been detected again, the AUV could circle around to the point where the edge was lost, entering this point with a heading perpendicular to the lost edge. This way, the AUV is able to map the whole edge. An improved commencement of the edge-following algorithm is also necessary if the convexity assumption is violated.
Figure 5.7: AUV trajectory around a stationary, simplified iceberg with steep walls. The desired and actual AUV track is shown along with the real and estimated iceberg edge.
5. **AUV guidance system for iceberg detection**

5.2.4 Termination criterion

After a full circumnavigation of the iceberg, the AUV should end the edge-following mode, and continue its pre-programmed mission. A method for switching between waypoints in the regular LOS algorithm, called *circle of acceptance* can also be used in this context [66, Chapter 10]. That is, the survey is considered completed when the position of the AUV in the horizontal plane \([x_{\text{auv}}, y_{\text{auv}}]\) satisfies

\[
[x_s - x_{\text{auv}}]^2 + [y_s - y_{\text{auv}}]^2 \leq R^2,
\]  

(5.17)

where \([x_s, y_s]\) is the start position of the survey, and \(R\) is the radius of the circle of acceptance. The start position of the survey can either be chosen as the position of the first detected edge point (offset by \(\epsilon\) to lie on the desired path of the AUV), or it can be chosen as the position of the AUV, once converged to the desired path (the latter is shown in the next section in Figure 5.7). When choosing \(R\), the estimated duration of the survey and the drift of the iceberg must be taken into account, or the AUV may miss on the circle after a complete circumnavigation of the iceberg. One solution is to make \(R\) grow according to the estimated iceberg drift rate as time passes. Another solution is to end the survey based on the calculated iceberg edge bearing. The stopping criteria can then be set to the bearing angle at the start of the survey, plus some angle margin (e.g. 45 degrees). The angle margin must also account for the rotation of the iceberg. This solution also assumes that the iceberg shape is convex, as the circumnavigation may be aborted prematurely otherwise. Depending on the slope of the iceberg, and the angle margin, a significant portion of the iceberg may be mapped twice.

5.3 Iceberg detection guidance system results

The guidance system presented in Section 5.2 was implemented as a C++ S-function and used in conjunction with the Arctic AUV simulator presented in Chapter 4. The guidance algorithm state machine is implemented using the Boost Statechart library [23], and the Eigen C++ library is used for linear algebra, matrix and vector representation [73]. The ALGLIB library [22] is used to solve the nonlinear least square optimization problem in the edge-detection algorithm.

A simulation of the complete guidance system can be seen in Figure 5.7. In this simulation the iceberg is stationary and ideal MBE measurements are assumed. The shape of the iceberg used in this simulation is a rectangular iceberg, with slightly sloped walls. This unrealistic shape is used to illustrate the guidance algorithm under ideal conditions. The AUV is able to circumnavigate the iceberg, as seen from Figure 5.7, and the detected edge corresponds to the actual edge quite well, except at the corners. There are also some edge detections anomalies in the area where the iceberg was first detected. This is likely caused by the large heading change of the AUV giving some inaccurate detections. There are some steady-state offsets between the detected and the real edge, which stem from the beams of the MBE not hitting the surface exactly at the edge.

Figure 5.8 presents the same simplified iceberg, but in this case the iceberg is drifting with a constant velocity of 0.5 m/s and rotating with a rate of 90°/h. The
Figure 5.8: AUV trajectory around a simplified iceberg with steep walls, drifting with translational velocity of 0.5 m/s and rotational velocity of 90 deg/h.
5. AUV guidance system for iceberg detection

AUV is able to circumnavigate the iceberg, and the warping of the path caused by the translation and rotation of the iceberg is clearly visible from the figure.

Iceberg translational velocity higher than 0.5 m/s caused problems at the corners of the iceberg. The edge was lost, and the relocate edge algorithm was invoked. However, due to the large velocity of the iceberg, the AUV missed the next iceberg side, and detected the side that was already mapped. This result indicates the need for a more sophisticated relocate edge algorithm, but this is left as further work.

Figure 5.10 shows a simulation tracking the edge of a rounded, oval iceberg, of similar length, width, and draft as the simple iceberg. This is a more realistic shape than the shape previously tested, and the shape does not strictly conform to our assumptions of steep walls and flat bottom. Figure 5.10 illustrates a successful circumnavigation of the rounded iceberg drifting with a velocity of 1 m/s and rotating with a rate of 90°/h. A U-turn can be seen at the start of the mapping, which is caused by a lost edge and initiation of the relocate edge algorithm. A snapshot from the edge detection algorithm from the rounded iceberg is presented in Figure 5.9. As seen from this figure, the AUV sees a rounded iceberg and the piecewise linear regression find a best fit that gives us three linear line segments.

5.4 Summary

Throughout this chapter, a guidance algorithm for circumnavigating an iceberg has been detailed. A state machine is used for transitioning between the different situations handled by the guidance scheme. When no iceberg is detected, the AUV follows a pre-programmed mission plan, and once an iceberg is detected, the AUV starts identifying the edge. The edge is detected using piecewise linear regression,
Figure 5.10: AUV trajectory around a rounded, oval iceberg drifting with translational velocity of 1.0 m/s and rotational velocity of 90 deg/h.
and the bearing of the edge is calculated using linear regression on several edge-points. Using the bearing angle and cross-track error to the edge, a LOS-based scheme is used to follow the iceberg edge. A simulation study shows that the guidance algorithm successfully guides the AUV around the iceberg, under the assumptions of noise free MBE range measurements and ideal position and attitude measurements. The guidance algorithm is also shown to successfully handle drift and rotation of the iceberg, as well as handling shapes that does not strictly conform to the assumptions of flat iceberg bottom and steep walls.

Further work includes testing the algorithm with noisy multibeam range measurements, as well as with noisy position and attitude measurements, to assess the algorithms ability to handle realistic data. Furthermore, the edge detection algorithm should be improved to robustly handle a generic iceberg shape, and to avoid potential problems with nonlinear least squares optimization (i.e., local minima). An interesting direction in this context can be to use machine learning to detect the iceberg edge. Improved methods for tracking the initial position of the edge-following procedure, and determine when a complete circumnavigation has been conducted, are also elements that should be investigated. A more sophisticated relocate edge search algorithm should also be considered.
Chapter 6

Iceberg mapping using simultaneous localization and mapping (SLAM)

This chapter presents an iceberg mapping navigation system, using a simultaneous localization and mapping (SLAM) algorithm for sensing the movement of the iceberg to determine its position in the global frame. The proposed method estimates the AUV’s pose in an iceberg-fixed coordinate system, as well as the relative velocity. The relative states can be used for both guiding the vehicle to achieve complete coverage, as well as estimation of a consistent iceberg topography. The algorithm also provides an estimate of the iceberg’s drift velocity – an important parameter for AUV trajectory planning as well as any related IM operations. The work in this chapter is presented in [139], which is based on [138].

6.1 Introduction

Localization is the problem of determining a robot’s position and orientation in a reference frame. When performing mapping of an unknown environment, the robot must know its location in order to build a map. Conventional underwater robotic navigation is usually performed using a combination of acoustic positioning systems and dead-reckoning by inertial navigation. The common methods for acoustic positioning are LBL and USBL, and where LBL requires two or more transponders to be deployed in the operational area, USBL usually requires a support ship to stay close to the AUV during the survey. The time between updates is also relatively long for acoustic systems, depending on range and other operational factors. Inertial navigation does not require external instrumentation, but the navigation uncertainty grows unbounded unless position fixes are acquired, either by using GNSS or acoustic positioning.
6. Iceberg mapping using simultaneous localization and mapping

Figure 6.1: Illustration of an AUV performing under-ice mapping using an MBE looking up at the ice.

SLAM is a method that attempts to build a map of the unknown environment, while using the same map to determine the robot’s location inside the map. Since the robot’s location is also needed for building the map, SLAM can be considered a chicken-or-egg problem, making it a hard problem to solve [62]. SLAM can be used to bound the error when performing inertial navigation without external instrumentation, and therefore SLAM is considered to be a requirement for truly autonomous operations [45]. Thus, much work has been conducted in the field of SLAM the last three decades (see e.g. Bailey and Durrant-Whyte [3], Cadena et al. [30], Durrant-Whyte and Bailey [45] and references therein).

Either solutions to the SLAM problem can consider the full trajectory of the robot, dubbed the full SLAM problem, or it can consider only the current pose of the robot. The latter is called online SLAM. The work presented in this thesis will only consider online SLAM, since the full SLAM problem is typically too computationally demanding to be solved online, and a mapping scheme requires an online solution. Furthermore, SLAM can be divided into two main groups based on its map representation. First, feature-based SLAM only store landmark locations (which may be updated upon re-observation). Detecting a landmark from sensor readings (e.g. laser, camera, sonar), and perhaps even more important, determining if it is the correct landmark, require a feature detector. Featureless approaches, on the other hand, rely on a sensor model to evaluate observations and update the map (often a grid map). Featureless approaches are often preferred in environments where clearly identifiable features are sparse. The method presented in this chapter is based on the bathymetric distributed particle SLAM (BPSLAM) algorithm presented by Barkby et al. [5, 6, 7]. The BPSLAM algorithm, which is a featureless, grid-map based approach to the online SLAM problem, was chosen.
since iceberg topography mapping has many similarities with bathymetric mapping, such as lacking clearly identifiable features and utilizing MBE as the main mapping sensor. The BPSLAM algorithm also has real-time properties. This is an important aspect since the end goal is to autonomously explore and map an iceberg, requiring the SLAM outputs to be available in real-time.

### 6.1.1 Bathymetric SLAM

Several SLAM algorithms for bathymetric mapping have utilized MBE as the main sensor for observing the environment. Many of the bathymetric SLAM algorithms are featureless approaches that stem from earlier work on TAN, which only considers the localization problem given a predefined map of the environment (see Carreno et al. [33] for a survey on TAN). The reason featureless approaches are often used for bathymetric surveys is the lack of clearly identifiable features on the seabed. An interesting TAN algorithm, which can be seen as a hybrid between TAN and SLAM, is presented by Hagen et al. [74], detailing a method for line-to-line terrain navigation. In this method, the terrain of the previous survey line in a lawn-mower pattern is used to bound the navigational error using synthetic aperture sonar on the HUGIN AUV.

A featureless bathymetric SLAM approach using extended Kalman filter (EKF) SLAM is presented by Roman and Singh [154], where the point cloud collected from the MBE is stored in submaps, and the submaps are pair-wise matched using correlation and an ICP algorithm. Other methods dealing with featureless bathymetric SLAM and submaps matched with ICP, extended from 2.5D (2D map with elevation, which is often used as map representation for bathymetry) to 3D, are presented in [145–147, 183]. An alternative method using factor graph SLAM and submaps matched with ICP is presented in [20], which is a full SLAM algorithm providing smoothing of the full trajectory.

Fairfield et al. [53, 54] propose a different approach to handle complex 3D underwater environments. By using an occupancy grid of cubic volume elements (voxels) as its map, a complex 3D geometry can be represented. The method uses a Rao-Blackwellized particle filter (RBPF) at the core of the SLAM algorithm (see [42, 131] for details on RBPF), and the evidence of occupancy in a certain voxel is updated by a log-likelihood update function. Fairfield et al. [54] state that the algorithm is robust to noise and that real-time constraints are achieved by adaptively changing the particle number.

Eliazar and Parr [48, 49, 50] introduce the distributed particle filter SLAM (DPSLAM) algorithm – a featureless real-time SLAM algorithm using an ancestry tree to store relations between particles. The ancestry tree algorithm makes it possible to use only one map for all particles (RBPF implementations usually require one map per particle), thus eliminating costly map-copy operations. While DPSLAM is intended for laser range sensor, Barkby et al. [5, 6, 7] suggest an alternative, namely the BPSLAM, which also uses RBPF and an ancestry tree, but is tailored for use with MBE and bathymetric surveys. Whereas the original BPSLAM is an online SLAM method, Barkby et al. [8, 9] adopt the method to solve the full SLAM problem, and eliminate the requirement for overlap in sensor data by using Gaussian processes.
6. Iceberg mapping using simultaneous localization and mapping

### 6.1.2 Iceberg SLAM

Kimball and Rock [95] report an extension to TAN intended for AUVs, that uses data captured from a side-mounted MBE on a ship to estimate the iceberg-relative ship track as well as iceberg motion, and Kimball and Rock [96, 97, 98] further extend the proposed method. The work presented in [98] utilizes a sideways-mounted DVL and MBE, and it optimizes the estimated iceberg trajectory and the measurement positions with respect to map consistency. The estimates of the iceberg trajectory, topography, and rotation are computed after a full circumnavigation of the iceberg, making this an offline SLAM approach with one loop-closure. An important aspect of the work presented by Kimball and Rock is that the iceberg is not instrumented, meaning estimates of iceberg motion must be calculated by the underwater vehicle itself. Hammond and Rock [77] build on the work by Kimball and Rock, and remove the need for external navigation aids in the iceberg trajectory estimation problem. The result is a method that generates a consistent iceberg topography map, not needing external positioning systems (like a ship with USBL, or LBL transponders), but without an estimate of the iceberg trajectory. In [76], the same authors present a GraphSLAM approach to underwater mapping with poor inertial information, with the intended application being iceberg mapping.

Kunz [106] presents a SLAM algorithm for mapping of ice floes using an AUV with upwards-mounted MBE and DVL. The presented method is a solution to the full SLAM problem, utilizing pose graph optimization. Kunz [106, Ch. 5] presents an AUV mission conducted under Antarctic sea-ice, and the results show how the proposed method performed in estimating the ice drift. During the mission, the AUV guidance system was able to track the translation of the sea-ice from measurements by the DVL, but the guidance system could not account for the rotation of the sea-ice, as this was not estimated until after the mission was completed.

### 6.2 Problem formulation

The problem considered is using an AUV equipped with an MBE to map the underwater topography of an iceberg using featureless bathymetric SLAM based on a particle filter estimator. The main challenge to be solved is accurate mapping of the underwater iceberg geometry in an iceberg-fixed coordinate frame that is translating and rotating at an assumed constant velocity. The AUV-iceberg relative coordinate system is illustrated in Figure 6.2.

SLAM algorithms work by utilizing a map of the environment to estimate the state of the vehicle. The objective is to estimate the relative state between the AUV and the iceberg, and therefore, information about the iceberg is required. If no a priori information about the iceberg is available, the AUV must build a map of the iceberg while simultaneously performing localization of the vehicle inside the map. An update of the estimated iceberg state will therefore only be performed upon loop-closures, that is, upon re-observation of a previously mapped area.

The following assumptions are made for the development of the presented algorithm:

1. Iceberg drift velocity (including rotational rate) is constant.
2. An upper bound on the iceberg’s size is known.

3. Drift velocity of the iceberg is much smaller than the AUV velocity.

4. Iceberg topography does not change during the survey.

The first assumption stems from the inherent inability of the SLAM algorithm to estimate the drift velocity and rotation when the AUV is between loop closures. This motivates the use of an active SLAM approach to optimize performance by minimizing time between loop closures. This thesis, however, will not study the development of an active SLAM guidance scheme. Thus, we assume there exists a guidance system capable of generating a lawn-mower pattern (in the iceberg-fixed frame), for which the MBE coverage area overlaps from leg to leg – resulting in frequent loop-closures after the first leg is completed. An a priori estimate of the drift velocity is also assumed known. This will greatly improve the performance of the estimator, since no update can be made before the first loop closure, and without any prior information, this error will propagate throughout the survey.
6. Iceberg mapping using simultaneous localization and mapping

The BPSLAM algorithm uses a fixed size grid map, with fixed resolution, thus requiring knowledge of an upper bound on the iceberg length and width in the survey setup. Knowledge of this size bound is reasonable, since it is typically provided by other systems, e.g., ship radar, UAVs, or satellites. However, if the AUV would be operating as a standalone system, without remote intervention, a possible solution would be to first run the AUV in an “iceberg size detection” mode, where the boundaries and keel depth of the iceberg are determined; e.g., by using the iceberg edge-detection method presented in Chapter 5. This could also be the phase where a priori estimates of the drift velocity are made, using measurements from an upwards-looking DVL. According to Yulmetov et al. [182], the rotation of an iceberg is mainly affected by tidal currents and the Coriolis effect, and in a given area multiple icebergs have been observed to exhibit the same rotational trend. Thus, an a priori rotational rate may be estimated based on the operational area.

The third assumption is an operational constraint – the AUV must be able to move faster than the environment it is mapping. To fulfil the constraint on relatively small loop closure periods, the AUV must move fast relative to the iceberg. This is similar to mapping bathymetry in the presence of ocean currents – the AUV must have a much larger velocity than the current to maneuver properly and obtain good data [178].

The fourth assumption is necessary, since we are utilizing the shape of the iceberg and loop closures to determine where the AUV is relative to the iceberg. This is a reasonable assumption if iceberg calving is disregarded, since other effects that change the iceberg shape occurs at a much larger timescale than a mapping survey.

6.2.1 AUV/Iceberg relative motion model

The ice-relative AUV pose in the \( i \)-frame, \( \eta^i_{rel} = [x^i_{rel} \ y^i_{rel} \ \psi^i_{rel}]^\top \), can be expressed in terms of the AUV and iceberg poses in the \( n \)-frame by

\[
\eta^i_{rel} = R^\top(\psi_{ice})(\eta^n_{auv} - \eta^n_{ice}),
\]

where \( \psi_{ice} \) denotes the heading of the iceberg relative to the NED-frame and \( R(\psi_{ice}) \in SO(3) \). By defining the relative velocity of the AUV in the \( b \)-frame as \( \nu^b_{rel} = \nu^b_{auv} - \nu^b_{ice} \in \mathbb{R}^3 \), the relative motion model can be expressed as

\[
\dot{\eta}^i_{rel} = R(\psi_{rel})\nu^b_{rel} - S(\tau_{ice})\eta^i_{rel} + \omega_1,
\]

\[
\dot{\nu}^b_{rel} = \dot{\nu}^b_{auv} + S(\tau_{rel})R^\top(\psi_{rel})\nu^i_{ice} - R^\top(\psi_{rel})\dot{\nu}^i_{ice} + \omega_2,
\]

where \( S = -S^\top \) is a 3 DOF skew-symmetric matrix [66, Ch.2] with the rotational rate, \( r \), about the z-axis as input. \( \psi_{rel} = \psi_{auv} - \psi_{ice} \) is the relative heading between the AUV and the iceberg, and \( \tau_{rel} \) and \( \tau_{ice} \) are the relative rotational rate and the rotational rate of the iceberg, respectively; see Figure 6.2. \( \omega_1 \) and \( \omega_2 \in \mathbb{R}^3 \) represent process noise, which are assumed to be zero-mean Gaussian (i.e., no bias). The AUV acceleration \( \dot{\nu}^b_{auv} \) is typically captured by the kinetic model [66]

\[
\dot{\nu}^b_{auv} = M^{-1} (\tau - C(\nu^b_{auv})\nu^b_{auv} - D(\nu^b_{auv})\nu^b_{auv} + \omega_1). 
\]
6.2. Problem formulation

This can be included as part of the filter dynamics, or it can be taken as a signal from a separate onboard navigation system. Since a 3 DOF model is used in the estimator, the depth of the AUV is not estimated. However, measurements of the depth are still used for processing topography measurements.

A pure kinematic model is sufficient for the iceberg, since we have assumed its velocity \( \nu_{\text{ice}} \) to be constant. However, to account for slow variations in its acceleration, the acceleration is modeled as driven by a stochastic process according to

\[
\begin{align*}
\dot{\eta}_{\text{ice}}^n &= R(\psi_{\text{ice}})\nu_{\text{ice}}^l, \\
\dot{\nu}_{\text{ice}}^l &= \omega_3,
\end{align*}
\]

where \( \omega_3 \in \mathbb{R}^3 \) is zero-mean Gaussian white noise. By defining the state vector

\[
x = \text{col}\left(\eta_{\text{rel}}^l, \nu_b^l, \eta_{\text{ice}}^l, \nu_{\text{ice}}^l\right) \in \mathbb{R}^{12},
\]

the state space representation of the motion model is described by

\[
\dot{x} = f(x, u) + \omega = \begin{bmatrix}
R(\psi_{\text{rel}})\nu_b^l - S(r_{\text{ice}})\eta_{\text{rel}}^l + \omega_1 \\
u + S(r_{\text{rel}})R^T(\psi_{\text{rel}})\nu_{\text{ice}}^l - R^T(\psi_{\text{rel}})\nu_{\text{ice}}^l + \omega_2 \\
R(\psi_{\text{ice}})\nu_{\text{ice}}^l \\
\omega_3
\end{bmatrix},
\]

where \( u = \dot{\nu}_b^i \) and \( \omega = \text{col}\left(\omega_1, \omega_2, 0_{3 \times 1}, \omega_3\right) \).

6.2.2 The topography map

The topography map is represented by a grid map \( M \) with fixed size and resolution, where the size must be set according to the size bounds of the iceberg. The resolution depends on the type of MBE used, the number of beams, and the distance between the AUV and the mapped environment.

In the framework of a particle filter, let \( \mathcal{M} \subset \mathbb{Z}^2 \) be the set of indices belonging to the grid map, and let a topography estimate be defined by

\[
\Lambda_{p_{id}} = \left\{ p_{id}, \xi, \Omega, t \right\},
\]

where \( p_{id} \in \mathbb{Z}^+ \) is the particle id that made the estimate, \( \xi \in \mathbb{R} \) is the information vector of the topography estimate, with corresponding information matrix \( \Omega \in \mathbb{R} \), and \( t \in \mathbb{R}_{\geq 0} \) is the timestamp when the estimate was made. From this, the topography map can be expressed as

\[
M(i, j) = \left\{ \Lambda_{p_1}, \Lambda_{p_2}, \ldots, \Lambda_{p_k} \right\},
\]

where \( (p_1, p_2, \ldots, p_k) \) is the set of particles that have made an update to grid node \((i, j) \in \mathcal{M} \). If no particle has made an update to node \((i, j) \), then \( M(i, j) = \emptyset \).

6.2.3 Motion model measurements

Measurements of a subset of the states of the relative motion model are required to reduce the dead-reckoning errors. We will assume that the AUV’s orientation is
available at each update, while the position is available sporadically. For simplicity, only the equations for the full position and orientation update are presented here. This gives the measurement model

$$\eta_{n_{\text{auv}}} = R(\psi_{\text{ice}})\eta_{i_{\text{rel}}} + \eta_{n_{\text{ice}}}. \quad (6.10)$$

To avoid large errors in the global position, the AUV can get acoustic positioning fixes (e.g., by using LBL or USBL) with update rate depending on measurement system, availability, and navigation system accuracy. Further, the relative linear velocity can be assumed measured using an upwards-looking DVL when the AUV is below the iceberg. For simplicity, the velocity measurement is assumed available at every update. The relative rotation rate cannot be measured directly, but the rotational (yaw) rate of the AUV is assumed measured using an onboard IMU. This gives

$$\begin{bmatrix} u_{\text{rel}} \\ v_{\text{rel}} \\ r_{\text{auv}} \end{bmatrix}^b = \nu_{\text{rel}}^b + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} R^T(\psi_{\text{rel}})\nu_{i_{\text{ice}}},$$

$$= \nu_{\text{rel}}^b + \text{diag}(0 \ 0 \ 1)\nu_{i_{\text{ice}}}. \quad (6.11)$$

Note that we do not assume that the velocity of the AUV is measured, since this can be hard to accomplish if acoustic position updates are not periodically available (and of sufficient quality). If the AUV velocity is available as well, it is straightforward to include these measurements, and that would improve the estimation of the iceberg velocity. Finally, the position and orientation of the iceberg that are estimated in the SLAM algorithm are used to update the relative model. Since a particle filter has been chosen as SLAM implementation, the current pose of the iceberg is be determined from a weighted average of the particle poses

$$\eta_{n_{\text{ice}}}^n = \frac{\sum_{i=1}^{N_p} w_i \eta_{n_{\text{ice}},i}^n}{\sum_{i=1}^{N_p} w_i}, \quad (6.12)$$

where $N_p$ is the number of particles, and $w_i$ is the particle weight of particle $i$. Thus, the measurement vector can be expressed as

$$y = \begin{bmatrix} x_{\text{auv}}^n \\ y_{\text{auv}}^n \\ \psi_{\text{auv}} \\ u_{\text{rel}}^b \\ v_{\text{rel}}^b \\ r_{\text{auv}} \\ x_{\text{ice}}^n \\ y_{\text{ice}}^n \\ \psi_{\text{ice}} \end{bmatrix}^\top,$$

and by combining (6.10), (6.11), and the iceberg position measurement, the combined measurement model is given by

$$y = h_m(x) = \begin{bmatrix} R(\psi_{\text{ice}})\eta_{i_{\text{rel}}}^i + \eta_{n_{\text{ice}}}^n \\ \nu_{\text{rel}}^b + \text{diag}(0 \ 0 \ 1)\nu_{i_{\text{ice}}} \\ \eta_{n_{\text{ice}}}^n \end{bmatrix}. \quad (6.14)$$

### 6.2.4 Topography measurements

To perform loop-closures using the SLAM algorithm, observations of the environment must be compared to a measurement model. The method presented in this...
6.2. Problem formulation

The chapter employs a method similar to the observation model used in BPSLAM presented by Barkby et al. [7]. MBE observations are modeled as sets of range \( r \), cross-track angle \( \alpha \), and along-track angle \( \beta \), i.e., \( z = [r \ \alpha \ \beta]^{\top} \). The along-track angle is typically zero, unless the MBE is mounted with a tilt angle. The across-track angles can be constant or varying, depending on the MBE used. Adding the angles to the observation model also provides the possibility to model uncertainty caused by the size of the beam width (unlike laser range measurements, the MBE beams have a non-negligible footprint). The observation model for one beam observation is given by

\[ z = h_s(E^i, p_{rel}^i, \Theta_{rel}) + \omega_{MBE}, \]  

where \( h_s \) is the SLAM measurement function that uses the ensonified grid in the map, \( E^i \), and the relative position and attitude, to calculate an expected observation. The relative position of the AUV in the NED-frame is defined as \( p_{rel}^n = [x_{rel}^n \ y_{rel}^n \ z_{rel}^n]^{\top} = [x_{auv}^n \ y_{auv}^n \ z_{auv}^n]^{\top} - [x_{ice}^n \ y_{ice}^n \ 0]^{\top} \), and the relative attitude is defined as \( \Theta_{rel} = [\phi_{auv} \ \theta_{auv} \ \psi_{rel}] \). Note that we cannot use the relative AUV/iceberg state that is input to the SLAM algorithm directly, since the relative state will differ from particle to particle. Using (6.10), the relative state of the \( j \)th particle can be expressed as

\[ \eta_{rel,j}^n = \hat{\eta}_{auv}^n - \eta_{ice,j}^n = R(\hat{\psi}_{ice})\hat{\eta}_{rel}^i + \hat{\eta}_{ice}^n - \eta_{ice,j}^n, \]

where \( \hat{\cdot} \) denotes the estimated states input to the SLAM algorithm, and \( \eta_{ice,j}^n \) is the iceberg position estimated by particle \( j \). The ensonified grid can now be found with the following relation

\[ E^i = R^{\top}(\psi_{ice})p_{rel}^n + R_b^{i}(\Theta_{rel})R_m^b(\Theta_{beam})\vec{k}_r_m. \]

It is assumed that roll and pitch are measured using the IMU, and the depth of the AUV is assumed available through pressure sensor measurements. \( \Theta_{beam} = [\alpha_m \ \beta_m \ 0]^{\top} \) is the measured beam angles (often fixed), and \( r_m \) is the beam range measured by the MBE. It should be noted that the observations are used to determine what grid node is ensonified in the measurement model. This simplification is disregarding the data association problem that arises by the uncertainties in the measurements. However, solutions that take this into account have been found to be too computationally complex [7]. The measurement function can now be expressed as

\[ h_s(E^i, p_{rel}^i, \Theta_{rel}) = \begin{bmatrix} \sqrt{b^2 + a^2 + d^2} \\ \arctan\left(\frac{a}{d}\right) \\ \arctan\left(\frac{b}{d}\right) \end{bmatrix}, \]

\[ \begin{bmatrix} b \\ a \\ d \end{bmatrix} = R_b^{i}(\Theta_{rel})\text{diag}(1\ 1\ \text{sgn}(k)) (E^i - p_{rel}^i). \]

For upwards-mounted MBE, the sign of the vertical component must be reversed, shown by the signum-function in (6.19). Note that some MBE models can output
processed xyz-points, that is, they output $p_{\text{mbe}} = \begin{bmatrix} dx & dy & dz \end{bmatrix}^\top$, corrected for roll, pitch, sound speed, and ray bending. This is the case for the multibeam used by the HUGIN AUV, the Kongsberg EM2040. To utilize this processing, (6.17) can be modified to

$$E^i = R^\top(\psi_{\text{ice}})(p_{\text{rel}} + R(\psi_{\text{auv}})p_{\text{mbe}}). \quad (6.20)$$

### 6.2.5 Problem statement

Suppose that an AUV equipped with an upwards-mounted MBE is mapping a drifting and rotating iceberg, using BPSLAM. Let $\hat{\eta}_{\text{rel}}^i$ and $\hat{\eta}_{\text{ice}}^n$ be the estimate of the AUV’s relative pose in the $i$-frame and the estimate of the pose of the iceberg in the $n$-frame, respectively, while $\hat{\nu}_{\text{ice}}^i$ is the estimate of the iceberg drift velocity. The primary objective is to design an estimator, such that

$$\lim_{t \to \infty} |\hat{\eta}_{\text{rel}}^i(t) - \eta_{\text{rel}}^i(t)| = 0, \quad (6.21)$$

$$\lim_{t \to \infty} |\hat{\eta}_{\text{ice}}^n(t) - \eta_{\text{ice}}^n(t)| = 0. \quad (6.22)$$

The secondary objective is to estimate the drift velocity $\nu_{\text{ice}}^i$ of the iceberg in the $i$-frame, such that

$$\lim_{t \to \infty} |\hat{\nu}_{\text{ice}}^i(t) - \nu_{\text{ice}}^i(t)| = 0. \quad (6.23)$$

The third objective is to estimate the topography of the iceberg in real-time in a fixed size grid map, such that

$$\lim_{t \to \infty} |\hat{M}(t) - M| = 0, \quad (6.24)$$

where $\hat{M}(t)$ is the map topography estimate.

### 6.3 Preliminaries on SLAM

Before delving into the iceberg mapping estimator, some of the details of SLAM and the BPSLAM method that the iceberg SLAM method has been based on must be detailed.

#### 6.3.1 Particle filters

The idea behind particle filters (PF), also called sequential Monte Carlo estimators, is that any probability density function (PDF) can be approximated by using a set of discrete particles. PFs have an advantage over the popular EKF algorithm when estimating non-gaussian models, since PFs can represent non-Gaussian (and even multi-modal PDFs). Monte Carlo methods rely on the law of large numbers [62] to approximate PDFs, and the PDF will only be exact when the number of particles is infinite. However, by using a technique known as Rao-Blackwellization, the number of particles necessary can be significantly reduced. The RBPF was introduced by Murphy [131] as an effective method for solving the SLAM problem. The RBPF
utilizes a factorization of the joint posterior, and as a result, the maps of each particle can be updated by using the particles pose estimate [42]. This means that the mapping part of the filter is reduced to mapping with known poses.

A particle is an estimate of the state of the system, often the pose of the robot. At each timestep in the PF, the state is propagated according to a probability distribution (called the proposal distribution), which will grow the uncertainty in all directions and remain centered on the last known state [62]. Then all particles are weighted according to their correspondence with the observed environment, before a resampling step is performed. The resampling process is necessary to avoid divergence of the particle filter, and is a process that eliminates unlikely particles. The last step in the particle filter is the map update step, where particle maps are updated using the observations of the environment.
Sampling importance resampling (SIR) is a method that attempts to prevent particle degeneracy – the case where one or a few of the particles have the majority of the weights [111]. The idea is to introduce a resampling step where the probability of picking a particle is proportional to the particles importance weight [62]. Once the new particle set is in place, all particles have their weights reset to a constant value. An illustration of three different resampling methods are presented in Figure 6.3.

### 6.3.2 Distributed particle mapping (DPM)

In general, particle filters use one map per particle, since the maps will differ due to different particle states when assigning measurements to the map. Upon resampling, the maps of the surviving particles must be copied to the new particles, while discarded particles are deleted along with their maps. This map copy operation is a costly process with complexity $O(MP)$, especially for large maps ($M =$ number of grids in the map) and high number of particles, $P$. The idea behind distributed particle mapping (DPM) is to use a common map for all particles and trace each particle update in each grid through an ancestry tree.

The DPM method is presented in Eliazar and Parr [48, 49] detailing the DPSLAM and DPSLAM 2.0, respectively. The runtime complexity of DPSLAM is $O(ADP\log P)$ [48], where $A$ is the sweep area of the sensor and $D$ is the depth of the ancestry tree. Using an improved search algorithm, the runtime complexity of DPSLAM 2.0 was reduced to $O(AP\log P)$. The DPSLAM 2.0 algorithm provides a significant reduction in runtime complexity, compared to the native particle filter implementation, since typically $M >> A\log P$. Further improvements to the DPSLAM algorithm is presented in Eliazar and Parr [50], reducing the runtime complexity to $O(AP)$, which is the same runtime complexity as pure localization using particle filters.

### 6.3.3 Ancestry tree

The DPM method retains an ancestry tree showing the ancestry of particles – indicating what particles were resampled (children) from a particular particle (parent). The full map for a given particle can be reconstructed by tracing the ancestry of a leaf node all the way to the root.

A key feature of the ancestry tree is that it does not grow unbounded as time progresses. After each resampling step, all particles that were not resampled are removed from the tree (referred to as dead particles). Deleting some particles can lead to some of the parent particles having only one child (this can also happen if a particle is only resampled once), and having a parent with only one child is not helpful – it only increases the size of the ancestry tree. Thus, a step called prune is performed on the ancestry tree after each resample, see Figure 6.4. The pruning removes all dead particles and merges parents of only-children with its child. This way, the size of the ancestry tree is guaranteed to never exceed $2N−1$ nodes, where $N$ is the number of particles. See Eliazar and Parr [49] and Barkby et al. [7] for more details.
6.4 Motion estimator for iceberg mapping

The iceberg mapping and motion estimator presented in this chapter has two layers. The bottom layer is the SLAM layer, which estimates the topography of the iceberg, as well as the iceberg’s position in the NED-frame. The top layer consists of an EKF estimating the relative position and velocity between the AUV and the iceberg. The EKF uses the weighted average state from the SLAM algorithm from (6.12) as the
measured iceberg pose, while the other measurements are from the AUV navigation system and the DVL. The velocity of the iceberg is also estimated in the top layer EKF. A block diagram of the estimator is shown in Figure 6.5.

### 6.4.1 Relative motion estimator

The relative motion estimator is implemented as a standard discrete EKF. The state of the EKF is defined in (6.6), and the state transition is given by (6.7), while the EKF predict equations are given by [28]

\[
\dot{x}_{k|k-1} = \dot{x}_{k-1|k-1} + \Delta_T f(\dot{x}_{k-1|k-1}, u_{k-1}), \quad (6.25)
\]
\[
P_{k|k-1} = F_{k-1} P_{k-1|k-1} F_{k-1}^T + Q_{k-1}, \quad (6.26)
\]

where $\Delta_T$ is the timestep, $Q$ is the model covariance matrix, and $P$ is the error covariance matrix. $F \approx I + \Delta_T \frac{\partial f}{\partial x} |_{\dot{x}_{k-1|k-1}}$ is the discretized Jacobian of (6.7). The EKF update equations are given by [28]

\[
K_k = P_{k|k-1} H_{m,k}^T (H_{m,k} P_{k|k-1} H_{m,k}^T + R_k)^{-1}, \quad (6.27)
\]
\[
\dot{x}_{k|k} = \dot{x}_{k|k-1} + K_k \left( y_k - h_m(\dot{x}_{k|k-1}) \right), \quad (6.28)
\]
\[
P_{k|k} = (I - K_k H_{m,k}) P_{k|k-1}, \quad (6.29)
\]

where $h_m$ is the measurement model defined in (6.14), and $H_{m,k} = \frac{\partial h_m}{\partial x} |_{\dot{x}_{k|k-1}}$ is the Jacobian of $h_m$, $R_k$ is the measurement covariance, $K_k$ is the Kalman gain, and $y_k$ is the measurement at timestep $k$, defined in (6.13).
Algorithm 1 Bathymetric Distributed Particle Filter SLAM

1: **Initialize** each particle from initial distribution and add any prior information to the map.

2: **while** running **do**

3:     **for** $N_p$ **do**

4:         **Propagate** by sampling from motion model.

5:         **Weight** according to map agreement.

6:         **Update** maps of particles.

7:     **end for**

8:     **if** $N_{\text{eff}} < \frac{N_p}{2}$ **then**

9:         **Resample** based on importance weight.

10: **Prune** ancestry tree.

11: **Update** particle set.

12: **end if**

13: **end while**

6.4.2 Iceberg BPSLAM

The SLAM algorithm chosen for the iceberg mapping problem is based on the BPSLAM algorithm presented by Barkby et al. [5, 6, 7]. BPSLAM uses DPM and is an efficient, featureless RBPF SLAM algorithm.

Particle filters are especially suitable for featureless approaches due to its ability to provide multiple hypotheses. This means that the filter will at all times retain multiple possible iceberg poses, called particles, and all hypotheses will be evaluated against the observed environment to find the best fit. The overall steps in the BPSLAM algorithm are shown in Algorithm 1. The following section provides an overview of the Iceberg BPSLAM algorithm and details the proposed modifications to the original BPSLAM methods.

**Particle propagation**

The particle filter will at all times keep a set of $N_p$ active particles

$$S_t = \begin{bmatrix} \eta_{\text{ice},1}^n & \cdots & \eta_{\text{ice},N_p}^n \\ p_{\text{id},1} & \cdots & p_{\text{id},N_p} \\ w_1 & \cdots & w_{N_p} \end{bmatrix},$$

(6.30)

where $p_{\text{id}}$ and $w_k$ are the particle id and weight of the $k^{th}$ particle. The set also contains the particle state vector, $\eta_{n,\text{ice,k}}^n$. At each timestep, each particle is propagated according to a proposal distribution

$$\hat{\eta}_{\text{ice,k}}^n = R(\hat{\psi}_{\text{ice}}^n)\hat{\nu}_{\text{ice}}^i + \omega_{\text{ice},t}^n,$$

(6.31)
where $\hat{\nu}_\text{ice}^1$ is the estimated iceberg velocity from the top layer estimator (see Figure 6.5). Equation (6.31) is similar to the iceberg motion model in (6.5), except that the SLAM filter does not estimate the iceberg velocity. Since the SLAM algorithm utilizes measurements of the iceberg topography to estimate the iceberg pose, it was deemed more suitable to have the velocity estimate in the top level estimator where measurements of relative velocity could be included.

\[ \omega_{n_{\text{ice}}} \sim \mathcal{N}(0, \sigma^2_{\nu_{\text{ice}}} \in \mathbb{R}^3) \]

is driving the particle filter with variance $\sigma^2_{\nu_{\text{ice}}} \in \mathbb{R}^3$. The variance should be on the order of the expected iceberg velocity variations, plus measurement noise and dead-reckoning errors.

**Particle weighting**

To assess whether or not a particle is a good estimate of the iceberg pose, each particle is evaluated against the map contained in the particle filter. Obviously it will not be possible to assess if a particle is good or bad if no prior map exist. If the observations contain areas overlapping the previously mapped terrain (either fully or partially), it is possible to determine how well the observations fit with the expected results from the map, by using the sensor model described in (6.18). Three different methods for weighting the measurements are discussed - the original BPSLAM method from [7] (converted to log-space for numerical stability); a modified version of the BPSLAM method; and an ICP based method.

**BPSLAM weighting**

Using the log-likelihood function for normal distributions for beam $j$ gives

\[
\ln \left( P \left[ (\hat{E}_{z,j} - \bar{E}_{z,j}) = 0 \right] \right) = -\frac{1}{2} \left( \frac{\hat{E}_{z,j} - \bar{E}_{z,j}}{\sigma^2_{E_{z,j}} + \sigma^2_{E_{z,j}}} \right)^2 - \ln \left( 2\pi \left( \sigma^2_{E_{z,j}} + \sigma^2_{E_{z,j}} \right) \right),
\]

(6.32)

where $j \in W_k \subset Z^+$ is an observation index in the set of all valid observations for a given particle. $\hat{E}_{z,j}$ and $\sigma^2_{E_{z,j}}$ are the estimated topography and its corresponding variance estimate, which are stored per grid node for all particles that have made an update to that particular node. $\bar{E}_{z,j}$ can be found using (6.17) and $\sigma^2_{E_{z,j}}$ can be estimated through backward transport using [7],

\[
\sigma^2_{E_{z,j}} = (H^T_{s,k} R_{\text{obs}}^{-1} H_{s,k})^{-1},
\]

(6.33)

where $H_{s,k}$ is the Jacobian of the measurement function in (6.18), and $R_{\text{obs}} = \text{diag}(\sigma^2_{r}, \sigma^2_{\alpha}, \sigma^2_{\beta})$ is the covariance of the observations. A weight will only be calculated for a given observation if it ensonifies a grid node already containing a topography estimate, i.e., it belongs to the set of valid observations $W_k$.

The particle weight can be calculated from the joint likelihood of the beam weights

\[
w_k = f_{z_k|x_k,M} = \prod_{j \in W_k} P \left[ (\hat{E}_{z,j} - \bar{E}_{z,j}) = 0 \right] = \sum_{j \in W_k} \ln \left( P \left[ (\hat{E}_{z,j} - \bar{E}_{z,j}) = 0 \right] \right).
\]

(6.34)
6.4. Motion estimator for iceberg mapping

where $\mathcal{W}_{s,k} \subseteq \mathcal{W}_k$ is a subset of the indices of the beam weights determined by sampling $N_{\text{min}} = \min(|\mathcal{W}_k|)$ for $k = 1...N_p$ random indices from $\mathcal{W}_k$ into $\mathcal{W}_{s,k}$ with equal probability. The subset $\mathcal{W}_{s,k}$ will be different for each particle, since the set $\mathcal{W}_k$ will differ. This means that only $N_{\text{min}}$ of the beam weights will be used to determine the particle weight. The particles will have differing number of valid weights (due to different number of overlapping observations). We can define a criterion for including a particle in the resampling step by setting a minimum overlap, $\gamma$. By for instance setting $\gamma = 50\%$, a minimum of 50\% of the ensonified grid nodes must contain a previous estimate for the particle to be included in the resampling step. Note that this is not the same as saying 50\% of the MBE beams must produce a valid weight, since different beams may ensonify the same grid node. If a particle is not included in the resampling process it will not be assigned a weight, and it cannot be removed or spawn new particles during resampling.

Modified BPSLAM weighting  The original BPSLAM method process measurements sequentially, i.e., each new MBE swath initiates a full particle filter step (see Algorithm 1). Since resampling and prune are relatively computationally expensive, a method that allows measurements to be buffered and processed batch wise (multiple swaths at the time) was desired. Furthermore, batch processing of swaths will allow adaptive sampling rate in the SLAM algorithm, which can be important to ensure real-time operation during run-time transients. Therefore, a new weighting method for the BPSLAM algorithm is proposed, based on the work by Hagen et al. in [74]. First, the beam likelihood is calculated as in (6.34), but with $\mathcal{W}_{s,k} = \mathcal{W}_k$, and then modified according to

$$w_k = \frac{\alpha(x_k)}{\mathcal{M}^{m(x_k)}_{x_k, M}},$$

where $0 < \alpha(x_k) < 1$ is a measure of the actual terrain information, which depends on terrain variation, map noise, and sensor noise (see [74] for details). This modifier makes the algorithm more robust, especially in segments with little terrain variations [74]. The modifier $m(x_k)$ represents the number of grid nodes supported at $x_k$, allowing use of all available beam information, rather than only the minimum number of beams as in the original BPSLAM method. Note that this will also improve the run-time for the algorithm for parallel execution, since calculating $N_{\text{min}}$ requires thread synchronization in a practical implementation, which produces significant overhead.

Particle filter ICP weighting  A method that is frequently used for EKF SLAM is the iterative closest point (ICP) method for matching point clouds. This weighting method is proposed as an alternative to the two BPSLAM weighting methods, and is also developed with the intention of batch processing MBE measurements to allow real-time execution. The details of the ICP algorithm is outside the scope of this thesis, but the ICP implementation has been taken from the source code provided by Bouaziz et al. [24], and an overview of the ICP algorithm can be found in [24] and references therein.

Let $E_{j,k} \in \mathcal{E}_k$ be observation $j$ of particle $k$ calculated from (6.17), where the set $\mathcal{E}_k$ represents the set of all observations at the current timestep, referred to as
the patch. The output of the ICP algorithm is a rigid body transformation \( T(E, \Theta) \) transforming the input data points \( E \) (our observations) to a set of model points \( M \) (our map). The rigid body transformation is calculated by minimizing a cost function. The particle weight can now be calculated from \([155]\)

\[
\begin{align*}
    f_{z_k|x_k,M} &= e^{\sum_{j \in E_k} \| M_j - T_k(E_j, \Theta_j) \|^2 }, \\
    w_k &= f_{z_k|x_k,M}^{m(x_k)}
\end{align*}
\]

(6.36)

(6.37)

where the modifier \( m(x_k) \) is the same as in the modified BPSLAM method.

The ICP weighting algorithm does not take the beam and grid uncertainty into account, like the two former methods, but provides a best fit between measurements and map points. Altering the ICP method to account for this uncertainty could be an interesting extension of the algorithm in future work.

Map update

After weighting each particle, the map must be updated. Since a static topography is assumed, the predict step can be omitted in the filter estimating the topography. By following the BPSLAM methodology and by using the dual form of EKF, the Extended information filter (EIF), the update equations can be formulated as \([7]\)

\[
\begin{align*}
    \tilde{E}_z &= \tilde{\Omega}^{-1} \tilde{\xi}, \\
    \Omega &= \tilde{\Omega} + H_s^T R_{obs}^{-1} H_s, \\
    \xi &= \tilde{\xi} + H_s^T R_{obs}^{-1} [ z - h_s(\tilde{E}_i^{p', \Theta_i^{rel}}) + H_s \tilde{E}_z ] ,
\end{align*}
\]

(6.38)

(6.39)

(6.40)

where \( \xi \in \mathbb{R} \) is the topography estimate vector in information form, \( \Omega \in \mathbb{R} \) is the information matrix, and \( E_z \) is the topography estimate of the selected grid. The notation \( \tilde{\cdot} \) indicates a priori estimate since time subscript has been omitted.

Particle resampling

In a particle filter, resampling is necessary to achieve convergence, but it can also be dangerous since it limits the memory of the filter and can potentially lead to situations where important particles are removed (particle depletion). Since the goal of resampling is to remove unlikely particles, while keeping particles that have good correspondence with the map, it only makes sense to perform resampling if the particle weights differ significantly. A method to accomplish this is to define an effective particle size as presented in \([7]\) and \([72]\),

\[
N_{eff} = \frac{1}{\sum_{i=1}^{N_t} \bar{w}_i^2},
\]

(6.41)

where \( \bar{w}_i \) is the normalized weight for particle \( i \). Resampling is only performed when \( N_{eff} < N_r / 2 \), where \( N_r \) represents the number of particles eligible for resampling.

If the effective particle size is small enough and resampling is allowed to continue, the resampling step is performed according to the principle of SIR, where
6.5. Iceberg SLAM results

the normalized particle weight defines the probability of a particle being drawn into the new particle set. If a certain particle with id equal to \( j \) is drawn, it is inserted into the ancestry tree as a child of particle \( j \) and assigned a new particle id. The systematic resampling algorithm has been selected since this method has been shown to provide smaller variance and lower computational cost than the other commonly used resampling strategies \[82\] (shown in Figure 6.3).

6.4.3 Summary of estimation algorithm

To wrap up the section describing the developed estimator, a short summary is provided. The reader is referred to Section 6.2.5 providing the problem statement, and Figure 6.5 providing a graphical overview of the estimator.

The top layer estimator is a standard EKF, running at high rate to continuously provide updated estimates to for example a guidance system. The top layer provides estimates of the relative position and velocity between the AUV and the iceberg, as well as estimates of iceberg position and velocity (see state vector in (6.6)), propagated according to (6.7). The inputs to the EKF are the measurements in (6.13), where the AUV pose and angular rate, as well as the relative velocity, are external signals, while the iceberg pose is an output of the bottom layer SLAM algorithm.

The input to the bottom layer is the relative pose and velocity from the top layer, which are used to propagate the particles according to (6.31). At each SLAM step, Algorithm 1 is executed, before a new SLAM estimate is generated according to (6.12), which is used to update the top layer estimator. In between SLAM steps, all MBE measurements are timestamped (along with the relative position, attitude, and velocity) and buffered. This architecture allows adaptive SLAM timesteps, which will handle run-time transients, as long as the average run-time is well below the real-time constraints.

6.5 Iceberg SLAM results

The following section presents an assessment of the performance of the iceberg mapping estimator detailed throughout this chapter. A real iceberg topography, from the PERD iceberg database \[168\] is used in a simulation study. The selected iceberg, no. R11i01, is a wedged iceberg with dimension 160 by 135 meters, a sail height of 31 meters, and a draft of 110 meters (see illustration in Figure 4.3). The results highlight the estimators performance with regard to the problem statement in Section 6.2.5. A run-time analysis is also presented to evaluate the algorithms real-time potential, to assess the feasibility of using it in closed-loop with an active guidance algorithm.

Since particle filters are probabilistic algorithms, they will provide different results each time they are run. To assess the performance and behavior of probabilistic methods, Monte Carlo simulations (MCS) should ideally be performed. The principle behind MCS is that the behavior of a stochastic system can be assessed by the empirical process of drawing a lot of random samples and observing the output \[127\]. The SLAM algorithm presented in this thesis consist of several random variables, and it is in itself computationally demanding. MCS have therefore
not been performed, as this has been deemed to computationally demanding in its current state.

In order to verify the performance of the algorithm, we first test it on a static seabed dataset. This is acquired by the HUGIN HUS AUV equipped with an EM2040 MBE [117] in November 2017 in the Trondheimsfjord in Norway. The EM2040 has 400 beams spread out over a varying swath sector, and can output processed xyz-points, corrected for AUV roll and pitch, sound speed, and ray bending. The objective of this preliminary test is to verify that the SLAM algorithm works well on a standard seabed bathymetry case with real sensor noise. The processed dataset is depicted in Figure 6.6. The bathymetry is collected from an area with large variations in topography to be comparable with mapping of an iceberg.

6.5.1 Case study: static real-world bathymetry

The first results presented are the bathymetric field tests. Figure 6.7(c) shows the AUV navigation system trajectory (real-time solution) in solid black and the processed offline NavLab-solution in solid red. NavLab is a post-processing tool developed by the Norwegian Defence Research Establishment (FFI) and provides a good estimate of the ground truth [69]. The NavLab estimate of the AUV trajectory is deduced by merging all available information from sensor measurements and mathematical error models through a complex post-processing estimator [69].
6.5. Iceberg SLAM results

(a) HUGIN pose north particle $3\sigma$-bound.

(b) HUGIN position error norm.

(c) HUGIN trajectory plot.

Figure 6.7: HUGIN dataset: SLAM pose estimation results. a) Particle cloud $3\sigma$-bound for SLAM estimate of HUGIN north position. Black dashed line shows particle cloud $3\sigma$-bound with no resampling. b) Shows the error norm of the north and east position for the average HUGIN pose from the particle cloud compared to the NavLab solution. c) HUGIN trajectory plot with particle cloud snapshots from the modified BPSLAM algorithm and trajectories from all SLAM methods and the AUV navigation system (including the NavLab-solution in solid red color).
Optimal smoothing is also applied to the estimates, since all data, both before and after the current timestep, are available. If we compare the AUV navigation with the NavLab-trajectory in Figure 6.7(c) and look at the AUV navigation error in Figure 6.7(b) we see that the AUV navigation has been quite poor during the survey, with a maximum error norm \( e = \sqrt{p_x^2 + p_y^2} \) of 36.40 meters, even with the aid of ship-mounted USBL. The large changes in the AUV navigation (especially on the left side of the figure) are caused by new USBL position fixes (noisy) entering the navigation solution. In the results presented here, we only study the SLAM algorithm, and thus, the AUV navigation has not been included in the SLAM results (i.e., pure dead-reckoning).

The SLAM trajectories are shown in Figure 6.7(c), and its corresponding error when compared to the NavLab-trajectory is shown in Figure 6.7(b). The errors for the SLAM methods are all greater than 10 meters, but the trajectories for the BPSLAM and the modified BPSLAM are similar, with maximum errors of 13.32 and 12.93 meters, respectively. The BPSLAM method suffers from particle depletion, as can be seen from Figure 6.7(a). This happens when the particle standard deviation in both directions are reduced to zero. The standard deviation tells us about the spread of the particles in a given direction, but a low standard deviation is not always desirable since this also reflects the available hypotheses of the particle filter. Particle depletion is when all particles stem from one or very few particles after a resampling, i.e., a low number of hypotheses. If neither of these particles reflect the correct state, it will be hard for the particle filter to recover. The 3\( \sigma \)-bound shown in Figure 6.7(a) should therefore ideally reduce to a limit defined by the measurement and map uncertainty, and map resolution. This seems to be the case for the ICP and the modified weighting method. A sudden decrease in the 3\( \sigma \)-bound happens upon resampling, where unlikely particles are resampled from more likely ones. The modified BPSLAM method is more robust to the particle depletion problem. The error for the ICP method is larger, which is believed to stem from convergence problems in the ICP algorithm (this method aborts after a given number of iterations). Due to the inaccurate AUV navigation, we cannot say anything about the expected error using the SLAM method, but all methods show significant improvement when compared to the real-time solution aided by USBL.

### 6.5.2 Case study: iceberg mapping

In the simulations presented in this section, the iceberg is drifting with a constant speed and a constant rotational velocity. Yulmetov et al. [182] study the drift of multiple icebergs using trackers, and report a mean iceberg speed in the range 0.08 – 0.28 m/s, and a maximum iceberg speed of 0.41 – 1.66 m/s. Further, the authors of [182] report a mean iceberg rotational rate of 1 – 2 revolutions per 24 hours, which is about 15 – 30 degrees/hour. They also report extreme rotational rates (of short duration) in the order of more than 200 degrees/hour. Based on this information the drift speed of the iceberg was set to 0.3 m/s with a course angle of 45 degrees (relative to north). The standard deviations for the noise driving the particle filter in (6.31) was set to 1.0 m/s for the linear velocity and to 200 degrees/hour for the rotational velocity.
6.5. Iceberg SLAM results

Figure 6.8: Case 1: SLAM and EKF iceberg pose estimation results. a) Particle cloud 3σ-bound for SLAM estimate of iceberg north position. Black dashed line shows particle cloud 3σ-bound with no resampling. b) Particle cloud 3σ-bound for SLAM estimate of iceberg east position. c) Shows the error norm of the north and east position for the iceberg pose estimate in the top level EKF estimator.

The multibeam is configured with the Imagenex DeltaT multibeam in mind, with 120 beams spread equally over a sector of 120 degrees, and 3 degrees beamwidth. The range resolution for the DeltaT multibeam is 0.02% [84], but to account for uncertainties in beam angle, and iceberg roll and pitch, a higher noise level of 0.5% was chosen for the range measurements. Therefore, the standard deviation for the multibeam is set to \( \sigma_r = 0.5 \) meters (a range of 100 meters is assumed), and the standard deviation for the multibeam cross-track and along-track error is set to half of the beamwidth. In the SLAM algorithm, the map size was set to 225 meters, and the resolution was set to 1.0 meter. Further, the patch size is set to...
6. Iceberg mapping using simultaneous localization and mapping

(a) Iceberg pose north particle 3σ-bound. (b) Iceberg pose east particle 3σ-bound.

(c) Iceberg position error norm.

(d) Iceberg north velocity error. (e) Iceberg east velocity error.

Figure 6.9: Case 2: SLAM and EKF iceberg pose estimation results. a) Particle cloud 3σ-bound for SLAM estimate of iceberg north position. Black dashed line shows particle cloud 3σ-bound with no resampling. b) Particle cloud 3σ-bound for SLAM estimate of iceberg east position. c) Shows the error norm of the north and east position for the iceberg pose estimate in the top level EKF estimator. d) and e) Iceberg velocity error in the north and east direction, respectively.
6.5. Iceberg SLAM results

15 seconds, which means that at each SLAM timestep, a total of 150 MBE swaths will be processed (the MBE is running at 10 Hz). The number of particles used is 200, unless otherwise specified.

Case 1 - Iceberg with linear drift

This case serves as a baseline for the estimator, and no rotation has been applied. The initial linear velocity is also assumed to be known. The results from this case is shown in Figure 6.8. From Figure 6.8(c), it is clear that the ICP version of BPSLAM outperforms the other methods in term of relative position error, which in the ICP SLAM case has a maximum error norm of 1.46 meters, while the original and the modified version has 6.67 and 2.83 meters, respectively. The improvement does come at a cost, which is discussed in Section 6.5.3. The error of the modified BPSLAM converges to about the same error as the ICP method at the end of the simulation, but is shown to consistently result in a larger maximum error compared to the ICP method through multiple simulations. From the particle cloud $3\sigma$-bound, shown in Figure 6.8(a) and 6.8(b), it can be seen that the original BPSLAM method has the largest variations in particle cloud standard deviation. We can also see that the particle cloud standard deviation goes to zero, or close to zero, multiple times. This is particle depletion, and if we look at the error at the time of depletion, we see that the estimate is not correct – resulting in a situation that is hard to recover from. The reason for the particle depletion is that some observations are unjustly weighted much lower than others. Since beam weights are selected by random sampling when only partial overlap is achieved, this can lead to a larger variation in particle weights than it should be. In the modified BPSLAM, this effect is reduced by including all beams and adjusting the weight with the modifier $1/m(x)$. It is believed that the effect seen with the original BPSLAM method will be reduced for applications where full overlap is required. It should also be noted that the original BPSLAM is only utilizing 1 out of 150 swaths for determining resampling since the SLAM algorithm is running once every 15 seconds. Running the algorithm on every MBE swath amplified the problem, leading to severe particle depletion and estimator divergence.

Figure 6.10(a) illustrates the estimated iceberg topography collected from the particle with the highest weight at the end of the simulation. Figure 6.10(b) shows the observation map error when compared to the actual map. The error is larger in areas with high topography gradient, due to the fixed resolution of the map and since the topography estimation is sensitive to small position errors in these areas. The overall root-mean-squared error (RMSE) over all the grids that contain a measurement is 1.89 meters for the simulation in Case 1 using the ICP method.

Case 2 - Iceberg with linear drift and uncertain initial velocity

In Case 2 the simulation parameters were the same as in Case 1, but initial drift speed and direction were assumed to be uncertain and were set to be 10% off from the actual values. Figure 6.9(d) and 6.9(e) illustrate the velocity estimate errors. The estimates converge, but rather slowly, since the states have been assumed to be constant. We can also see that the velocity estimate converges faster for the
Figure 6.10: Iceberg topography map extracted from the SLAM algorithm. a) Shows the topography extracted from the particle with the highest weight at the end of the simulation. b) Topography error map showing the error when compared to the real topography.
6.5. Iceberg SLAM results

(a) Iceberg pose north particle $3\sigma$-bound.

(b) Iceberg pose east particle $3\sigma$-bound.

(c) Iceberg position error norm.

(d) Iceberg pose heading particle $3\sigma$-bound.

(e) Iceberg rotational rate absolute error.

Figure 6.11: Case 3: SLAM and EKF iceberg pose estimation results. a) Particle cloud $3\sigma$-bound for SLAM estimate of iceberg north position. Black dashed line shows particle cloud $3\sigma$-bound with no resampling. b) Particle cloud $3\sigma$-bound for SLAM estimate of iceberg east position. c) Shows the error norm of the north and east position for the iceberg position estimate in the top level EKF estimator. d) Particle cloud $3\sigma$-bound for SLAM estimates of iceberg heading. e) Absolute heading error for iceberg orientation estimate in the top level EKF estimator.
6. Iceberg mapping using simultaneous localization and mapping

(a) Relative trajectory in ICE-frame. (b) AUV and iceberg trajectory in the NED-frame.

Figure 6.12: Case 3: Relative and global AUV and iceberg trajectory. a) True and estimated relative AUV trajectory with snapshots of the iceberg origin point cloud projected onto the AUV track (older clouds are more yellow, newer clouds are more red). b) AUV trajectory in NED-frame, showing the real and estimated iceberg outline at end of simulation, as well as real and estimated iceberg trajectory.

north-direction than for the east-direction. This is believed to stem from the AUVs survey direction, which is mainly in the east-west during the first 650 seconds, and north-south during the rest of the simulation (see trajectory plot in Figure 6.12).

In Figure 6.9(c) we can see that the maximum error is larger for all methods, but the position estimates for ICP and the modified version converge to within a few meters once the velocity estimates have converged.

Case 3 - Iceberg with linear and rotational drift and uncertain initial velocity

Case 3 studies how iceberg rotation affects the estimates, and the results are depicted in Figure 6.11. A rotational rate of 30 degrees/hour was applied to the iceberg, with initial uncertainty of 10%. Figures 6.11(a) - 6.11(c) show similar results as seen in Case 2, but again with slightly larger maximum errors. Figures 6.11(d) - 6.11(e) display particle cloud heading 3σ-bound and the rotational rate estimate error, respectively. From the plot of the heading 3σ-bound it is clear that it is difficult to estimate the rotation of the iceberg. The estimate of the rotational rate further supports this claim, since the estimates have troubles with converging. It looks like the original BPSLAM estimate converges, but multiple simulations have shown this to be a coincidence. The rotation estimate for the ICP SLAM is better, but from Figure 6.11(d) we see that the 3σ-bound is not significantly reduced.

Figure 6.12 shows the relative trajectory and the NED-trajectory during the simulation of Case 3. Figure 6.12(a) illustrates snapshots of the particle cloud (projected from the iceberg origin to the relative AUV position for the illustration).
Figure 6.13: Comparison of execution time for the different weighting methods.

The figure shows that the state estimate gets a steady state error, which is due to the inaccurate velocity estimates at the start of the simulation.

### 6.5.3 Run-time analysis

The run-time of a SLAM algorithm is always an important criteria, and especially important when the algorithm is intended for use with a guidance algorithm. Figure 6.13 shows a run-time comparison with the three different methods studied in this chapter, for two different number of particles. The execution time of a particle filter clearly depends on the number of particles, as can be seen from Figure 6.13. The run-time also depends on several other parameters, such as number of measurements and number of grids covered by the measurements, map size, and map resolution. From the run-time results shown in Figure 6.13 it can be seen that the run-time of the original BPSLAM algorithm is several times faster than the other two methods. This is misleading since the BPSLAM only uses 1 out of 150 of the measurements in the simulations presented here. The original and the modified version will have similar run-time complexities for the same amount of information. The modified BPSLAM method has an average run-time of 4.45 and 11.99 seconds for 200 and 500 particles, respectively. Both are below the limit of 15 seconds (which is the execution period of the SLAM algorithm in the simulations presented here). The maximum execution time is above 20 seconds for the run using 500 particles, so adaptive sampling time would have to be employed in this case for real-time constraints to be met.

The situation is different for the ICP method, which is significantly more computationally expensive. For 200 particles, the mean run-time is just above 11 seconds,
and maximum run-time of above 20 seconds, making this comparable to the modified version’s run-time with 500 particles. Using 500 particles and the ICP method gives an average run-time of almost the double of the target run-time. It should be noted that the focus of this study has been on the overall concept, rather than the ICP method itself. A custom designed ICP method for the BPSLAM method could potentially improve both speed and convergence properties. For example by limiting the ICP method to search for 3 DOF transformations, the performance would likely be improved.

The simulations presented have been performed on a PC with Intel Core i7 3770 @ 3.4 GHz using 8 logical processor cores in parallel execution. The algorithm presented in Algorithm 1 is suitable for parallel execution, especially the first for-loop (line 3-7), since each particle is independent. The use of modern graphical processing units (GPUs) with several thousand of cores could ease the load on the processor and speed up the algorithm. In recent years, single board computers with more than 250 GPU cores have been developed, which is suitable for use in unmanned vehicles (e.g., NVIDIA Jetson TX2).

6.6 Summary

Through this chapter, an estimator designed for mapping of drifting and rotating icebergs has been detailed. The estimator consists of a top level EKF estimating the relative position and orientation between the AUV and the iceberg, as well as the relative velocity. The iceberg position, orientation, and velocity are also estimated, using inputs from a bottom-level estimator. The bottom-level estimator is based on the BPSLAM algorithm, and two new methods for weighting of multibeam range measurements are proposed. An additional output of the SLAM algorithm is a gridded map containing the topography of the iceberg, which can be extracted in real-time or upon completion of the survey. This can be an important input to the decision-making process in an IM operation.

The results show particle depletion when using the original BPSLAM algorithm, believed to stem from using MBE swaths with partial overlap. The modified version of the BPSLAM weighting algorithm is more robust with respect to areas with less information, and can better handle multiple measurements. This opens the possibility for adaptive sample time for the SLAM algorithm – which can help to ensure real-time execution as long as the average execution time is faster than real-time. The third method that is compared is an ICP method for BPSLAM, and shows improved accuracy in the simulated cases, on the cost of significantly increased computational complexity. For the actual bathymetry, on the other hand, the ICP perform worse. This is believed to stem from ICP convergence problems due to a more complex optimization problem in the bathymetric case, due more than three times the number of beams.

Further work include development of a custom ICP method for the BPSLAM, testing the iceberg SLAM algorithm using real iceberg drift data, and evaluation of the algorithm using a real under ice dataset. Furthermore, the use of GPU programming should be investigated to improve real-time performance, and to reduce the load on the CPU. The inclusion of GPU programming may also open
the possibility of running MCS on the algorithm, within a reasonable time frame.

The MBE is set to have a constant sample rate of 10 Hz, which may be optimistic, depending on the range. Reduced MBE sample rate will reduce the computational complexity, but will also reduce the amount of information available to the SLAM algorithm. This is not believed to be a problem, since the original BPSLAM method performed similar to the modified version in the bathymetric case, using only $\frac{1}{150}$ of the measurements for resampling. The map will, however, be more sparsely populated, which may require the resolution of the map to be decreased. Regardless, extending the MBE simulator to be range dependent and investigating how this affects the SLAM estimation are interesting points of future work. Similarly, how DVL dropouts affect the algorithm should be investigated, since this may occur frequently in challenging acoustic environments like under the ice.

To extend the algorithm towards complete iceberg mapping, the realm of active SLAM in conjunction with the iceberg SLAM method should be investigated.
Chapter 7

Conclusions and further work

There is no real ending. It’s just the place where you stop the story.

Frank Herbert

This thesis has focused on using AUVs for ice monitoring and surveys, and as an Arctic research tool. The main scientific contributions are related to navigation and guidance of the AUV under ice, and topography mapping of the subsea iceberg geometry. Field results and experiences are also presented, as well as some experimental results for the developed SLAM algorithm.

7.1 Conclusions

In Chapter 2, different aspects and challenges for Arctic AUV operations were presented and discussed. The use of AUVs as an ice monitoring platform was also motivated. The main technological challenges that must be overcome before AUVs can be applied to continuous ice monitoring are related to infrastructure, autonomy, and navigation. Autonomy, in this context, includes fault-tolerant control and fault-detection, situational awareness, as well as sensor fusion and SLAM. This means that the AUV must be aware of its systems and its surroundings, and be able to base decisions on the information gathered. Navigational challenges are both related to the ice mapping problem, as well as recovery and subsea residency in a continuous monitoring operation. That is, the AUV must be able to determine its state with respect to the global frame to be able to return to e.g., a docking station, and it must know its location relative to the environment it is mapping to construct a consistent map. Navigational challenges must also be overcome when using AUVs as an Arctic research tool, where increased autonomy can optimize data collection.
Field experiments and experiences were outlined in Chapter 3, detailing two Arctic AUV operations, as well as two experiments in the Trondheimsfjord. The experiences from the field campaigns confirmed several of the findings from Chapter 2, especially related to navigational challenges and fault tolerance for Arctic research operations. The USV experiments were intended as a demonstration of a concept, and it is believed that the use of USV as a support tool in Arctic operations will be important.

The main contribution of the Arctic AUV simulator presented in Chapter 4 was a tool for developing guidance and navigation algorithms centered around MBE measurements of a drifting and rotating terrain, such as an iceberg. A 6 DOF AUV model was considered necessary to capture all necessary dynamics, and the use of real iceberg topographies from the PERD iceberg sightings database increase the scientific value of the results. The modular design of the simulator also allowed blocks to be replaced with real data (e.g., such as in the bathymetric SLAM case presented in Chapter 6).

Chapter 5 presented a guidance system for determining an iceberg’s main particulars, and an edge-detection algorithm was used to identify and follow the edge of an iceberg. The state machine based guidance system was able to detect and circumnavigate icebergs under the assumption of icebergs with steep edges and flat bottom. The guidance system was also shown to handle iceberg shapes where the strict requirements on the topography were relaxed. The edge-detection algorithm using piecewise linear regression was computationally efficient, and was designed to handle noisy MBE measurements. However, as the method was restricted to a specific type of iceberg shape, a more general approach could have been used.

Motivated by the need to estimate the relative iceberg-AUV position to generate a consistent iceberg topography, an iceberg mapping navigation system was developed and presented in Chapter 6. The navigation system utilized a SLAM algorithm to sense the movement of the iceberg in the global frame. The iceberg mapping filter was able to estimate the position and velocity of the iceberg, as well as the relative position and velocity of the AUV in an ice-fixed coordinate system. The iceberg heading and rotational rate proved to be hard to determine from the particle filter SLAM algorithm, but the position was determined with reasonable accuracy in the simulation study. One of the main contributions in this chapter was the development of two novel weighting algorithms for the BPSLAM method, which were shown to significantly reduce the particle depletion problem in the original BPSLAM algorithm during loop-closures with only partial MBE swath overlap. In the simulation results using real iceberg topography, the ICP weighting method was shown to provide improved accuracy compared to the other two methods, with the cost of significantly increased computational complexity. The modified weighting algorithm showed an overall improved accuracy compared to the original weighting scheme, due to the problems with particle depletion. The SLAM algorithm was also demonstrated on a real bathymetric dataset, collected with the HUGIN HUS AUV. Due to noisy USBL measurements entering the online AUV navigation solution, the SLAM method was shown to provide improved navigational accuracy when compared to this trajectory (when using a post-processed solution as reference). The ICP weighting method suffered from convergence problems on the real dataset, and the two other methods showed improved performance.
7.2 Further work

Modeling of navigation sensors, such as LBL and USBL (and GNSS at the surface) in the Arctic AUV simulator would be beneficial both to include reasonable sensor noise, but also to simulate measurements from an acoustic network fixed to the drifting and rotating ice. Furthermore, inclusion of sensor models for IMU, DVL, and depth sensors would be useful for navigation system development, and would result in a more realistic simulation environment. An improved ice drift model should also be considered.

Strict assumptions were made on the iceberg shape in the edge-detection algorithm in Chapter 5, and an approach that supports a more general iceberg shape would increase the robustness of the method in a real iceberg mapping scenario. The use of machine learning to detect multiple ice features (e.g., icebergs or ridges) could be a solution to this problem. This would also increase the applicability of the algorithm, since it could be used to detect and map icebergs, but also to follow and determine the extent of a pressure ridge. Lack of real 3D data and actual MBE datasets may be a limiting factor when training machine learning algorithms in this case.

The SLAM algorithm presented in Chapter 6 had problems with estimating the heading and the rotational rate of the iceberg. Solutions to this problem could be to develop an ICP method specifically designed for the purpose of iceberg mapping and BPSLAM, or to investigate other SLAM solutions rather than particle filters. The use of GPU programming should be considered for the proposed modifications to the BPSLAM method, as this could allow real-time execution of the algorithm even with a considerable number of particles. The iceberg SLAM method should be tested on a real dataset of a drifting and rotating iceberg, as well as a dataset of drifting sea-ice to investigate the applicability of the method in other ice monitoring operations.

In Chapter 6, the guidance problem has been disregarded. Integrated exploration, or active SLAM, is an emerging field of research, and is a method that evaluates the need for loop-closures in the SLAM algorithm against the objective of exploring an unknown terrain. Applying these methods toward iceberg mapping would be an interesting area of research.

Formalizing the conceptual Arctic guidance and navigation system presented in Figure 2.9 would be of high value to AUVs performing Arctic research under drifting sea-ice. Especially, the separation of the local and the global position estimates are useful for an Arctic AUV. This system would also require integration of collision avoidance methods – a topic that has been been considered outside the scope of this thesis.

This thesis has studied important features relevant for IM operations, like iceberg detection and mapping, but it is still a significant amount of research that must be performed before AUVs can be applied to IM operations. Open research questions are related to guidance of the AUV to ensure reliable topography estimates, generation of paths that limit the amount of unmapped ice that reach a
protected vessel, seen in combination with other complementary sensor platforms, as well as infrastructure developments that allow subsea resident vehicles to be used in extended Arctic marine operations. Redundancy, fault-tolerant control, autonomy, and how these functions can be applied to IM operations are also aspects that should be investigated.
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Appendix A

NTNU AUR-lab AUVs

A.1 REMUS 100

The REMUS AUVs were originally developed by WHOI, but have been commercialized by the spin-off company Hydroid (now a part of the Kongsberg Group). An illustration of the NTNU REMUS 100 AUV can be seen in Figure A.1. This AUV is a small size AUV with proven robustness in many different applications. Specifications for the NTNU REMUS AUV are found in Table A.1.

A.1.1 Mathematical model

Chapter 4 provided a mathematical 6 DOF model of the REMUS AUV, and values for the model are given in this section. The values for the vehicle dynamics and fin model are taken from Prestero [151], while the propeller coefficients are estimated

Figure A.1: The NTNU REMUS 100 AUV.
Table A.1: NTNU AUR-lab AUV specifications.

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from the values in Allen et al. [2]. The values presented in this section have been used in all simulations presented throughout this thesis.

The matrices for rigid-body mass, added mass, and damping are given by (A.1), (A.2), and (A.3), respectively, while the last parameters are given by Table A.2.

\[
M_{RB} = \begin{bmatrix}
30.479 & 0 & 0 & 0 & 0.597 & 0 \\
0 & 30.479 & 0 & -0.597 & 0 & 0 \\
0 & 0 & 30.479 & 0 & 0 & 0 \\
0 & -0.597 & 0 & 0.189 & 0 & 0 \\
0.597 & 0 & 0 & 0 & 3.462 & 0 \\
0 & 0 & 0 & 0 & 3.45 & 0 \\
\end{bmatrix} \tag{A.1}
\]

\[
M_A = \begin{bmatrix}
0.93 & 0 & 0 & 0 & 0 & 0 \\
0 & 35.5 & 0 & 0 & 0 & -1.93 \\
0 & 0 & 35.5 & 0 & 1.93 & 0 \\
0 & 0 & 0 & 0.07 & 0 & 0 \\
0 & 0 & 1.93 & 0 & 4.88 & 0 \\
0 & -1.93 & 0 & 0 & 4.88 & 0 \\
\end{bmatrix} \tag{A.2}
\]

\[
D(\nu_r) = \begin{bmatrix}
1.62|u_r| & 0 & 0 & 0 & 0 & 0 \\
0 & 1310|v_r| & 0 & 0 & 0 & -0.632|r| \\
0 & 0 & 1310|w_r| & 0 & 0.632|q| & 0 \\
0 & 0 & 0 & 0.13|p| & 0 & 0 \\
0 & 0 & -3.18|w_r| & 0 & 188|q| & 0 \\
0 & 3.18|v_r| & 0 & 0 & 0 & 188|r| \\
\end{bmatrix} \tag{A.3}
\]

A.2 HUGIN HUS AUV

The HUGIN HUS AUV is owned and operated by the Norwegian Defence Research Establishment (FFI). The AUV is designed as a scientific AUV, with modular payload sensor suite. Several Norwegian institutions contribute to the HUGIN HUS consortium financially, and have the possibility to use the vehicle in cruises. Specifications for the HUGIN HUS AUV are shown in Table A.2 (note that endurance is payload dependent). An illustration of the HUGIN HUS during recovery is shown in Figure A.2.

A.3 LAUVs

The LAUV (Light AUV) is developed by OceanScan - Marine Systems and Technology, which is a spin-off company from the University of Porto in Portugal. The LAUV is designed to be cheap, lightweight, and the software is open-source. This makes the vehicles ideal for software development and testing. The two vehicles delivered to NTNU in 2016 have a separate application area for each vehicle. The LAUV Harald, a long-endurance vehicle with an oceanographic sensor suite, is
designed for water-column surveys, while the LAUV Fridjof is designed for benthic surveys, with a sensor suite consisting of sidescan sonar and black and white (B&W) camera. Specifications for the two LAUVs are shown in Table A.1.

Table A.2: AUV model parameters.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>CG lever arm w.r.t CO</td>
<td>$r_b^b$</td>
<td>0 0.0196 [m]</td>
</tr>
<tr>
<td>CB lever arm w.r.t CO</td>
<td>$r_b^g$</td>
<td>0 0 0 0 [m]</td>
</tr>
<tr>
<td>Weight of vehicle</td>
<td>$W$</td>
<td>299 [N]</td>
</tr>
<tr>
<td>Vehicle buoyancy</td>
<td>$B$</td>
<td>306 [N]</td>
</tr>
<tr>
<td>Density of sea-water</td>
<td>$\rho$</td>
<td>1025 [kg/m$^3$]</td>
</tr>
<tr>
<td>Fin lift coefficient</td>
<td>$c_{L, \alpha}$</td>
<td>3.12 [-]</td>
</tr>
<tr>
<td>Fin surface area</td>
<td>$S_{fin}$</td>
<td>6.65 $\times$ 10$^{-3}$ [m$^2$]</td>
</tr>
<tr>
<td>Fin placement w.r.t CO</td>
<td>$x_{fin}$</td>
<td>-0.638 [m]</td>
</tr>
<tr>
<td>Thrust coefficient</td>
<td>$K_T$</td>
<td>2.5075 [-]</td>
</tr>
<tr>
<td>Torque coefficient</td>
<td>$K_Q$</td>
<td>0.3203 [-]</td>
</tr>
<tr>
<td>Propeller diameter</td>
<td>$D_{prop}$</td>
<td>0.1397 [m]</td>
</tr>
</tbody>
</table>

Figure A.2: The HUGIN HUS AUV during recovery.
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*(earlier: Faculty of Marine Technology)*

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