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MASTER THESIS

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Lina Kuzmicheva

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ABSTRACT

Arctic regions have lately been in the centre of increasing attention due to high vulnerability to climate change and the retreat in sea ice cover. Commercial actors are exploring the Arctic for new shipping routes and natural resources while scientific activity is being intensified to provide better understanding of the ecosystems. Marine surveys in the Arctic have traditionally been conducted from research vessels, requiring considerable resources and involving high risks where sea ice is present. Thus, development of low-cost methods for collecting data in extreme areas is of interest for both industrial purposes and environmental management.

The main objective of this thesis is to investigate the use of underwater vehicles as sensor platforms for oil and gas industry applications with focus on seabed mapping and monitoring. Theoretical background and a review of relevant previous studies are provided prior to presentation of the fieldwork, which took place in January 2017 in Kongsfjorden (Svalbard). The fieldwork was a part of the Underwater Robotics and Polar Night Biology course offered at the University Centre in Svalbard. Applied unmanned platforms included remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs) and an autonomous surface vehicle (ASV). They were equipped with such sensors as side-scan sonar, multi-beam echo sounder, camera and others. The acquired data was processed and used to provide information about the study area.

The carried out analysis of the vehicle performance gives an insight into challenges specific to marine surveys in the Arctic regions, especially during the period of polar night. The discussion is focused on the benefits of underwater robotics and integrated platform surveying in remote and harsh environment. Recommendations for further research and suggestions for application of similar vehicles and sensors are also given in the thesis.

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AUV	Autonomous Underwater Vehicle
cDOM	Coloured Dissolved Organic Matter
Chl *a*	Chlorophyll *a*
CTD	Conductivity, Temperature And Depth
DP	Dynamic Positioning
DVL	Doppler Velocity Log
GPS	Global Positioning System
GSM	Global System For Mobile Communications
HD	High Definition
IMCA	International Marine Contractors Association
IMU	Inertial Motion Unit
INS	Inertial Navigation System
Iridium SBD	Iridium Short Burst Data
LAUV	Lightweight Autonomous Underwater Vehicle
LED	Light-Emitting Diode
NORSOK	Competitive Position Of The Norwegian Continental Shelf
NTNU	Norwegian University Of Science And Technology
OOI	Object Of Interest
ROTV	Remotely Operated Towed Vehicle
ROV	Remotely Operated Vehicle
RSV	Rov Support Vessel
SSS	Side-Scan Sonar
UMV	Unmanned Marine Vehicle
UNIS	University Centre In Svalbard
USBL	Ultra-Short Base Line
USV	Unmanned Surface Vehicle
UUUV	Unmanned Untethered Underwater Vehicle
UUV	Unmanned Underwater Vehicle
WHOI	Woods Hole Oceanographic Institute

1. Introduction

Petroleum potential of the Arctic has been recently drawing increasing attention as the climate change in the near future may enable oil and gas activities in previously unreachable areas. Operating in the Arctic regions is challenging: infrastructure is lacking, weather conditions are harsh and environmental costs are high. Success of oil and gas industry in these remote areas depends on sustainable nature resource management and knowledge-based decision making. Underwater robotics is already essential in providing information for oil and gas operations worldwide. Application of proven as well as new technologies in the Arctic settings is, therefore, an interesting and promising field of studies.

Background to the study

The Arctic is believed to be holding a considerable share of the world undiscovered hydrocarbon reserves. Figure 1.1 shows the main oil and gas provinces and basins located in the Arctic and in the circumpolar Arctic areas.

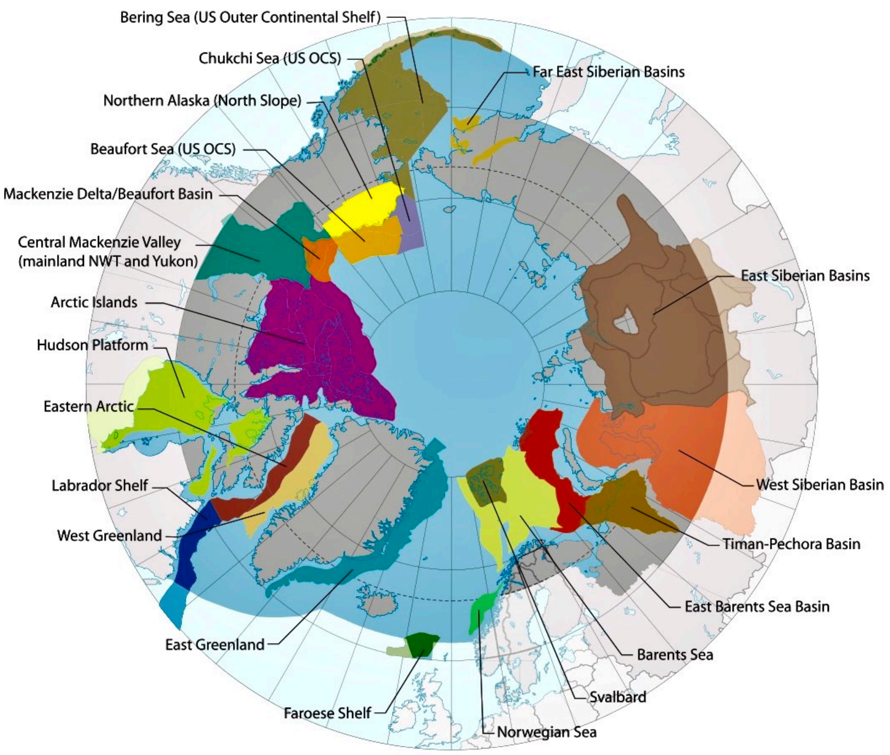


Figure 1.1. Major oil and gas provinces and basins around the Arctic (John Bellamy, AMAP)

The Arctic region is often perceived as one of the most intact in the world. However, commercial production from the Arctic oil and gas fields began in Canada as early as in the 1920s. Since then, interest in the Arctic developments has fluctuated, mostly due to high associated costs and operational constraints (AMAP, 2007; Mikkelsen & Langhelle, 2008).

The findings of the Arctic Climate Impact Assessment project (ACIA, 2004) suggest that conditions in the Arctic offshore areas may become more favourable for natural resource extraction already in the near future. The reduction of sea ice implies improved marine access to remote locations and, at the same time, new transport options for produced oil and gas, as shown in Figure 1.2. As a result, higher intensity of oil and gas marine operations is expected in the Arctic.

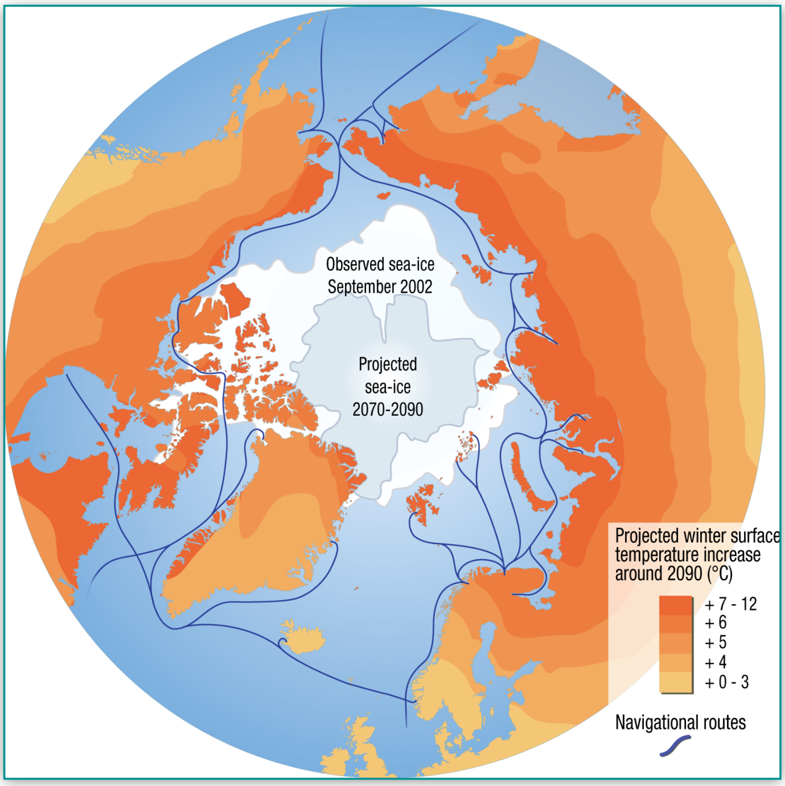


Figure 1.2. Projected changes in the Arctic climate and new shipping routes
(Hugo Ahlenius, UNEP/GRID-Arendal)

On the Norwegian continental shelf, an increased interest in the Barents Sea has recently been a clear trend. According to the Norwegian Petroleum Directorate (2017), a record number of exploration wells are scheduled to be drilled in 2017 in the area. A significant achievement will be to assess the potential for discovering oil and gas in the southeastern part of the Barents Sea. This part has only recently been opened for petroleum activities - first awards were given in the 23rd licensing round. No exploration wells have yet been drilled there.

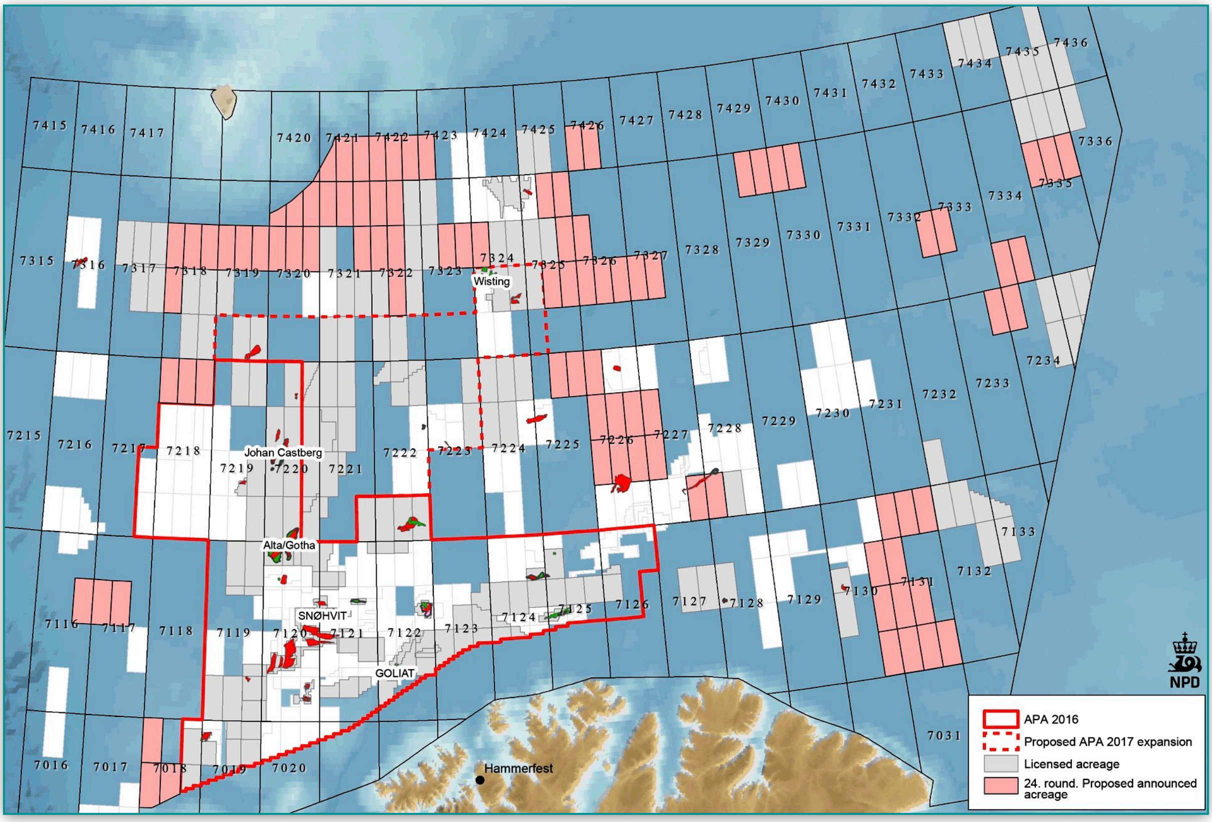


Figure 1.3. Barents Sea area open for petroleum activities
(Norwegian Petroleum Directorate)

Figure 1.3 shows the up-to-date state of activities in the Barents Sea. Today only the area south of 74°30′ N is open for petroleum activities. Nonetheless, the Barents Sea is the largest sea area on the shelf of the country and also the area with the largest oil and gas potential. Most of the Barents Sea is still regarded as a frontier petroleum province, although exploration in the area has been carried out for more than 30 years, and the first discovery was made in the early 1980s (Norwegian Petroleum, 2017).

There are currently only two fields in production in the Barents Sea: Snøhvit, producing since 2007, and Goliat, which came on stream in 2016. Snøhvit is producing gas, which is transferred to the Melkøya onshore processing facility by pipeline. Liquefied natural gas (LNG) vessels carry the processed product to the consumers. Goliat is producing oil and gas. The field concept utilises a Floating Production Storage & Offloading (FPSO). The processed oil is distributed further by tankers, the produced gas is injected back into the reservoir formation (Norwegian Petroleum, 2017).

As follows from the above, the Barents Sea has scarce infrastructure at the present time. However, the majority of the confirmed oil and gas deposits are situated at a great distance from land. This implies that the development with existing technology is commercially feasible only for the fields exceeding in reserves those found in the North Sea and the Norwegian Sea. Otherwise, cooperation within the industry and new solutions are essential for the profitable operations in the region (Norwegian Petroleum Directorate, 2017).

Offshore oil and gas operations involve a variety of marine surveys, which are especially demanding in the hostile conditions of the Arctic. Data collection in Arctic waters has traditionally been conducted from research vessels. This approach is usually associated with high costs and risks for humans, assets and environment. Thus, development of low-cost methods for collecting data in extreme areas, which have previously been off limits due to depth, distance or safety concerns, is of interest for both industrial and scientific purposes.

As natural resources get depleted around the world and human activities keep on expanding further into the High North, which is already susceptible to the rapid climate change, environmental concerns appear more urgent than ever (Mikkelsen & Langhelle, 2008). All companies operating on the Norwegian continental shelf are required to carry out environmental mapping and monitoring to obtain information on the actual and potential environmental impacts of their activities (Iversen et al., 2015). In the Arctic regions, including the Barents Sea, environmental mapping and monitoring becomes crucial. The belonging marine ecosystem is considered to be fragile and exceptionally vulnerable to eventual discharges or oil spills, as shown in Figure 1.4 (Sakshaug et al., 2016).

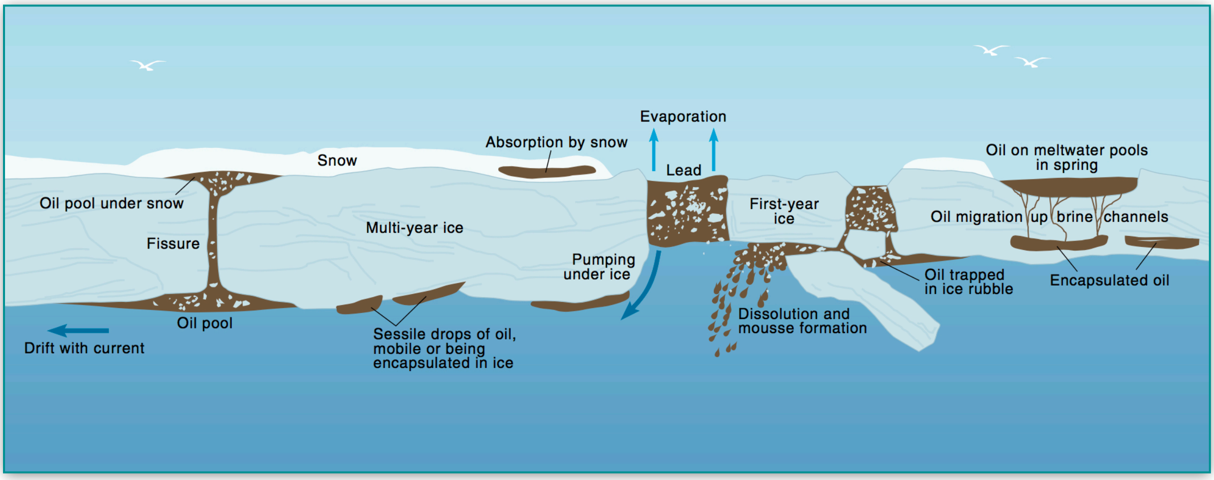


Figure 1.4. Behaviour of oil in waters with sea ice
Details: drops under the ice, new ice growth below the oil, oil appearing on the surface in the spring, wind herding of oil on melt pools, and the appearance of emulsified oil on top of the ice
(AMAP Assessment Report, 1998)

What is more, the marine ecosystem in the Arctic is also characterised by significant knowledge gaps. Recent studies and investigations into the biology of the Arctic during the period of polar night have revealed high levels of productivity and fully functioning ecosystems, disproving earlier beliefs that biological processes at higher latitudes were reduced to a minimum in the absence of sun (Berge et al., 2009; Berge et al., 2012; Osterholz et al., 2014; Berge et al., 2015b; Vader et al., 2015; Marquardt et al., 2016).

It is now known that, although the ambient light during the polar night is limited, the relative change in light is sufficient to trigger behavioural changes in marine organisms (Båtnes et al., 2013; Johnsen et al., 2014; Cohen et al., 2015). Thus, the effect of artificial lighting on the measurements during marine surveys rises new challenges. Similarly, the environmental impact of light pollution from petroleum activities becomes a major concern.

In addition, changing climate contributes to the continuous transformation of the marine ecosystems in the Arctic (Vinnikov et al., 1999; Berge et al., 2005 and 2015a; Hegseth & Sundfjord, 2008; Buchholz et al., 2010; Screen & Simmonds, 2010; Krause-Jensen & Duarte, 2014; Lydersen et al., 2014). As a result of all the above, assessing environmental impacts of oil and gas operations in the Arctic is a complex and resource consuming task. Other tasks associated with offshore field developments include, for instance, geophysical and hydrographic surveys for evaluation of proposed pipeline routes, geotechnical surveys for design of the foundations of subsea structures. All this work involves application of a variety of complex equipment (Bai & Bai, 2012).

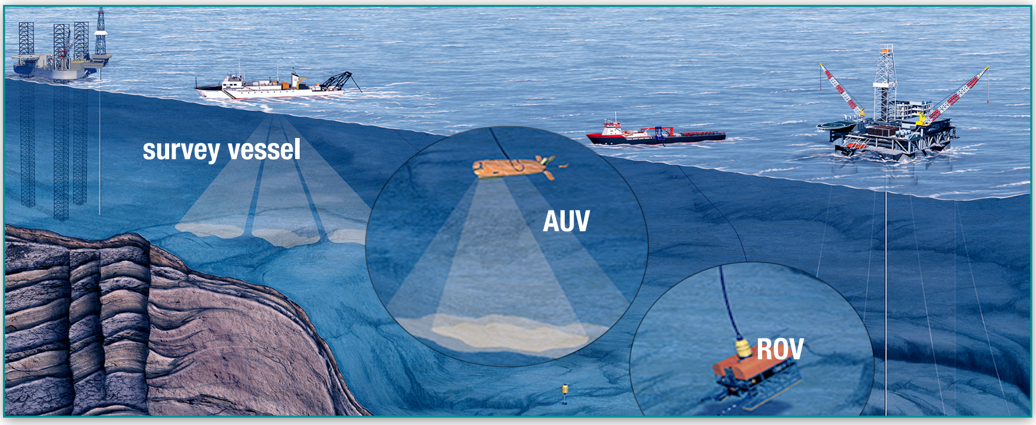


Figure 1.5. Variety of survey equipment for offshore oil and gas industry (modified from Survey Services illustration by Oceaneering)

Apart from a wide range of survey vessels, the oil and gas industry employs remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), accompanied by advanced remote sensing techniques. However, when the described tasks are to be performed in the Arctic environment, new challenges arise and new solutions are needed for the future oil and gas operations.

Scope of the research

Research question

In what way existing and developing underwater robotic systems can facilitate future oil and gas operations in the Arctic environment?

Aims

Answering the research question implies achieving the following aims:

- to investigate existing and developing underwater robotics technology
- to make an overview of applications of underwater robotics in the oil and gas industry
- to evaluate the application of underwater robots for mapping and monitoring of objects of interest in the Arctic conditions
- to discuss possible future applications of underwater robotics for arctic oil and gas operations

Objectives

To pursue the aims of the study the following objectives are set:

- review of relevant literature
- participation in the field campaign in Kongsfjorden (northwestern coast of Spitsbergen, Svalbard archipelago, Arctic Ocean) during polar night in January 2017
- information gathering in the Svalbard area
- discussion of underwater robotics applications for petroleum industry in the Arctic environment

Limitations

Although the area of sensor technology is relevant to this study, it is considered to be out of the scope of the conducted research. Measurement science and technology is a broad and rapidly developing field of its own and suggests extensive and independent inquiry (see, for example, Tengberg et al., 2006; Swanson, 2017). This thesis, therefore, contains only a brief description of the navigational and payload sensors employed during the field campaign.

One of the most important applications of underwater robotics in the oil and gas industry is intervention, maintenance and repair (IMR), performed by work class ROVs. It is a well-established service, managed by multiple guidelines, regulations and standards. However, this project is mainly concerned with mapping and monitoring tasks of underwater vehicles. At the same time, only pure observation class ROVs were deployed during the field campaign. Thus, underwater intervention is only presented briefly and otherwise is not included in the scope of the research.

The field campaign, which formed the basis for the practical part of the thesis, took place in an ice-free Arctic fjord during the period of polar night. This study addresses multiple encountered challenges for marine measurements in the Arctic, such as remoteness and harsh weather conditions, with a special emphasis on the darkness. The lack of sea ice partly limits the scope of the research to marine operations in open waters.

Outline of the thesis

The thesis is divided in several chapters, which correspond to the research aims. Chapter 1, this chapter, is an introduction to the chosen theme of the research. Scope of the project is defined, and followed by the description of the structure of the thesis.

Chapter 2 presents a brief overview of underwater robotics with intent to place the particular vehicles used during the field campaign into a broader perspective. A short introduction into the historical development of unmanned marine vehicles is given, followed by description of types and classes of modern underwater robots, the level of autonomy they possess and spatial and temporal domains of their operations. Finally, current trends in further development of underwater vehicles are presented along with potential future applications of underwater robots.

Chapter 3 discusses the role of underwater vehicles in the oil and gas industry. Today offshore field developments depend greatly on the assistance of marine robotics for installation and inspection of platforms and subsea equipment. Application of ROVs during oil and gas operations is well established, while AUVs are only entering the industry. Most common tasks performed by the underwater vehicles are presented with respect to the field life cycle.

Chapter 4 covers the details of the field campaign, which provided the data and the firsthand experience for the work on this thesis. The field campaign took place in January 2017 in Kongsfjorden on the northwestern coast of Spitsbergen, an island in the Svalbard archipelago in the Arctic Ocean. The introduction of the study area includes the description of the actual seabed features from previous studies. A total of five robotic platforms were deployed during the fieldwork: two AUVs, two ROVs and an unmanned surface vehicle (USV). All of them are described in detail in the corresponding sections along with the deployed payload sensors. The chapter ends with a overview of the missions accomplished during the field campaign.

Chapter 5 displays the results of the field campaign. Considering the large amounts of gathered data, this study presents only the most prominent and relevant information. The testing of underwater robotics in the Arctic conditions was one of the goals of the field campaign, however, the scientific focus was on the polar night biology. Oil and gas industry and marine biology share numerous measurement techniques and often pursue similar objectives, such as mapping of the seabed, including seabed habitats, or collecting hydrographic data. Yet, not all the results of the field campaign are within the scope of this study. The results of particular interest to a marine biologist, but of little or no relevance to a petroleum engineer are presented briefly or completely omitted.

Chapter 6 is a discussion of the results, including the evaluation of the performance of the underwater robots deployed during the field campaign. The chapter highlights the main challenges encountered during the work in the Arctic environment and the benefits of the application of unmanned vehicles in such conditions compared to the conventional methods.

The thesis ends with conclusions, which summarise the accomplished work and provide suggestions for improvements and further research.

2. Overview of underwater robotics

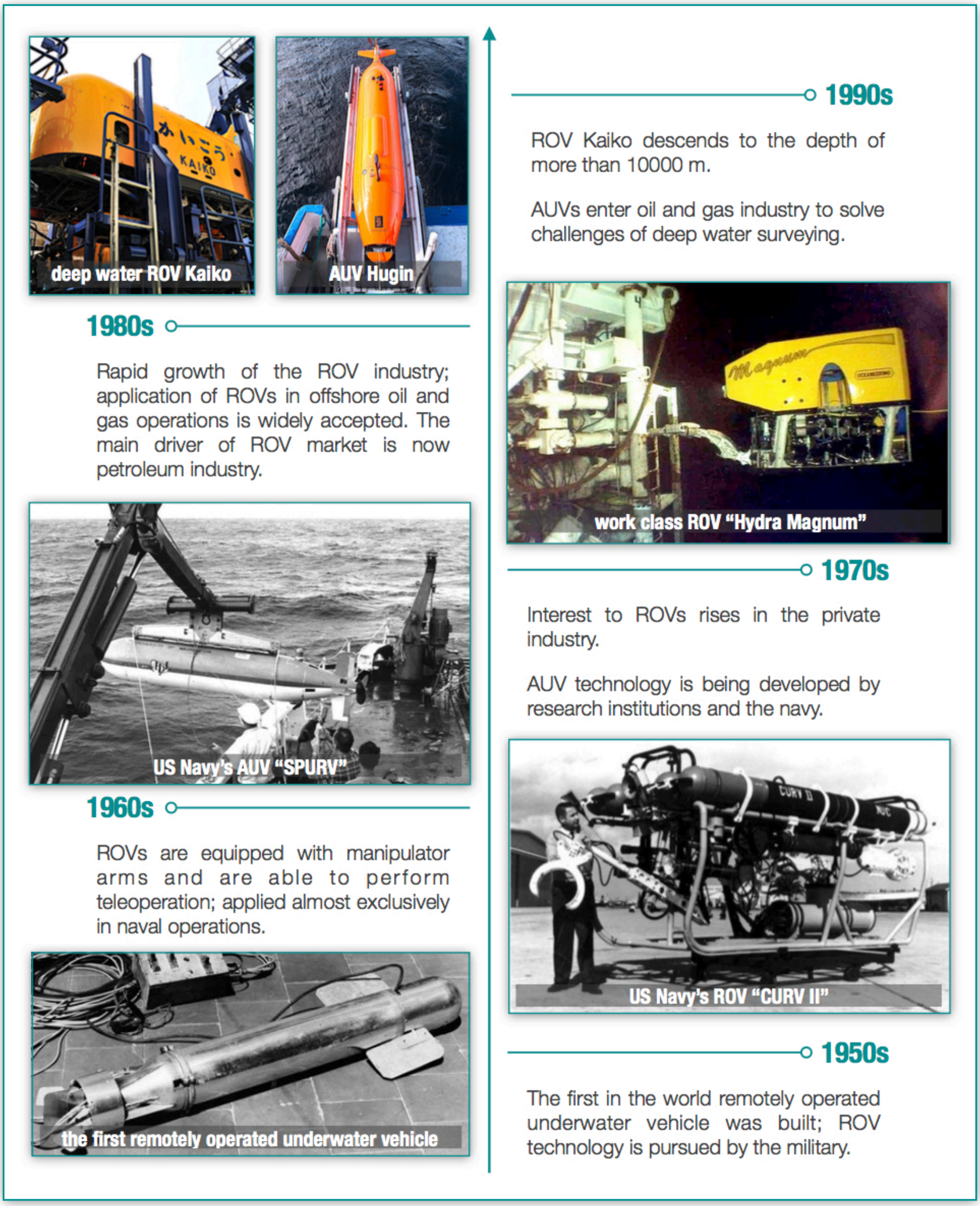
Chapter 2 presents a brief overview of underwater robotics with intent to place the particular vehicles used during the fieldwork into a broader perspective. A short introduction into the historical development of unmanned marine vehicles is given, followed by description of types and classes of modern underwater robots, the level of autonomy they possess and spatial and temporal domains of their operations. Finally, current trends in further development of underwater vehicles are presented along with potential future applications of underwater robots.

History and timeline

The history of unmanned underwater vehicles is much shorter compared to manned submersibles, however, it is filled with groundbreaking events that challenged the established boundaries in various scientific and industrial areas and continue to evolve at a rapid pace today. Figure 2.1 shows some of the main milestones of this technological journey, which took place before the extensive development and diversification of underwater vehicles started in the 2000s.

The first ever ROV is believed to be built in early 1950s by a diving enthusiast Dimitri Rebikoff for the purposes of underwater archeology. However, later on the main technological advances in development of remotely operated underwater vehicles belonged primarily to the military. Industrial use of ROVs flourished in 1980s when they became common instruments in offshore oil and gas field development. At the same time, the appearance of low-cost and light-weight models of ROVs made this technology available for practically any other areas of application. In 1990s ROVs demonstrated that “sky is the limit” or, in the case of underwater technology, that the deepest point on the Earth's seafloor is the actual restraining factor: the ROV Kaiko descended to the Challenger Deep - the deepest point in the Mariana Trench, reaching the depth of 10909 m (Christ & Wernli, 2014).

Although ROVs have proven to perform tasks impossible to divers or manned submersibles, their applications are nonetheless limited due to the presence of a tether tying an ROV to the surface. In pursuit of truly autonomous and tetherless underwater vehicles, AUVs were actively developed in 1970s, even though first attempts were made in the late 1950s. The main driver of the AUV technology for a long time was the navy, where the vehicles found their application in countermine operations. However, in 1990s new applications of AUVs were explored, such as cable and pipeline inspections and operations under sea ice in the Arctic. Today, the AUV technology is a field of active study aiming to produce an intelligent underwater robot able to complete complex missions with no necessity for human assistance (Bellingham et al., 1994; Yuh & West, 2001; Christ & Wernli, 2014).



1990s

ROV Kaiko descends to the depth of more than 10000 m.

AUVs enter oil and gas industry to solve challenges of deep water surveying.

1980s

Rapid growth of the ROV industry; application of ROVs in offshore oil and gas operations is widely accepted. The main driver of ROV market is now petroleum industry.

1970s

Interest to ROVs rises in the private industry.

AUV technology is being developed by research institutions and the navy.

1960s

ROVs are equipped with manipulator arms and are able to perform teleoperation; applied almost exclusively in naval operations.

1950s

The first in the world remotely operated underwater vehicle was built; ROV technology is pursued by the military.

Figure 2.1. Timeline of the development of underwater vehicles

The majority of AUVs are currently applied in research surveys, however they are becoming increasingly accepted in offshore industry as an alternative for towed vehicles and ships. For instance, BP accomplished their first commercial implementation of AUVs in 2001 (Bingham et al., 2002).

A separate technological story has led to development of unmanned surface vehicles (USVs), also called autonomous surface vehicles (ASVs) or autonomous surface crafts (ASCs). These unmanned marine platforms perform operations at the sea surface without any crew onboard and are gaining popularity in different scientific, commercial and military areas. The main advantage of USVs is the ability to use global positioning systems (GPS), which makes them suitable and cost-efficient options for numerous applications (Manley, 2008).

Types and classes of marine robots

Categorisation of modern marine robots is a challenging issue. Even the short historical overview presented above demonstrates that unmanned marine vehicles come in a vast variety of designs, sizes and capabilities. Rapid development of more autonomous modifications of existing vehicles and continuous appearance of completely new types of robots lead to a true struggle when it comes to establishing relevant standards and regulations (Hegde et al., 2015). Figure 2.2 demonstrates the diversity of state-of-the-art unmanned marine vehicles.

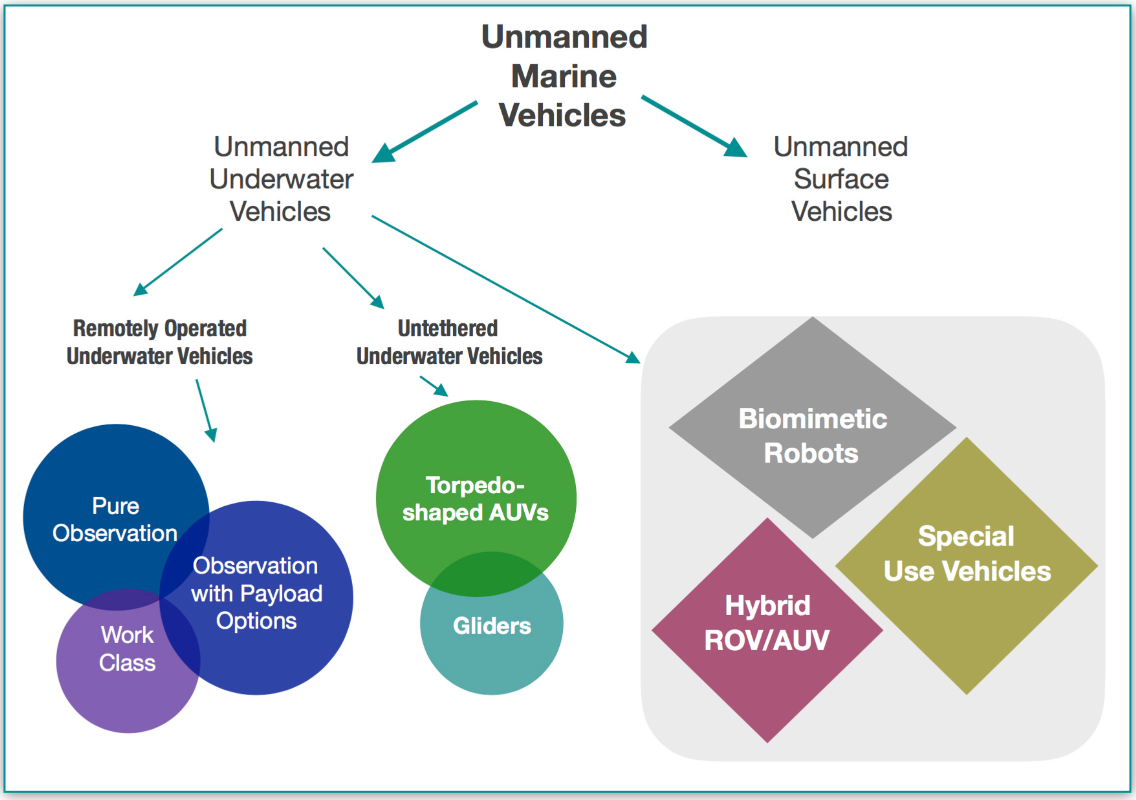


Figure 2.2. Diversity of unmanned marine vehicles

Currently, most common unmanned underwater vehicles are ROVs. An ROV is an underwater vehicle piloted remotely by an operator and connected to the surface by an umbilical for power supply and communication. ROVs comprise a wide range of vehicles with differences in technical specifications and areas of application.

ROVs used for pure observation vary from small vehicles easily handled by one person with no need of additional launch equipment to vehicles weighing up to 100 kg. These vehicles are normally equipped only with a camera and lighting system. Depth limit of observation class ROVs in seawater is in most cases less then 300 m. Depths beyond 1000 m are reached by mid-sized ROVs. Their weight is in the range of 100-1000 kg, thus requiring a launch and recovery system. This class of vehicles usually offers a minimal selection of manipulators and tools operated with limited hydraulic power in addition to electric thrusters in comparison to all-electric observation class ROVs. Work class ROVs are heavy electromechanical vehicles providing a wide variety of tools and manipulator options (Christ & Wernli, 2014).

The other type of unmanned underwater vehicles is an AUV - a tetherless vehicle able to move freely in the water column. Since there is no umbilical present and, therefore, no transfer of power supply from the surface, AUVs are powered by incorporated batteries. Communication with the vehicle in the water is established by the means of acoustics. While ROVs are remotely guided vehicles, AUVs are autonomous and rely on certain level of intelligence. Commercially available AUVs vary in size and purpose almost as much as ROVs. For instance, Bluefin 21 is rated for up to 4500 m depth and Hugin 3000 holds a sufficient power supply for 50 hours of autonomous operation (Antonelli, 2014).

Another type of untethered underwater vehicles is a glider. Gliders are uncomplicated ocean data gathering instruments, which use gravity and change in buoyancy to move through the water column. They are able to perform measurements in weeks and even in months. A weight is moved internally to provide the vehicle an upward or downward heading. At the same time, positive or negative buoyancy is obtained. Thus, hydrostatic forces lead to the movement of the device without any further use of power. Glider move in a zigzag pattern down to a predetermined depth. The direction of the dive can also be controlled by the planes on the sides of the vehicle. When at the surface, glider normally update their position by GPS and transmit the data (Gallett, 2008).

Special use vehicles include underwater vehicles designed for particular tasks. Some examples include: rail cameras - cameras travelling along a leg of a drilling rig to provide a view of a wellhead; bottom crawlers - vehicles moving on the sea bottom, applied in subsea mining and, for example, installation of pipelines; towed cameras; swim-out ROVs - small free-swimming vehicles, connected to a larger ROV, an AUV or a manned vehicle system (Christ & Wernli, 2014).

As a result of the rapid development in the field of underwater robotics, official industrial documents can rarely represent the full extent of existing unmanned marine vehicles. The latest revision of the Guidance for the Safe and Efficient Operation of Remotely Operated Vehicles by the International Maritime Contractors Association (IMCA R 004 Rev. 4 - May 2016) suggests an updated ROV classification, which reflects most recent technical developments. Unmanned underwater vehicles are divided into the following classes (IMCA, 2016):

- Class I - Pure Observation ROV

  The application of these vehicles is limited to video observation. The only possible additional sensors are for the purpose of navigation. These ROVs are normally small vehicles equipped with a video camera, lighting and thrusters. They are not capable of other tasks without significant modification. They may also be further categorised as ROVs being deployed by hand, that is, without any mechanical launch and recovery system. Pure observation ROVs may be carried by another ROV in a "mother-daughter" system.

- Class II - Observation ROV with Payload Option

  These vehicles are also often called "intermediate class" ROVs. IMCA suggests dividing these vehicles further into: Class IIA - observation class vehicle with payload option, and Class IIB - observation class vehicle with light intervention, survey and construction support capabilities. The detailed description of capabilities of these ROVs is provided in the IMCA R 004 Rev. 4 (IMCA, 2016).

- Class III - Work Class Vehicle

  According to IMCA (2016), the work class ROVs have faced the most significant changes caused by the application of technology and the demands of the subsea tasks, which the vehicles are required to perform. Work class ROVs may be further divided into standard work class vehicles (Class IIIA) and advanced work class vehicles (Class IIIB).

- Class IV - Towed and Bottom-Crawling Vehicles

  This class includes towed vehicles (Class IVA), such as remotely operated towed vehicles (ROTV), and bottom-crawling vehicles (Class IVB), which usually move across the seafloor by means of a track system.

- Class V - Prototype or Development Vehicles

  Vehicles in this class include those still under development and those regarded as prototypes or one-off versions. Special-purpose and single-purpose vehicles, which cannot be assigned to one of the other classes will also be included into Class V, according to IMCA classification.

- Class VI - Autonomous Underwater Vehicles (AUV) and Unmanned Untethered Underwater Vehicles (UUUV)

  Class VI vehicles have been subject to considerable growth in both types and capabilities. Commercial applications of these vehicles are mostly associated with support of survey and inspection activities. However, military applications are the most common and productive. The previous revisions assigned AUVs to prototype and development vehicles.

  There has been development of AUVs away from the traditional torpedo-shaped vehicles. The aim is to make AUVs capable of hovering. These vehicles are expected to conduct structural inspections of subsea installations.

  Traditionally, payload of these vehicles is a range of acoustic sensors. However, advances in additional technologies provide the ability to capture visual images by AUV/UUUV.

> Class VI vehicles are present in various sizes and configurations. Therefore, IMCA classification suggests a minimum of two sub-classes. Class VIA - AUVs weighing less than 100 kg, which are typically deployed manually and have a depth rating of up to 100 m. Class VIB - AUVs Weighing more than 100 kg, which require mechanical launch and recovery system and have a depth rating of up to 6000 m.

The IMCA classification of underwater vehicles has become the conventional naming practice. Initially, petroleum industry in Norway implemented IMCA classification, but the latest revision of NORSOK standard U-102 defines only three classes of ROVs: class I - pure observation vehicles; class II - observation vehicles with payload option; class III - work class vehicles. It is stated that the standard is intended not only for ROVs, but also for similar vehicles such as AUVs, remotely operated tools (ROTs), ROTVs, trenchers and dredging machines. However, no sections regarding these types of robots specifically are present (Standards Norway, 2016).

A classification of AUVs, which was suggested nearly a decade ago by Ura (2006), is highly applicable to the modern AUVs as well. Three types of AUVs are defined based on their functionality and possible applications:

- Cruising (type C) AUVs travel in the water column and provide a means to collect data about water properties and pelagic species, and to apply sonars for the seafloor observations.
- Bottom reference (type B) AUVs operate directly at the seafloor and near man-made subsea installations to conduct seafloor surveys and inspections of underwater structures.
- Advanced autonomy (type A) AUVs are able to interact with the environment, including man-made subsea structures, and perform tasks, which today are assigned exclusively to ROVs, for example, underwater sampling.

Levels of autonomy of unmanned systems

Discussion of underwater robotics requires understanding of differences between existing levels of autonomy. According to Autonomy Levels for Unmanned Systems (ALFUS) Framework by the National Institute of Standards and Technology, unmanned system operational modes include remote control, teleoperation, semi-autonomous and fully autonomous modes (Huang, 2004).

- Remote control is a mode of operation characterised by continuous control from a location, where direct observation is possible. In this mode, the unmanned system takes no initiative and relies on continuous or nearly continuous input from the human operator.
- Teleoperation relies on sensor feedback. The operator either directly controls the actuators or assigns incremental goals on a continuous basis, from a remote location. No direct visual access to the unmanned system is required.
- Semi-autonomous mode of operation requires various levels of interaction between the operator and the unmanned system. The system is capable of autonomous actions without continuous commands from the human operator.
- Fully autonomous mode of operation implies that the unmanned system accomplishes its assigned mission, within a defined scope, without human intervention while adapting to operational and environmental conditions.

Currently, ROVs operate mostly in the mode of teleoperation, while AUVs are semi-autonomous. Higher level of autonomy, however, is not necessarily a benefit at the current state of technological development. The need of human intervention varies greatly on the purpose of a specific survey or mission. Nonetheless, it is recognised that full autonomy is the overall aim of advances in the field of robotics.

Spatial and temporal resolution and coverage

Unmanned underwater vehicles are essentially a means of transportation for the required sensors to the areas or objects of interest. In this context, it is important to consider in the mission planning process the changes of the parameters in question both in space and time. The capability of a sensor carrying platform for the spatial and temporal resolution and coverage is, therefore, a critical factor in choosing a suitable solution (Nilssen et al., 2015).

Figure 2.3 illustrates the temporal and spatial resolution and coverage capabilities of various UUVs. The spatial and temporal coverage of AUVs is similar to ROVs. However, the survey area coverage per time is significantly higher compared to ROV as the ROV has limited spatial range due to the loads and drag forces on the umbilical (Nilssen et al., 2015).

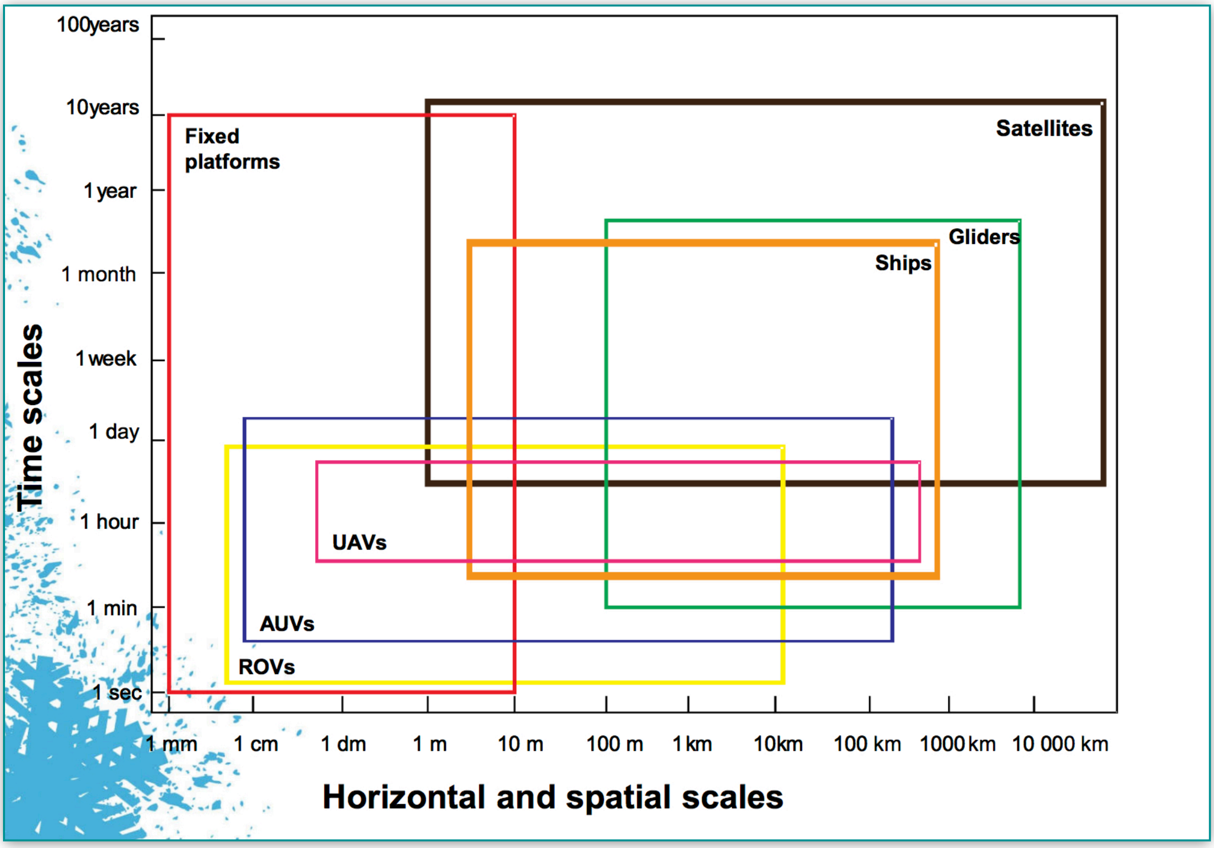


Figure 2.3. spatial and temporal domains of marine robotics
(Nilssen et al., 2015)

Development and future applications

Unmanned underwater vehicles have become valuable instruments in commercial, scientific and military marine operations. Their further development is essential to cost-effective marine resource management in the future, and certain trends, which can be seen today, suggest several new areas of possible applications.

Integrated operations

Deploying multiple vehicles from one surface unit is not necessarily more demanding than handling of a single vehicle, however, it may increase the overall operational efficiency. The efficiency can be enhanced even further by allowing the vehicles to communicate and run adaptive missions. Networks consisting of several unmanned platforms with complementary configurations require establishment of communication between the vehicles to fully embrace the potential of the integrated platform operations. The concept is displayed on Figure 2.4. As an example, it is possible to envision a network containing a vehicle for fast surveys over large areas, which is used to identify specific objects of interest in a time-efficient manner. Another vehicle with capability of closer investigations is assigned to follow the first one and to provide the details about the identified objects of interest (Ludvigsen & Sørensen, 2016).

Figure 2.4. Future applications of underwater robotics
(Bjarne Stenberg/NTNU)

Increased autonomy

For ROVs, improved autonomy can be achieved by automating defined tasks like manoeuvring, inspection, sampling and simple manipulations like valve turning. This will provide increased capabilities, repeatability and efficiency and be a step further towards the intervention AUV and persistent underwater vehicles. Increased autonomy in ROV operations will require online data processing and interpretation, but also contingency handling. More autonomy for ROVs can reduce the required surface support for these vehicles and hence reduce the overall cost of such underwater operations. This will require the systems to be more robust, but also a market adaption and the installation and standardisation of subsea infrastructure for the future vehicles for navigation and for docking to a tether for energy and communication (Fernández et al., 2013; Schjølberg & Utne, 2015; Ludvigsen & Sørensen, 2016).

Autonomy is naturally most developed for AUVs and increasing the level of intelligence in the vehicles will make the survey and mapping operations more efficient, either by optimising the available range or optimising the entire survey including prioritising the instruments. Mapping of processes with varying temporal dynamics will particularly benefit from adaptive systems using aboard data interpretation creating adaptive path plans (Ludvigsen & Sørensen, 2016).

Resident systems

The launch and recovery of underwater vehicles is a procedure associated with several risks. The idea of underwater robotic systems, which do not normally require rising to the surface, is therefore currently pursued in research. There have been experimental work on docking stations for many years, however, the technology is not yet implemented for commercial operation. When this technology matures, it will open up for applications such as range extensions, persistent vehicles, under ice operations, moon pool launches and intervention AUVs (Ludvigsen & Sørensen, 2016).

Biomimetics

Alternative path of development of underwater robotics has been increasingly productive in the field of biomimetics - the use and implementation of concepts and principles from nature to creating new materials, devices and systems (Kruusmaa, 2017).

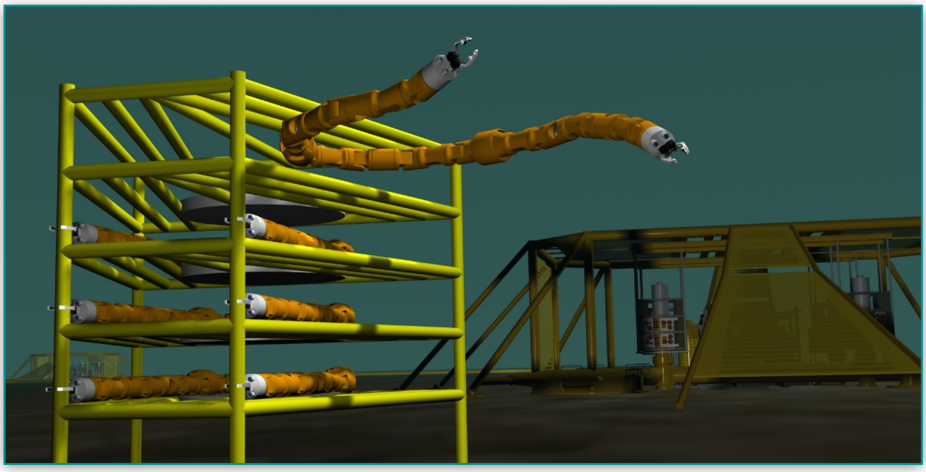


Figure 2.5. Snake-like underwater robot Eelume
(Eelume)

One of such new concepts - a snake-like robot Eelume - is currently being developed for industrial applications by an NTNU spin-off in collaboration with Kongsberg Maritime and Statoil. Eelume vehicles, shown in Figure 2.5, are modular combinations of joints, thrusters and various payload modules. The slender body allows for precision hovering and manoeuvring even in strong ocean currents. Sensors and tools can be mounted anywhere along the flexible body. A dual-arm configuration is achieved by mounting tooling in each end and forming the vehicle body into a U-shape. One end of the arm can grab hold to fixate the vehicle, while the other end can carry out inspection and intervention tasks. One end of the arm can also provide a perspective camera view of a tool operation carried out at the other end. The tasks, which the robot can perform, include visual inspection, cleaning and operating valves and chokes (Kruusmaa, 2017; Eelume, 2017).

3. Use of underwater vehicles in the oil & gas industry

Chapter 3 discusses the role of underwater vehicles in the oil and gas industry. Today offshore field developments depend greatly on the assistance of marine robotics for installation, inspection and maintenance of platforms and subsea equipment. Application of ROVs during oil and gas operations is well established, while AUVs are only entering the industry. Most common tasks performed by the underwater vehicles are presented with respect to the oil field development stages: mapping, installation, inspection and production.

Mapping

Detailed mapping of the seabed is required prior to any offshore installation or activity. Traditionally geophysical surveys have been conducted with towed or ship mounted acoustic devices. However, ROVs and light AUVs can successfully perform such surveys at a lower cost. Seabed mapping process includes deployment and retrieval of different reference systems such as differential pressure sensors and acoustic data transmitters, which can be accomplished by an ROV. AUVs carrying multi-beam echo sounders (MBES) and side-scan sonars (SSS) are a suitable alternative to ships and towed vehicles (Hagen et al., 2008).

In fact, the first area being developed in the commercial sector is for the AUV to be used for site survey work in the deepwater oil & gas sector to gain knowledge of the seabed when planning a subsea field. Up to now this has been achieved by towing a ROV equipped with SSS and MBES in a lawn mower pattern. In very deep water this is very slow and AUV surveys have thus been found to take days rather than weeks and to produce much better quality data. The main system being deployed at the moment is based on the HUGIN vehicle produced by Kongsberg Maritime. It is torpedo shaped and is 5.33 m long. The method of operation of this system is for the mother vessel to follow above the AUV, checking samples of data and updating the AUV's navigation system. Other vehicles are intended to dispense with the following mother vessel. For example, the GEOSUB vehicle of Subsea 7, developed from NOC, Southampton's research vehicle Autosub, is 6,82 m long, again torpedo shaped and is intended for site survey and pipeline and cable route surveys totally autonomously. A trial to the west of the Shetlands last September on a working pipeline proved very successful (Gallett, 2008).

It is required that seabed mapping is not only accurate, but also cost and time efficient. Simultaneous use of several sensors is, therefore, often desirable. On the other hand, MBES and SSS operate almost in same frequency which creates a possibility of acoustic interference. To avoid this problem, a terrain adaptive seabed mapping system was proposed (Thurman et al., 2007). Sub-bottom profilers are used for detection of buried objects, this sensor is combined with other detection techniques such as SSS for improved detection of offshore pipelines. Combined MBES and SSS sensors can also be applied for real-time detection of buried offshore pipelines (Shukla & Karki, 2016).

Installation

Initially the use of ROVs during installation was mainly a contingency plan in case of emergency. However, now ROVs are extensively used for various applications. For example, a recoverable system for mooring mobile offshore drilling units was developed where ROVs are used for remote manipulation of the suction anchor of the drill ships (Fulton et al., 2000). ROVs are also equipped with multiple instruments to help pre-drilling mooring process in various tasks such as measuring horizontal–vertical alignment, measuring seabed penetration of anchor by gyroscopes and cameras, usage of ROV thrusters for applying desired torque on the anchor, manipulation of the pump valves of the seabed anchor for creating pressure differences (Shukla & Karki, 2016).

Other types of underwater robots are also highly valuable during the installation process. For example, the construction of foundations and anchors for offshore installations is very dependent on the geotechnical properties of the sea floor. Robotic drilling rigs that are lowered onto the sea floor from multi-purpose research vessels and that retrieve cores from the sub-bottom by remote control from the ship can help to fill the gap between relatively inexpensive conventional methods - like vibracoring, gravity coring or piston coring - and the use of drill ships. For deployment on the sea floor, several drill rigs have been developed that use a single core barrel and can drill to a depth of up to 5 m, as well as other rigs that have a drill-pipe magazine (multi-barrel). For the latter, extension pipes can be attached to the drill string and thus significantly greater coring depths can be achieved (Shukla & Karki, 2016).

Inspection, maintenance and repair

The majority of IMR operations are now conducted with ROVs. However, in recent years an AUV has been successfully deployed for the inspection of subsea infrastructure at several deep water field developments offshore West Africa. The surveys took place in 2014 and 2016 at water depths up to 1400 meters, and the total length of inspected pipelines exceeded 978 kilometres. The experience showed that the AUV pipeline inspection surveys provided data of higher quality compared to traditional ROV methods, while significantly reducing the offshore HSE exposure and the required time and costs of the operation (Ghis & Fischer, 2017).

The average speed of an ROV inspecting a pipeline is 0,2 knots, whereas AUVs perform the survey at a speed of 3,5 to 4,0 knots. However, currently pipeline inspection by AUVs require conducting the survey with multiple lines to cover the whole area of interest and still only 96% of pipeline length can be reached by an AUV due to its way of moving. Therefore, at this time AUVs cannot completely replace ROVs in pipeline inspection tasks, but they can provide data to determine exact sites in need of further actions in a much more efficient way compared to the standard time and cost consuming ROV surveys (Ghis & Fischer, 2017).

In addition to standard payloads such as SSS and MBES, the AUV applied for the pipeline surveys offered a variety of new advanced sensors including laser bathymetry system, high resolution monochromatic still camera and sub-bottom profiler (SBP). Ongoing research is focused on addition of mass spectrometers, hydrocarbon sniffers and cathodic protection measurement sensors to the future toolbox of AUVs (Ghis & Fischer, 2017).

Efforts are currently being made in the area of pipeline tracking systems that would provide increased autonomy and intelligence and allow an AUV to actively adjust its course in real time based on the received measurements to precisely follow the pipeline when collecting data (Ghis & Fischer, 2017).

Some commercial tasks, such as inspection of risers and pipeline touchdown, will require a hovering capacity and an ability to move in all six degrees of freedom. For these purposes autonomous ROVs are being developed. The idea is that an autonomous vehicle can move from a garage under water, avoiding all obstacles on the way, to an intervention site such as a well head. Here it would perform its function, such as inspection or light intervention, and then move on to the next location. It is not meant that it could undertake heavy intervention work, not least because of the power required for that. For heavy intervention, the leading concept is that an ROV-like vehicle would travel autonomously to the intervention site, where it would plug itself in to pre-laid power and telemetry cables. It would then become a conventional ROV with an operator, albeit a remote one, who would take over control and perform the intervention work. On completion, the vehicle would then be instructed to return autonomously to the garage or go on to another intervention site. The various components for this, such as docking and autonomous light intervention have all been successfully demonstrated through various European research programmes such as SWIMMER and ALIVE (Gallett, 2008).

Production

There are various kinds of offshore structures to support drilling and extraction of oil and gas such as jack-up rigs, fixed tower structures, compliant towers, floating production-storage-offloading vessels, tension leg platforms, sub-sea systems and SPAR platforms. Specific choices out of these structures for a particular offshore field development project depend on many factors such as water depth, environmental conditions, required topside equipment, construction costs.

Keeping people on these platforms is not only challenging from HSE point of view, but also expensive. Researchers have described success of automation of offshore facilities with multiple unmanned-remotely-operated satellite platforms with reduced shutdown and lower maintenance cost around a focal manned platform equipped with major processing and compression machineries. This model has successfully provided significant savings to companies in terms of capital investment and operating cost. These remotely controlled unmanned platforms work on the principle of teleoperation where all the processes on the offshore facilities are closely monitored by a skilled operator from the safe location of a manned focal platform. These platforms perform their tasks for at least six months or a year without any local human intervention and human interferences are only required in the cases of emergency and routine system inspections. This saves lot of time and money required for sending highly skilled manpower to offshore platform for monitoring and supervising production operations (Shukla & Karki, 2016).

To improve further upon this concept recently Statoil in association with SINTEF embarked upon developing a more advance remote controlled unmanned platform equipped with redundant manipulators, multiple sensors, high quality audio, visual and haptic feedback to the control center operator located on the safe location (Shukla & Karki, 2016).

Environmental monitoring

Focus related to the aims of the environmental baseline and consecutive monitoring surveys in the marine environment have shifted over the last years. Whereas earlier focus was mainly on assessing the pollution status of the area, more companies are now focusing on exploring the biodiversity of an area, and many companies, for example Statoil, have stated in their governing documents that they will "conserve biodiversity". Another focused area is "cost". Sampling, and especially in deep water is expensive, so how to get as much information as possible out of each sample is important. Investigations of macrobenthic fauna are traditionally included in offshore environmental monitoring. The reason for this is that the study of benthic communities can give an indication of the effects of pollution from offshore activities, while chemical monitoring of sediments is aimed at assessing the dispersion and concentration levels of pollutants around offshore installations. The benthic fauna is a suitable biological parameter for monitoring the effects of pollution since most of the species have limited mobility and changes in species composition and densities of individuals can therefore easily be identified. The distribution of the fauna can be related to natural variations in environmental parameters such as depth and type of sediment. The distribution can also be related to the levels of heavy metals and hydrocarbon in the sediment in order to assess the effects of these pollutants on the fauna. Benthic fauna near oil installations can be affected by a number of factors. The most important of these are discharges of drilling fluids, cuttings and others, including accidental releases of oil and physical disturbances (Myhrvold et al., 2004).

Eni has developed an underwater robotic system Clean Sea for environmental monitoring and asset integrity in oil & gas offshore installations. It is composed of a commercial hybrid ROV/AUV (Sabertooth DH by SAAB Underwater Systems) and a set of interchangeable payloads that feature a common power and data interface for data logging and intelligent autonomous mission online reprogramming, according to payload measurements or other external events (Lainati et al., 2017).

Clean Sea technology had been validated in extensive trials carried out in simulated and real oil & gas scenarios in 2014 and 2015: Lake Vattern (Sweden), Barents Sea, Caspian Sea, Mediterranean Sea. In 2015, Clean Sea system had completed the transition from research to operational applications with two pipeline network surveys in the Mediterranean Sea. Results obtained show high value of the technology, especially in terms of improved environmental monitoring and protection, high versatility due to the payload modularity, low logistics requirements with significant cost savings (Lainati et al., 2017). A comprehensive technical overview of the Clean Sea concept is provided by Gasparoni et al. (2013).

4. Integrated field campaign in Kongsfjorden, January 2017

Chapter 4 covers the details of the field campaign, which provided the data and the firsthand experience for the work on this thesis. The field campaign took place in January 2017 in Kongsfjorden on the northwestern coast of Spitsbergen, an island in the Svalbard archipelago in the Arctic Ocean. The introduction of the study area includes the description of the actual seabed features from previous studies. A total of five robotic platforms were deployed during the fieldwork: two AUVs, two ROVs and an USV. All of them are described in detail in the corresponding sections as well as the payload sensors on each one of the platforms. The chapter ends with an overview of the missions accomplished during the campaign.

Study area and description of actual seabed features

The survey area was the glacial fjord Kongsfjorden adjacent to the research town Ny-Ålesund, Svalbard, at 79°N 12°E, as shown in Figure 4.1.

Figure 4.1 Kongsfjorden & Ny-Ålesund, Svalbard, Norway
(Norsk Polarinstitutt)

Kongsfjorden is a unique research site at such a high latitude, with direct access from a well established settlement. It has been the study area for the research in the fields of climate change, marine biology, oceanography and geology. Kongsfjorden is a well examined area, and a suitable location for the experimental studies related to the marine operations in the Arctic regions.

Seabed surveys showed that central and outer part of the fjord is dominated by an outcrop of bedrock, with a thin (<10 m) sediment cover. The bedrock displays a relict sub-glacial, ice-scoured topography smoothed by bottom currents. The inner Kongsfjorden is characterised by moraines caused by surges of Kronebreen glacier (Howe et al., 2003).

Gas-rich sediments were present throughout Kongsfjorden during the surveys by Howe et al. (2003), however, no surface expression of pockmarks or other gas release structures could be observed. At the same time, a later study of the inner area in Kongsfjorden showed high abundance of pockmarks (Streuff, 2013), as shown in Figure 4.2.

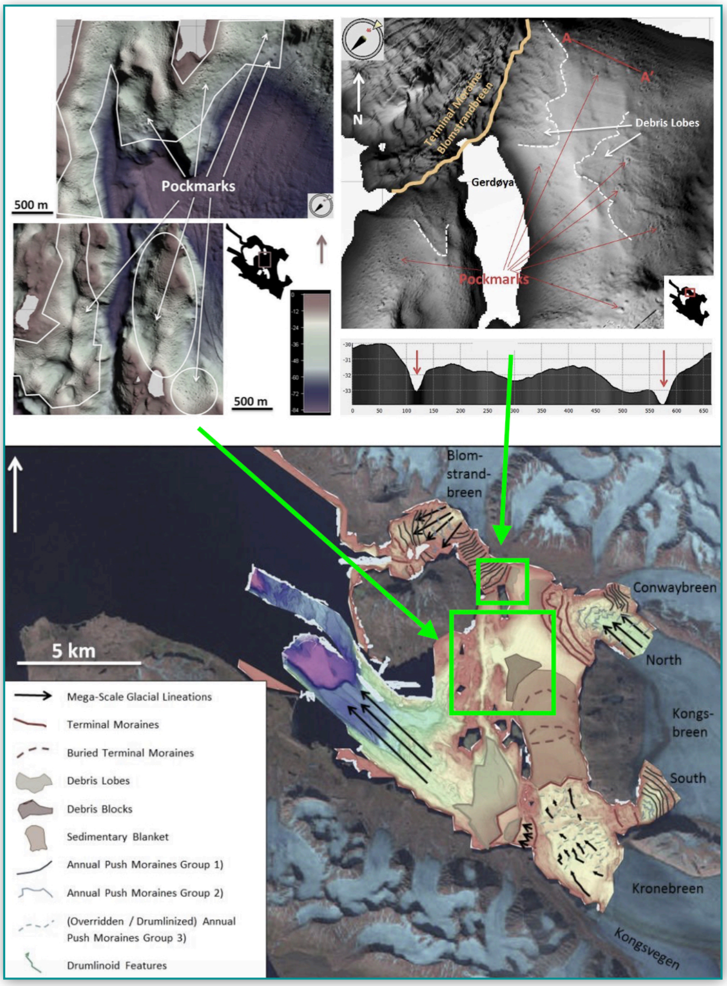


Figure 4.2. Pockmarks in the inner Kongsfjorden (Streuff, 2013)

Considering oceanography, Kongsfjorden is characterised by a large volume of glacial meltwater discharge and high turbidity in summer. The fjord is located at the western part of Spitsbergen which is influenced by northward flowing West Spitsbergen Current (WSC). The WSC is driven by the Gulf Stream and leads to a comparatively warm climate. The water of the WSC mixes with the Arctic-derived, cold South Cape Current. Kongsfjorden has no sill at the entrance and the depth is increasing towards the eastern shallow shelf (Svendsen et al., 2002; Cottier et al., 2005; Divya & Krishnan, 2016). The marine ecosystem of Kongsfjorden was extensively described by Hop et al. (2002). A number of studies in the area focused on various biological processes (Hodal et al., 2012; Kedra et al., 2010).

The centre for all surveys during the field campaign was the Kings Bay Marine Laboratory located at the harbour area in Ny-Ålesund with direct access to Kongsfjorden. The windows of the building were covered as well as street lights were turned off prior to the operations to minimise the effect of artificial light on the survey site.

Application of platforms and sensors and their relevance to the theme of the thesis

The trial of platforms and sensors in the Arctic conditions was one of the main goals of the field campaign, while the scientific focus was on the polar night biology. Oil and gas industry and marine biology share numerous measurement techniques and often pursue similar objectives, such as mapping of the seabed, including seabed habitats, or collecting hydrographic data. Therefore, marine surveys by means of innovative underwater robotics in the harsh Arctic environment, especially during polar night is of high relevance both for the science and for the industry.

A total of five robotic platforms were deployed during the fieldwork: two AUVs, two ROVs and an USV. Some of the deployed vehicles were prototypes, and some were never used in the Arctic conditions before. The payload sensors included SSS, MBES, cameras and a number of environmental sensors, all of which are normally used in the offshore surveys for the oil and gas industry. Processing and interpretation of the gathered data provided a valuable firsthand experience of working with mentioned sensor technologies.

LAUV Fridtjof and LAUV Harald

LAUV termed "Fridtjof" was built for the purpose to be used for seafloor mapping by combining side-scan sonar and camera images. A special focus in this study is to evaluate if Fridtjof was able to record structures prevalent on the seabed of the fjord, e.g. kelp forests (Kruss & Tegowski, 2011; Kostylev, 2012; Montefalcone et al, 2013). This task is considered highly relevant to the area of seabed mapping.

The second LAUV termed "Harald" was designed for oceanographic investigation, defining water masses and to map biological, biogeochemical and physical features in the water column. The objective for LAUV Harald is to perform cross-section surveys of Kongsfjorden, indicating e.g. the influence of Atlantic water (Hop et al., 2002), the distribution of Chlorophyll *a*, and oxygen concentration.

Figure 4.3 shows the two LAUVs Fridtjof and Harald that were used for the surveys.

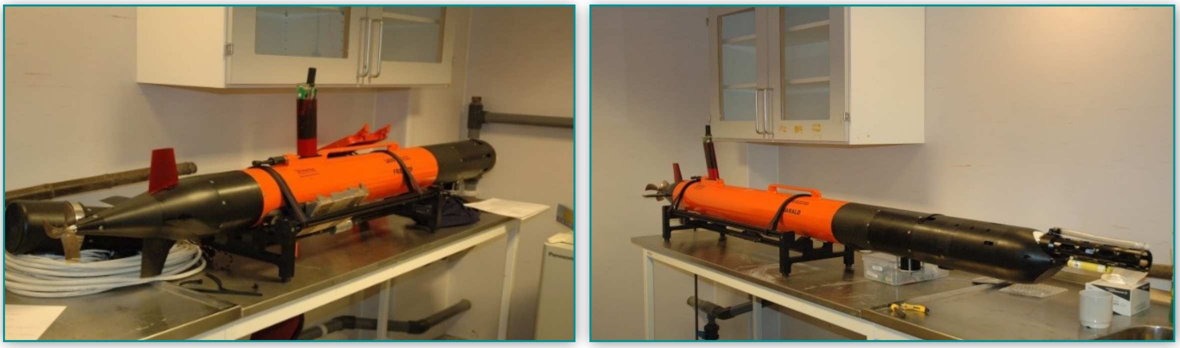
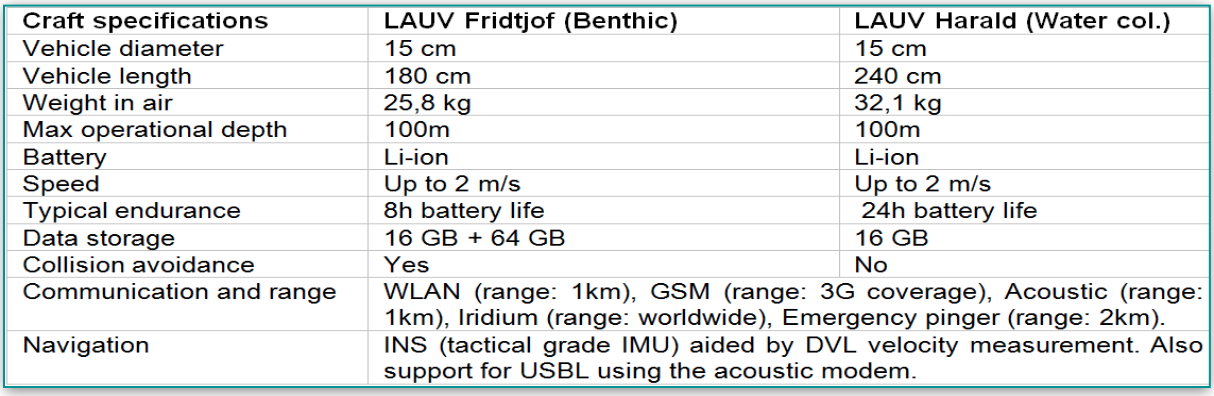


Figure 4.3 LAUV Fridtjof (left) and LAUV Harald (right)

The LAUVs used were developed by OceanScan for the purpose of cost-effective oceanographic and hydrographic surveys (OceanScan-MST, 2017). The focus in the development was to provide a lightweight, one-man portable vehicle, which can be easily launched, operated and recovered with a minimal operational setup. Table 4.1 shows the specifications of the two LAUVs.

Table 4.1: Technical specifications of LAUV Fridtjof and LAUV Harald



Craft specifications	LAUV Fridtjof (Benthic)	LAUV Harald (Water col.)
Vehicle diameter	15 cm	15 cm
Vehicle length	180 cm	240 cm
Weight in air	25,8 kg	32,1 kg
Max operational depth	100m	100m
Battery	Li-ion	Li-ion
Speed	Up to 2 m/s	Up to 2 m/s
Typical endurance	8h battery life	24h battery life
Data storage	16 GB + 64 GB	16 GB
Collision avoidance	Yes	No
Communication and range	WLAN (range: 1km), GSM (range: 3G coverage), Acoustic (range: 1km), Iridium (range: worldwide), Emergency pinger (range: 2km).	
Navigation	INS (tactical grade IMU) aided by DVL velocity measurement. Also support for USBL using the acoustic modem.	

Payload Sensors

Fridtjof was developed for seafloor surveys and contains acoustic sensor and camera images. A Deepvision type OSM2 side-scan sonar (SSS) and a camera (Lumenera Le165), with external light source, are used. Being close to the bottom, the risk of obstacles is high and the vehicle is therefore equipped with forward-looking sonar (Imagenex 852). To support the navigation by providing velocity measurements, a doppler velocity log (DVL) is installed (Nortek DVL 1 MHz). Communication is handled by an acoustic modem (Evologics S2CR 18/34).

Harald's main purpose is to investigate the water column. The main sensor for Harald is a Fastcat 49 CTD from SeaBird, measuring the temperature, salinity and pressure. Aanderaa's Optode 4831 oxygen sensor provides the in-situ oxygen concentration and WetLabs Triple-Measurement Meter ECO (Environmental Characterization Optics) Puck measures cDOM, Chl *a* and optical backscatter.

Communication and Navigation

The LAUVs have one external antenna providing GSM, Wi-Fi, and satellite communication (Iridium SBD). The crafts have acoustic modems capable of ultra-short base line (USBL) navigation, which also function as communication link between vehicle and operator. A Manta Gateway (a portable centralised communication hub) supporting both wireless and acoustic communication coordinates the traffic while the vehicle is submerged. The Manta Gateway was used during the surveys to start, control and eventually abort missions. The LAUVs have LED lights integrated into the antenna making the vehicles easy to track in the dark, and easier to find in an emergency. Both LAUVs use GPS navigation while the vehicle is at the surface. Subsurface navigation is based on inertial navigation (INS) using a tactical grade inertial motion unit (IMU), aided by the DVL. This system estimates the continuous change in vehicle position in relation to the seafloor. In addition, obstacle avoidance (only on LAUV Fridtjof) is provided following the forward distance measurement from the forward looking sonar.

ROV Blueye Pioneer One and ROV U-CAT

Two prototype ROVs, one eyeball vehicle and one biomimetic robot, termed "Blueye Pioneer One" and "U-CAT" respectively, were used during the field campaign. Although both vehicles were small observation class ROVs, the gained experience is relevant considering the current trends in development of ROVs for application in oil and gas industry, including the advances in the field of biomimetics and the idea of complementary or swim-out small vehicles.

BluEye Pioneer One

The Blueye Pioneer One – P1 is a commercial Observation class ROV prototype built by the Trondheim based company BluEye. It is the predecessor of the Pioneer 2, which will be commercially available from mid/late 2017 onwards. The P1 has a depth rating down to 100 m in seawater (Ludvigsen, 2017), which is however limited by a tether length of 50 m at the used prototype. The total weight in air is 13 kg, which makes it easy to transport. It is equipped with a HD camera and is driven via a smartphone and a controller. The communication takes place via a communication buoy and wifi signal. Two thrusters allow forward and backwards movement and one thruster each enables upwards/downwards and side wards movements. Illumination comes from a white light, which is mounted below the camera.

Due to software limitations, the used prototype was not able to record video from the onboard camera and an additional GoPro camera was mounted on top of the rover, leading to a difference between navigation video and recorded video. The setup is also shown in Figure 4.4. Most significant hereby is the difference in illumination between the on board camera used for navigation and the GoPro camera used for recording videos as well as the difference in the field of view.

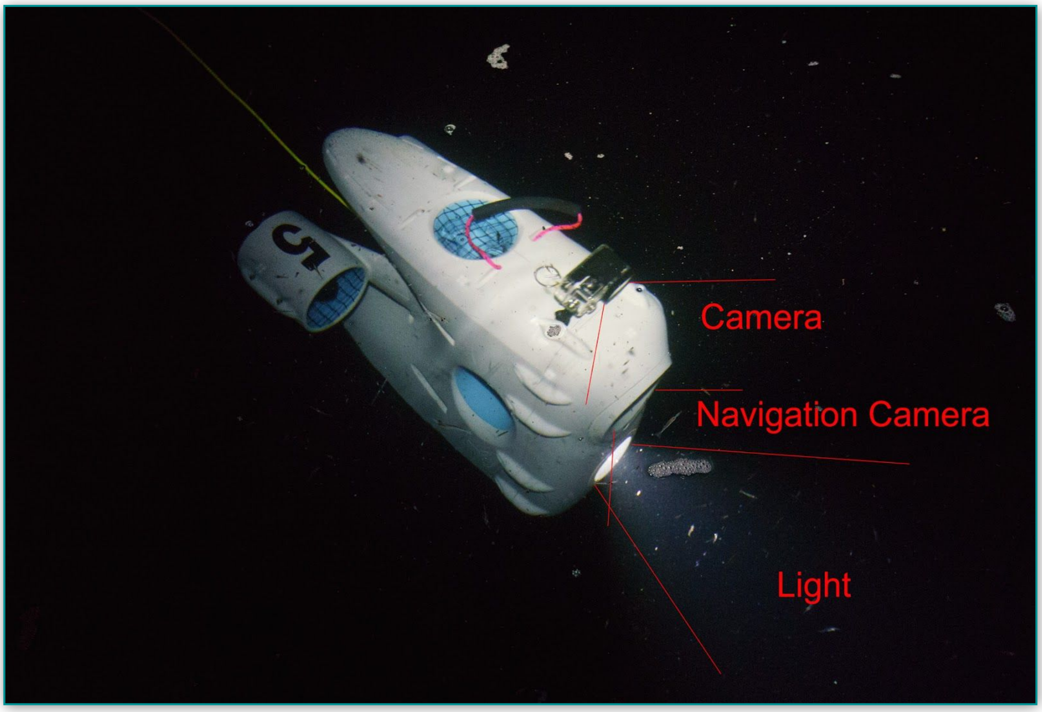


Figure 4.4. Blueye Pioneer One diving with external camera

U-CAT

U-CAT is a biomimetic underwater vehicle developed by the Center for Biorobotics at the Tallinn University of Technology in Estonia. It uses fins instead of thrusters and thereby imitates the movement of a turtle. The four fins give it a total of six degrees of freedom (Figure 4.5) and make it highly maneuverable and ideal for uses in underwater archaeology (Kruusmaa, 2017).

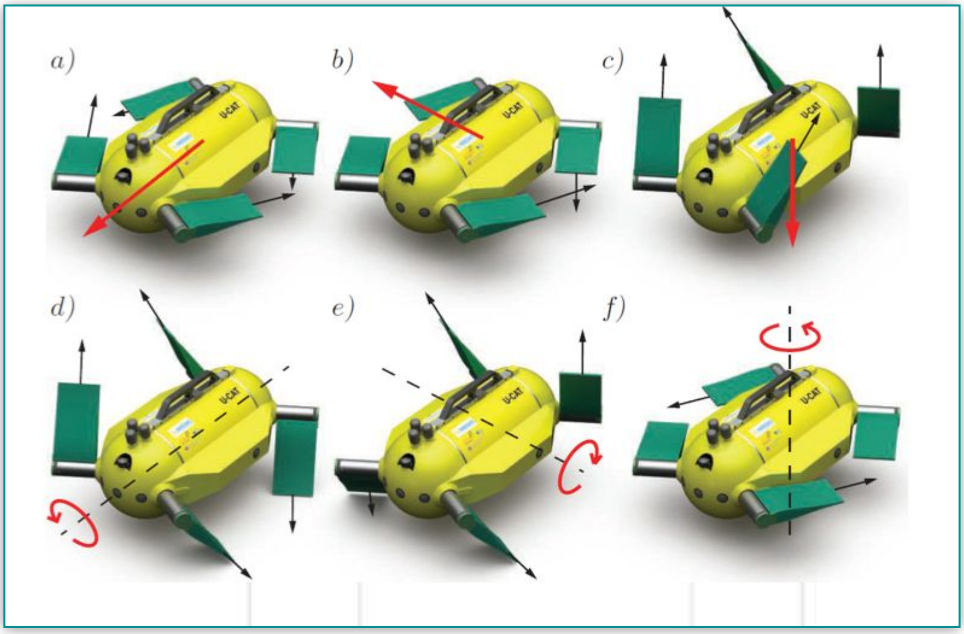


Figure 4.5. Different degrees of freedom of the U-CAT vehicle (Kruusmaa, 2017)

It has an overall weight of 19 kg and communicates to the surface via a wifi router on top of the rover. A semi-automatic control allows it to keep its position and hover in the water. A downwards facing camera is mounted in the front of the robot (figures) and a downwards facing light in the back of the robot. This setup is supposed to avoid the “snow effect” of reflecting zooplankton in the water column, which would reduce the visibility. However it also means that the rover needs to have a minimum altitude above the seafloor in order to have enough illumination for the camera. This limitation is sketched in Figure 4.6 and the minimum altitude can be estimated to around 0.5 m.

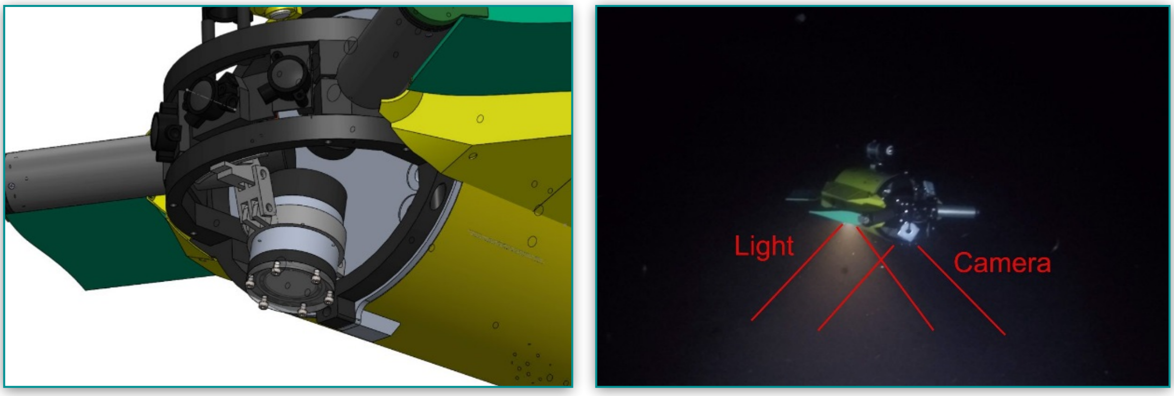


Figure 4.6. Mounted camera on the U-CAT and light and camera setup (Kruusmaa, 2017)

USV Jetyak

The Jetyak is an unmanned surface vehicle (USV) originally developed by the Woods Hole Oceanographic Institution (WHOI). The Jetyak used in Ny-Ålesund was a non-stock version, modified by the Norwegian University of Science and Technology (NTNU). With a chassis based on the motorized and commercially available kayak, Mokai Eskape, the Jetyak can be equipped with a wide variety of sensors suited for different applications. The chassis is divided into three parts: the stern section, the cockpit section and the bow section (empty). The stern section houses a propeller-connected 5 HP Subaru EX21D engine that provides thrust to the vehicle. Two 12 V, 70 Ah rechargeable batteries located in the cockpit section power the Jetyak instrumentation.

The navigation instruments of the Jetyak are located within a controller box positioned close to the bow in the cockpit section (Figure 4.7). An ArduPilot Mega APM 2.6 board connected to a GPS, compass and gyro circuit, serves as the flight controller of the Jetyak. The flight controller receives signals from a Spektrum DX7 remote control, and permits both manual and automatic (pre-programmed) navigation.

Figure 4.7. USV Jetyak - platform and interior

In order for the Jetyak to perform surveys along specific track lines, pre-programmed paths have to be uploaded to the flight controller prior to the start of each mission. This can either be achieved through a micro USB connection, or through radio communication with the Jetyak's RF Adeunis ARF868ULR radio modem. Planned paths are created in the software ArduPilot Mission Planner, where geo-referenced commands and waypoints may be set.

In terms of scientific instrument payload, the Jetyak can be equipped according to operational goals. As of now, a range of instruments including an acoustic Doppler current profiler (ADCP), a side scan sonar, a multibeam echo sounder and an acoustic zooplankton fish profiler (AZFP) have been successfully deployed from the Jetyak. Instruments are typically deployed from a module-based moon pool, situated in the middle of the cockpit section. A benefit of the module-based system is that the scientific payload can be exchanged relatively quickly, and that mounts for new instruments easily can be designed given that moon pool dimensions are known.

Payload sensors

During the fieldwork several types of acoustic instruments were used. Echo sounders are instruments used by the petroleum industry, researchers and fishers to transmit and receive sound vertically through the water column. With their noninvasive nature, acoustic instruments can sample organism data that would be missed by net sampling. Human impact on seafloor environments is increasing. To assist authorities in management decisions, accurate and comprehensive seabed maps are needed. With major breakthroughs in acoustic survey technology, marine scientists are now able to map the seabed, matching the quality of terrestrial mapping. Multibeam echo sounders (MBES) transmit acoustic impulses by a transmitter. With the use of acoustic beams, X,Y,Z, points can be established resulting in 2.5D or 3D model of the seabed (Ludvigsen and Sørensen, 2016).

AZFP

The Acoustic Zooplankton Fish Profiler (AZFP) is an instrument used to measure and record acoustic backscatter returns from the water column. It can be deployed down to 600 m depth and can operate for extended periods with its internal battery. The AZFP can contain up to four acoustic echo sounder channels, and the available frequencies are 38, 125, 200, 455 and 770 kHz. The transducers for the four higher frequencies can be located within a single housing (ASL, 2014; Lemon et al., 2012). Figure 4.8 presents an overview of the AZFP instrument and an illustration data collection applications.

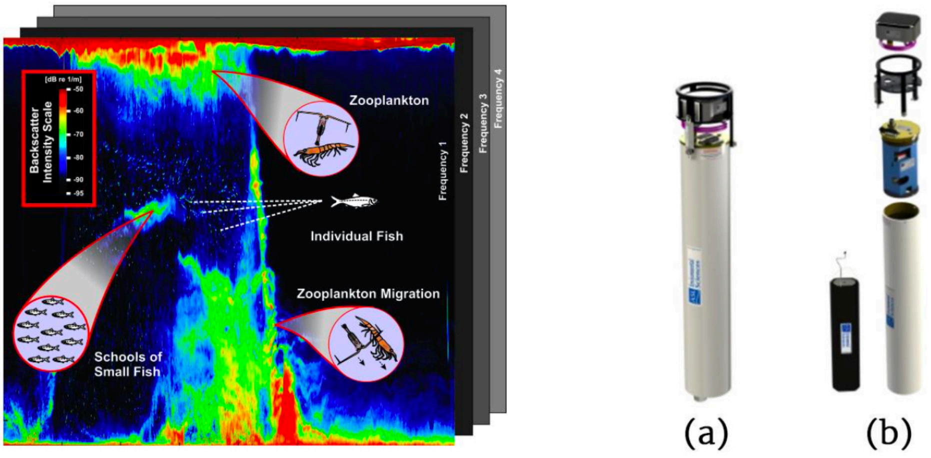


Figure 4.8. Overview of the AZFP sensor
Left: illustration of how acoustic backscatter detects zooplankton migration and fish. Right: (a) AZFP unit, (b) exploded view of the AZFP unit. (ASL Environmental Sciences)

The producer, ASL Environmental Sciences, states in the product guidelines that the standard built-in battery allows for sampling on four channels to 100 m range with pinging every 2 seconds for 150 days. However, this will vary with different settings. Each echo sounder channel utilises a logarithmic receiver, and with a dynamic range of more than 80 dB it does not require time-varying gain, simplifying data processing. To make AZFP data collection more reliable in the field, the instrument is calibrated at different tilt angles ranging from -45 degrees to +45 degrees. This is done to compensate for platform and instrument movements once deployed.

An AZFP was mounted into a module-based moon pool in the centre of the Jetyak. The AZFP was used to estimate presence, abundance and distribution of different zooplankton and fish species in the water column. The AZFP measured acoustic backscatter at four different frequencies; 125kHz, 200kHz, 455kHz and 769kHz, however data from only two frequencies were used (125kHz and 200kHz) due to excessive noise at depth from the higher frequencies.

The deepest area that would be surveyed from the Jetyak during this study was a little over 300 m, and as such the AZFP was set to a maximum range of 350 m. Pulse duration from the AZFP was initially set to 300 microseconds, but was increased to 1000 microseconds to increase the signal to noise ratio, however this is at the expense of a lower resolution of individual targets. The collection threshold was set to 120 dB, which is roughly equivalent to the background noise value at a 1 m depth. Other targets picked up by the AZFP include bubbles from waves, so the upper 2.5 m (10 m in some cases) were excluded as these were often indistinguishable from biota.

WBAT

The Simrad WBAT is an autonomous echo sounder with frequencies ranging from 30 to 500 kHz (Figure 4.9). It connects two split-beam or four single-beam transducers. The WBAT can be left deployed for up to 15 months and at depths down to 1500 m. When deployed the WBAT will follow the programmed mission control and record acoustic data at given time intervals.

Figure 4.9. The WBAT transceiver is cylinder formed
(Simrad - Kongsberg Maritime AS)

The WBAT is typically used for ocean observatory, long-term biological studies, water column profiling, and fish migration studies. It can be deployed on its own or be deployed as instrumentation on autonomous vehicles.

MBES

The Norbit compact wideband multibeam sonar (iWBMSc) offers high resolution bathymetry and has an inertial navigation system. It is based on a flexible sonar platform that utilises the latest in analogue and digital signal processing. The iWBMSc can be used for shallow water bathymetry and marine environment surveys.

CTD

Conductivity temperature depth (CTD) sensors measure conductivity, temperature and pressure, which then can be used to calculate speed of sound, salinity and seawater density. Speed of sound is crucial for acoustic imaging e.g. with reference to the AZFP and MBES, while salinity and density are key parameters for oceanography (Ludvigsen and Sørensen, 2016).

Missions overview

Missions by LAUVs

This campaign was the first deployment of LAUVs in Arctic waters. Thus, the missions had to gradually increase in complexity to account for the potential uncertainties concerning the performance and robustness of the sensor platforms in the extreme conditions, such as low temperatures, strong wind, darkness, possible encounters of icebergs. All survey missions were conducted in the period between January 13th and 19th 2017 during the civil polar night (Fossum et al., 2017). The survey areas are shown in Figure 4.10.

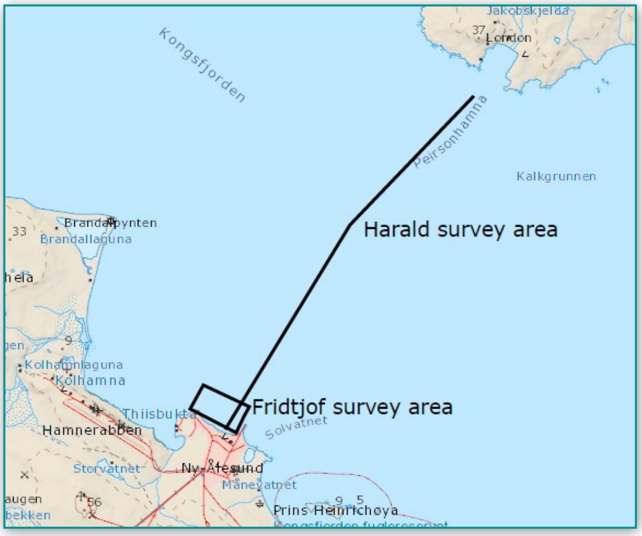


Figure 4.10. Survey areas for LAUVs Fridtjof and Harald

The weather conditions showed considerable variations in both precipitation, temperature and wind speed, with recorded wind speed up to 16.9 m/s and average daily temperature between -1.6°C and -15.3°C (average temperature around -10°C) with significant wave height below 0.5 m (Norwegian Meteorological Institute, 2017).

Normal mission duration was between 1-3 hrs. All missions were programmed in Neptus, a software developed by the research group LSTS (Underwater Systems and Technologies Laboratory), at the University of Porto (Dias et al., 2005). For every mission, two safety/ backup plans were programmed to avoid damage or loss of the vehicles, which could be activated, if necessary, using acoustics or iridium. The LAUV Fridtjof seafloor mapping missions were run outside the Marine Lab in Ny-Ålesund within 400 m from the shore. Again it has to be emphasised that special focus of this report was to evaluate if LAUV Fridtjof was able to record structures prevalent in the fjord's coastal area, e.g. kelp forests, and to investigate if LAUV Harald is able to conduct CTD measurements over a transect and collect data about the distribution of Chl *a*, and oxygen concentrations.

Pre-mission and buoyancy tests

Before the LAUVs were deployed in the water, a vehicle check was run according to the AURLab checklist and both vehicles went through buoyancy tests. The optimal positions of for the vehicles in a buoyancy test are shown in Figure 4.11.

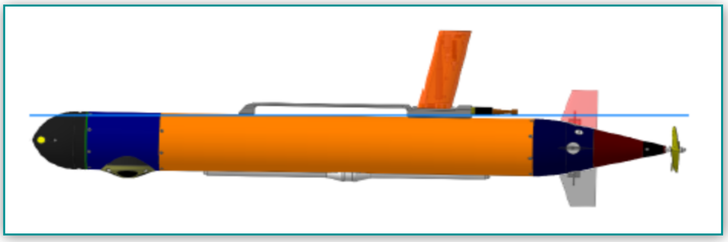


Figure 4.11. LAUV buoyancy target, note the slight positive pitch (OceanScan MST)

Function Tests

Both LAUVs had to perform function tests before full missions could be initiated. This included tests of the navigation, payload sensors, deployment and recovery. In high latitudes navigation based on magnetic compass require caution due to the proximity to the north pole and the near vertical magnetic field (McEwen et al., 2005). Compass calibration was therefore the first operation for both LAUVs.

Figure 4.12. Compass calibration and deployment of LAUV Fridtjof

Compass calibrations were performed by circling with a given radius for 20-30 minutes. LAUV Fridtjof had a successful compass calibration following a predefined calibration circle (see Figure 4.12). LAUV Harald had problems during the calibration, and had to redo the calibration the following day. LAUV Harald was slightly too buoyant and did not dive at the first attempts. The problem was solved by adding 100 g of weight.

Function tests of LAUV Fridtjof were performed using the side-scan sonar and camera. The function test uncovered navigation problems, with a drift off approximately 13% of the distance travelled (DT), which was more than anticipated. All sensors logged normally. LAUV Harald executed a short yoyo/triangular mission, moving vertically in a transect line outwards in Kongsfjorden. CTD, ECO Puck, and oxygen optode were active. Sensor and navigation data were confirmed to be reasonable and within specifications.

Deployment and recovery of the vehicles was performed from the beach (see Figure 4.12) and the crafts were manually controlled through a mobile connection when close to shore. After the LAUVs were taken on land to a dry warm place to avoid freezing of the instruments, they were rinsed and data was downloaded to Neptus for post-processing.

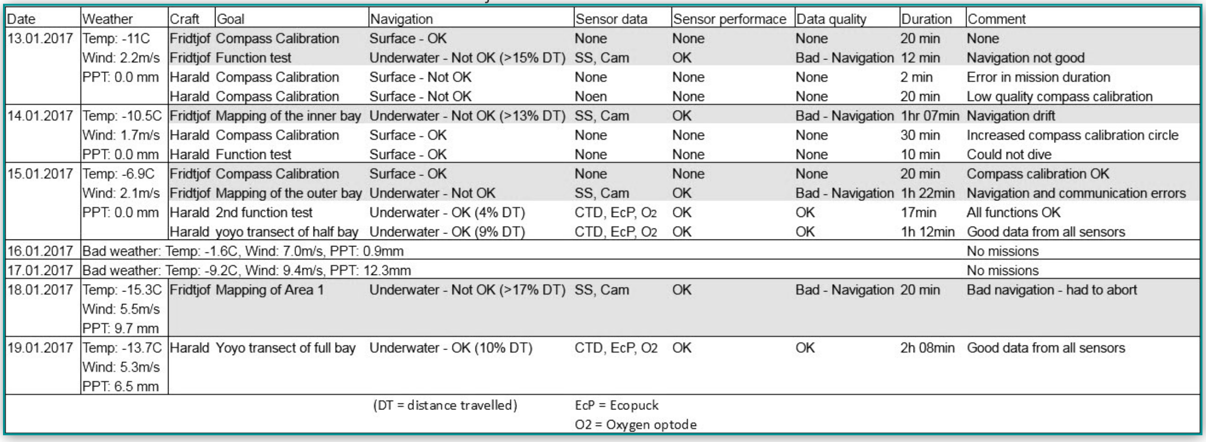
Mission Execution

This section gives a brief overview of the missions conducted during the campaign. All mission details for both crafts can be seen in Table 4.2. Note the two days with bad weather.

LAUV Fridtjof performed function tests and compass calibration on January 13, 2017, and then three survey missions in the period January 14-18, 2017, with continuous navigation problems throughout the campaign with position drift-off around 15% of the total distance travelled, more details can be found in Chapter 5.

LAUV Harald initially had trouble with compass calibration, and could not go through function test before January 14, 2017. After a successful verification of the system functions, LAUV Harald completed two survey missions successfully, with drift-off below 10% of the total distance travelled.

Table 4.2: Mission overview for LAUV Fridtjof and LAUV Harald



Date	Weather	Craft	Goal	Navigation	Sensor data	Sensor performace	Data quality	Duration	Comment
13.01.2017	Temp: -11C	Fridtjof	Compass Calibration	Surface - OK	None	None	None	20 min	None
	Wind: 2.2m/s	Fridtjof	Function test	Underwater - Not OK (>15% DT)	SS, Cam	OK	Bad - Navigation	12 min	Navigation not good
	PPT: 0.0 mm	Harald	Compass Calibration	Surface - Not OK	None	None	None	2 min	Error in mission duration
		Harald	Compass Calibration	Surface - Not OK	Noen	None	None	20 min	Low quality compass calibration
14.01.2017	Temp: -10.5C	Fridtjof	Mapping of the inner bay	Underwater - Not OK (>13% DT)	SS, Cam	OK	Bad - Navigation	1hr 07min	Navigation drift
	Wind: 1.7m/s	Harald	Compass Calibration	Surface - OK	None	None	None	30 min	Increased compass calibration circle
	PPT: 0.0 mm	Harald	Function test	Surface - OK	None	None	None	10 min	Could not dive
15.01.2017	Temp: -6.9C	Fridtjof	Compass Calibration	Surface - OK	None	None	None	20 min	Compass calibration OK
	Wind: 2.1m/s	Fridtjof	Mapping of the outer bay	Underwater - Not OK	SS, Cam	OK	Bad - Navigation	1h 22min	Navigation and communication errors
	PPT: 0.0 mm	Harald	2nd function test	Underwater - OK (4% DT)	CTD, EcP, O_2	OK	OK	17min	All functions OK
		Harald	yoyo transect of half bay	Underwater - OK (9% DT)	CTD, EcP, O_2	OK	OK	1h 12min	Good data from all sensors
16.01.2017	Bad weather: Temp: -1.6C, Wind: 7.0m/s, PPT: 0.9mm								No missions
17.01.2017	Bad weather: Temp: -9.2C, Wind: 9.4m/s, PPT: 12.3mm								No missions
18.01.2017	Temp: -15.3C Wind: 5.5m/s PPT: 9.7 mm	Fridtjof	Mapping of Area 1	Underwater - Not OK (>17% DT)	SS, Cam	OK	Bad - Navigation	20 min	Bad navigation - had to abort
19.01.2017	Temp: -13.7C Wind: 5.3m/s PPT: 6.5 mm	Harald	Yoyo transect of full bay	Underwater - OK (10% DT)	CTD, EcP, O2	OK	OK	2h 08min	Good data from all sensors
				(DT = distance travelled)	EcP = Ecopuck O2 = Oxygen optode				

Data Processing

The Neptus software was used for accessing the raw data from both crafts. As the system is new, the data export is not streamlined for processing outside the Neptus environment, and considerable time has been spent on attaining the recorded data.

Missions by ROVs

Starting from the Marine Laboratory as home base, two main locations were investigated: The harbour area in close vicinity to the Marine Laboratory and Area 1, close to the airport, as shown in Figure 4.13.

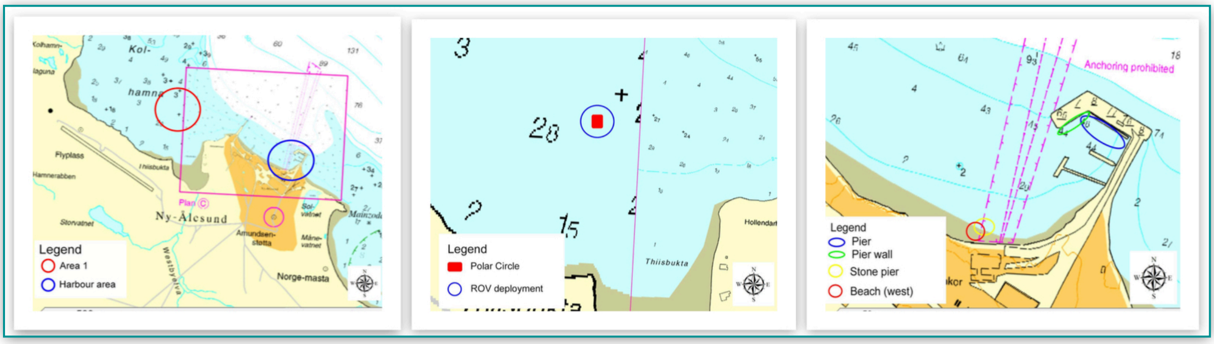
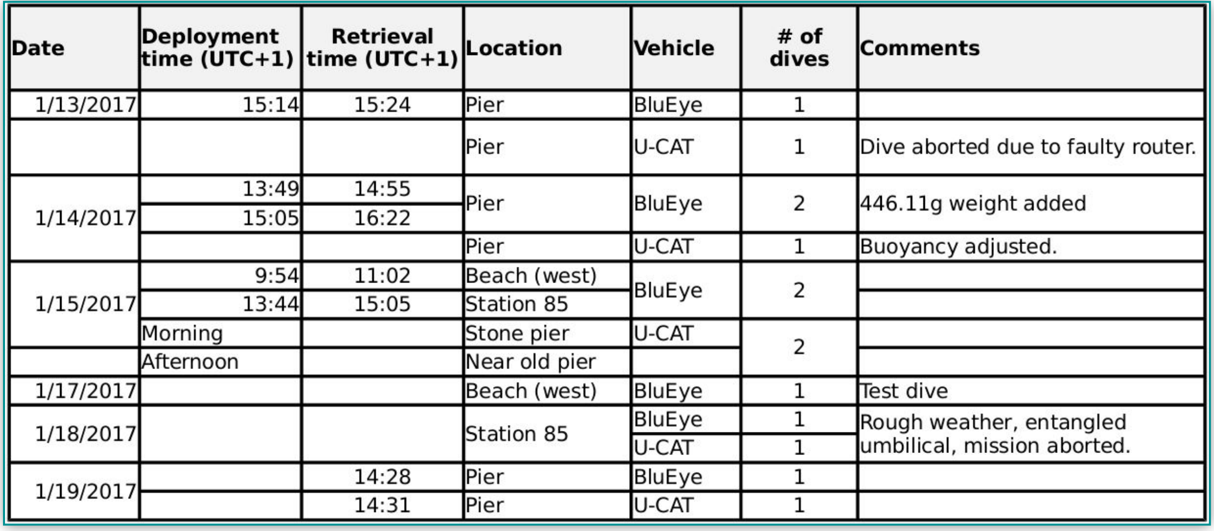


Figure 4.13. Overview map showing the main investigation areas

In Area 1 the Polar Circle anchored in shallow water with 2.5 to 3 m water depth and the ROVs were deployed directly from the boat. Due to the tether length of the ROVs and the weather conditions, only a small area around the boat, indicated by a blue circle was covered.

Several ROV deployments were performed in the harbour area. The floating pier, indicated with a blue circle in figure 2, was used as main starting point and is characterised by a water depth between 4 and 5 meters. One investigation was made along the wall of the pier (indicated with a green circle in Figure 4.13). Additionally, the BluEye was deployed from the western part of the beach in front of the Marine Laboratory (red circle in Figure 4.13) and the U-CAT from the stone pier in front of the laboratory (yellow circle in Figure 4.13). This area is characterised by a rocky ground and shallow waters with a maximum depth of 2 meters. Table 4.3 presents the missions performed by the ROVs.

Table 4.3. Mission overview for ROVs BluEye and U-CAT



Date	Deployment time (UTC+1)	Retrieval time (UTC+1)	Location	Vehicle	# of dives	Comments
1/13/2017	15:14	15:24	Pier	BluEye	1	
			Pier	U-CAT	1	Dive aborted due to faulty router.
1/14/2017	13:49	14:55	Pier	BluEye	2	446.11g weight added
	15:05	16:22				
			Pier	U-CAT	1	Buoyancy adjusted.
1/15/2017	9:54	11:02	Beach (west)	BluEye	2	
	13:44	15:05	Station 85			
	Morning		Stone pier	U-CAT	2	
	Afternoon		Near old pier			
1/17/2017			Beach (west)	BluEye	1	Test dive
1/18/2017			Station 85	BluEye	1	Rough weather, entangled umbilical, mission aborted.
				U-CAT	1	
1/19/2017		14:28	Pier	BluEye	1	
		14:31	Pier	U-CAT	1	

Deployment protocol and mission log

In order to ensure manoeuvrability, buoyancy tests were conducted before both of the ROVs were sent out on missions. For the buoyancy tests, vehicles were adjusted in tanks filled with the same seawater as in which the vehicles would be deployed. The vehicles were then equipped with weights and/or floating elements to reach a neutral or slightly positive buoyancy.

During deployment of the BluEye on the 13th it turned out that the sensitivity of the controlling joysticks was making precise steering of the vehicle difficult. Hence, sensitivity of the joysticks was reduced and 446.11 g of weight were added inside the hull of the vehicle to prevent sensitivity to currents and slow down the response of the vehicle to thruster activity.

Data analysis

After every dive the video footage collected was retrieved from the internal storage devices and information regarding the date, dive number and video number was added. The videos were watched separately for Blueye and U-CAT and the sighted organisms were identified as detailed as possible, not all down to species level. Screenshots were taken once per species to create a picture catalogue. Two species lists for BluEye and U-CAT were arranged separately for the three locations pier, beach, and area 1. Additionally, a presence/absence list with every species of the three different habitats pelagic, benthic and epifauna was created. The number of taxa/species of each habitat at each location was compared for BluEye and U-CAT.

From the video material of the BluEye, four transects were identified at a depth between 2-4 m and analysed to assess the relative abundance of macroalgae at the beach station. A transect was defined as a stretch of two minutes where the BluEye was moving in a relatively straight line and at a speed where individual macroalgae could be identified. All individuals that were visible and identifiable in the videos were counted, and mean and standard deviation of the relative abundances were calculated from the four replicates.

Missions by USV Jetyak

All missions conducted by the Jetyak or the Polarcirkel with an AZFP deployment during the fieldwork in January 2017 are depicted in Figure 4.14.

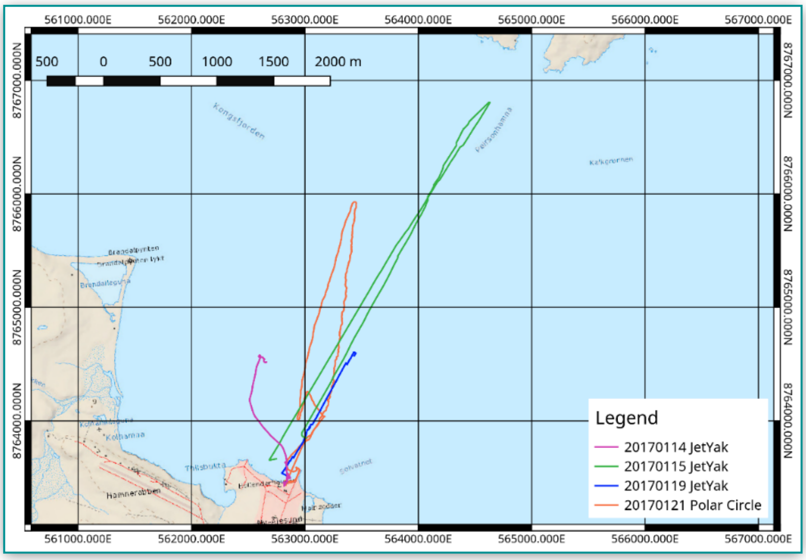


Figure 4.14. Map of USV Jetyak missions in Kongsfjorden in January 2017

Mission details are listed in Table 4.4.

Table 4.4: Overview of the fieldwork missions and deployed sensors

Mission	Date	Sensors	Platform	Location	Mission	Comment
1	11.01	AZFP & WBAT	Polarcirkel	Harbour area	Sensor testing	Testing of the WBAT and AZFP
2	13.01	AZFP & WBAT	Polarcirkel	Harbour area	Sensor testing	Testing of the WBAT and AZFP
3	14.01	AZFP	Jetyak	Kongsfjorden	Fjord crossing	Communication problems with the Jetyak, was towed back to harbour
4	15.01	AZFP	Jetyak	Kongsfjorden	Fjord crossing	Net catch sample obtained to verify species in water column
5	18.01	Side-scan sonar & Multibeam	Jetyak	Area 1	Sensor testing	Mission cancelled due to bad weather
6	18.01	Side-scan sonar & Multibeam	Jetyak	Harbour area	Sensor testing	Testing of new equipment
7	19.01	AZFP & WBAT	Jetyak & Polarcirkel	Kongsfjorden	Fjord crossing	Parallel run: AZFP deployed on Jetyak, WBAT deployed on Polarcirkel. Too strong water currents for the Jetyak, was towed back to harbour
8	21.01	AZFP	Polarcirkel	Kongsfjorden	Fjord crossing	

Prior to the start of the fieldwork, one of the scientific goals was a joint operation with a bottom- following AUV (Fridtjof) and the JetYak trailing its position. This would provide a bounded position reference for the AUV through an ultra short baseline (USBL), while simultaneously mapping the area with an multibeam echo sounder (MBES). Due to weather and technical constraints, this goal was not fulfilled. Instead, a brief survey in the harbour area was performed with multibeam and side-scan sonar (SSS) mounted on the Jetyak.

There are still lessons to be learned from this shorter mission. The weather was near the upper limit of what the vessel could take, and the therefore illustrates the limitations of the platform with respect to data quality. The Norbit multibeam is equipped with a motion reference unit (MRU), which can be used to mitigate some of the movement of the vehicle through active beam steering and post-processing. The amount of pitch and roll experienced exceeds the limits of these techniques, and artefacts appeared in the collected dataset. The magnitude of these artefacts is limited, however, due to the shallow water depths, and the bathymetry is recognisable but noisy. A figure of the post-processed result is presented in Chapter 5. Further work is required to improve this type of platform for seabed mapping.

5. Results from the field campaign

Chapter 5 displays the results of the field campaign. Considering the large amounts of gathered data, this study presents only the most prominent and relevant information. The trial of underwater robotics in the Arctic conditions was one of the goals of the field campaign, however, the scientific focus was on the polar night biology. Oil and gas industry and marine biology share numerous measurement techniques and often pursue similar objectives, such as mapping of the seabed, including seabed habitats, or collecting hydrographic data. Yet, not all the results of the field campaign are within the scope of this study. The results of particular interest to a marine biologist, but of little or no relevance to a petroleum engineer are presented briefly or completely omitted.

Results from LAUVs Fridtjof and Harald

This section discusses the results of the mission execution and the data collected during the surveys. For all missions with LAUV Fridtjof, navigation was inaccurate and the estimated subsurface position could not be trusted. After calibration of the compass and buoyancy, LAUV Harald had no problems during mission execution, except communication drop-outs.

Figure 5.1 displays the final survey path for LAUV Harald; note the different lengths on the half- fjord (brown) and cross-fjord (green) missions. The little swirls are surfacing action used for attaining GPS correction.

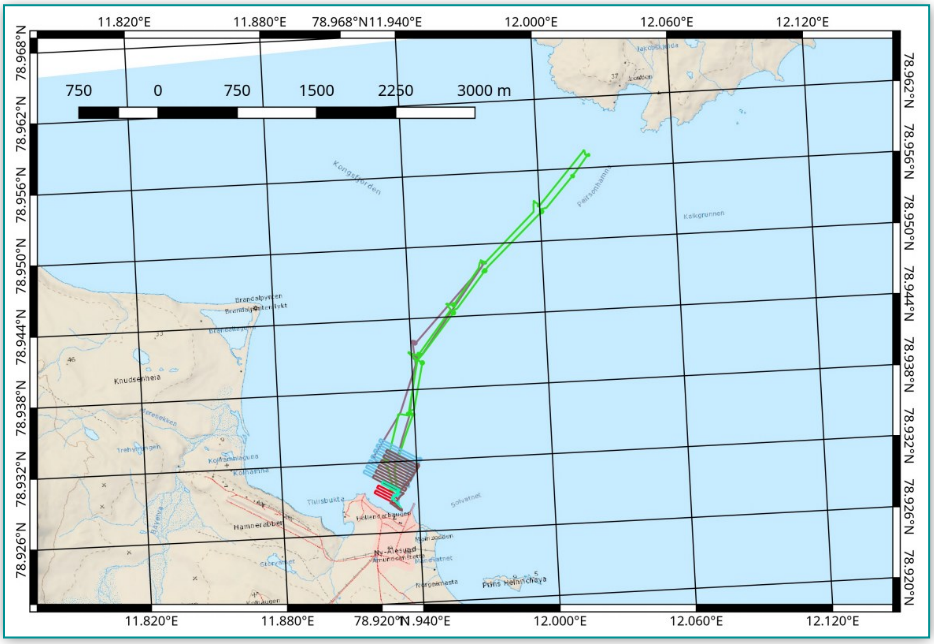


Figure 5.1. Mission overview LAUV Harald
15th of January (in dark red, half-fjord mission) and 19th of January (in green, cross-fjord mission)

In Figure 5.2 the initial survey lines of LAUV Fridtjof are visible. They do not constitute the actual path taken by the craft, since the inaccurate navigation has corrupted this data; they only display the planned survey path.

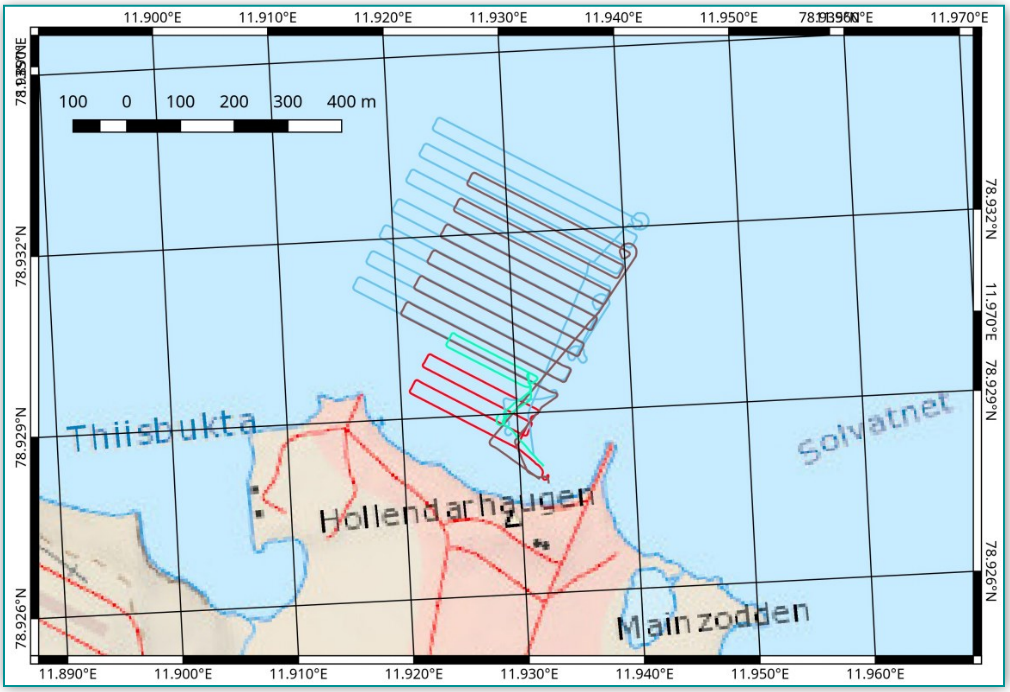


Figure 5.2. Mission overview LAUV Fridtjof
13th of January (in green); 14th of January (in brown); 15th of January (in blue); 18th of January (in red)

Data processing

The Neptus software was used for accessing the raw data from both crafts. As the system is new, the data export is not streamlined for processing outside the Neptus environment, and considerable time has been spent on attaining the recorded data.

The data from the SSS was visualized in Neptus, and values for normalization and TVG (Time Varying Gain) were adjusted to 24 and -32 respectively. The camera pictures were first visualized in VLC media player in order to adjust parameters like contrast, brightness, gamma value. Then, the objects of interest were analyzed and the time when the objects appeared was recorded. Finally, those times were identified in the SSS and, considering the overlap between transects, the objects seen in the pictures were attempted to be identified in the acoustic image in order to get ground-truth data.

The distance between the track lines was set to 27 meters. The SSS covers 30 meters from the track line both in the left and in the right direction with a blind spot of approximately 2 meters directly below the vehicle. The imager captures the area in the blind spot. Thus, the objects observed on the images are located on the SSS data from the neighboring tracks at a distance of approximately 26-28 meters from the midline, see Figure 5.3.

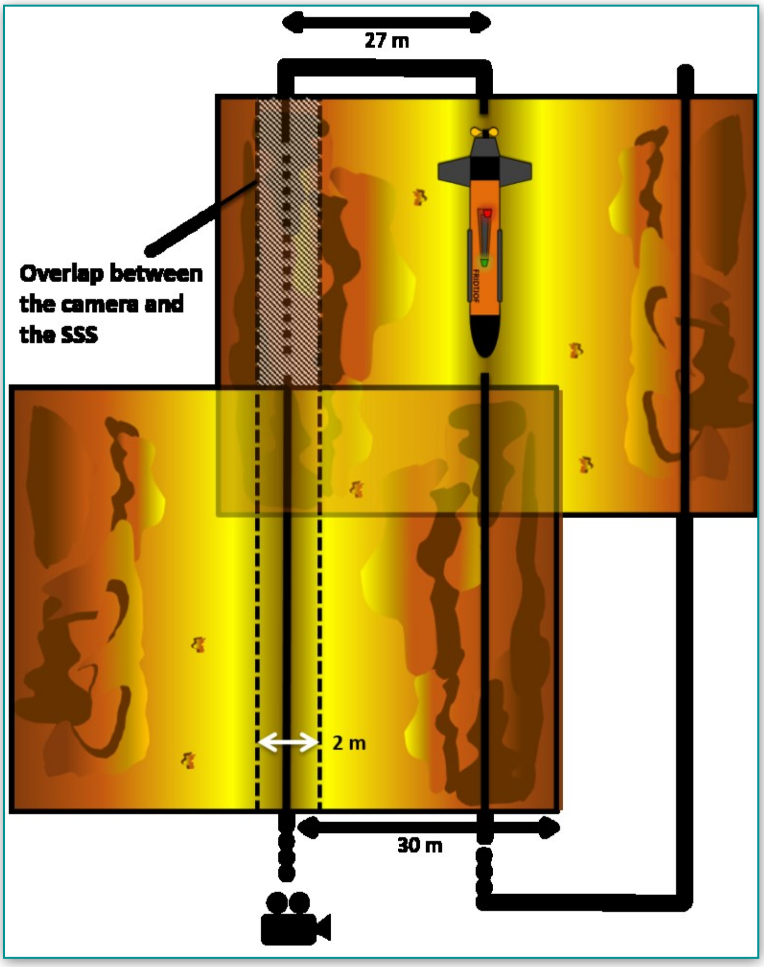


Figure 5.3: Side-scan and camera sampling configuration.

For the images of the camera along the transects, relative abundances were assessed using a subjective perception of the frequency in which some of the main features appeared. No numeric values were given, as the exact area observed was unknown due to bad navigation.

Water column properties

The measurements from LAUV Harald (CTD, ECO Puck and Oxygen Optode) were exported from Neptus to .csv-files (comma separated value) containing the relevant data, including timestamp, geographical location and measured values. To correct the data files for non- matching timestamps, Microsoft Excel was used for matching the associated data from the different sensors. The open source software Ocean Data View (ODV, https://odv.awi.de/), developed by the Alfred Wegener Institute, was used to interpolate the recorded data points using the DIVA interpolation method (Troupin et al., 2012), which is comparable to spatial interpolation, but taking into account coastlines, sub-basins and advection data, available from map databases. The "Apparent Oxygen Utilization" (AOU) was obtained by ODV using temperature, salinity, depth, and oxygen concentration as base for calculation.

Seafloor mapping

The results obtained from the missions performed by the LAUV Fridtjof showed considerable variation in quality according to the different set-ups for the vehicle. As a consequence the data cannot be used for mapping, but only as a point of reference for the structures prevalent in fjords coastal area, e.g. kelp forests. Furthermore, several sections of the missions were carried out in areas that were too deep for kelp growth.

Use of SSS

The SSS provided acoustic images of the seafloor. In those, a variety of features (both natural and human-made) were identified, see Figure 5.4.

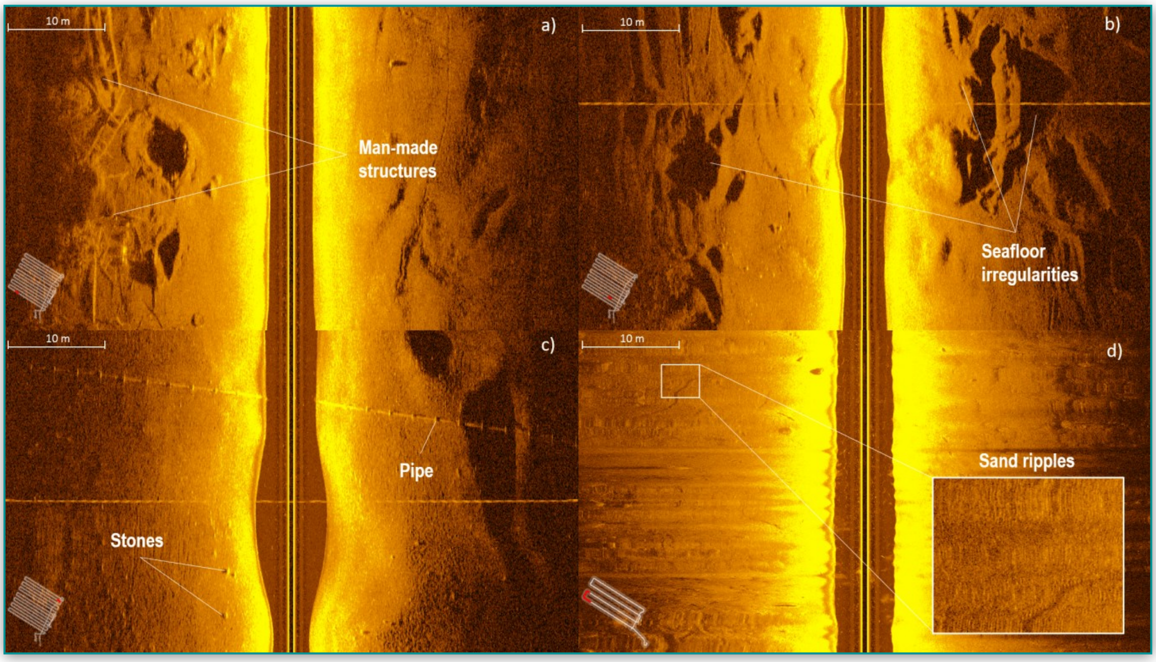


Figure 5.4 Acoustic images of the seafloor

Submarine pipes were clearly recognisable. Other features that could be observed by looking at the SSS output were sedimentary formations like submarine sand dunes, small stone aggregations, and other irregularities of the seafloor.

Use of optical camera

The images with the most optical backscatter were taken during the mission conducted on the 15th with an altitude of 2.5 m above the seafloor, while the mission conducted on the 13th at 4 m altitude appears so dark that it was almost impossible to distinguish between any features of the sea bottom.

Once all the images were adjusted and filtered in the VLC media player software for contrast and lighting, the visualisation improved significantly. Due to inability of mapping with georeferenced positions, relative abundances were assessed along the sampled transects for both physical and biological features of the seabed. The result of the analysis of the images and some examples are shown in Figure 5.5.

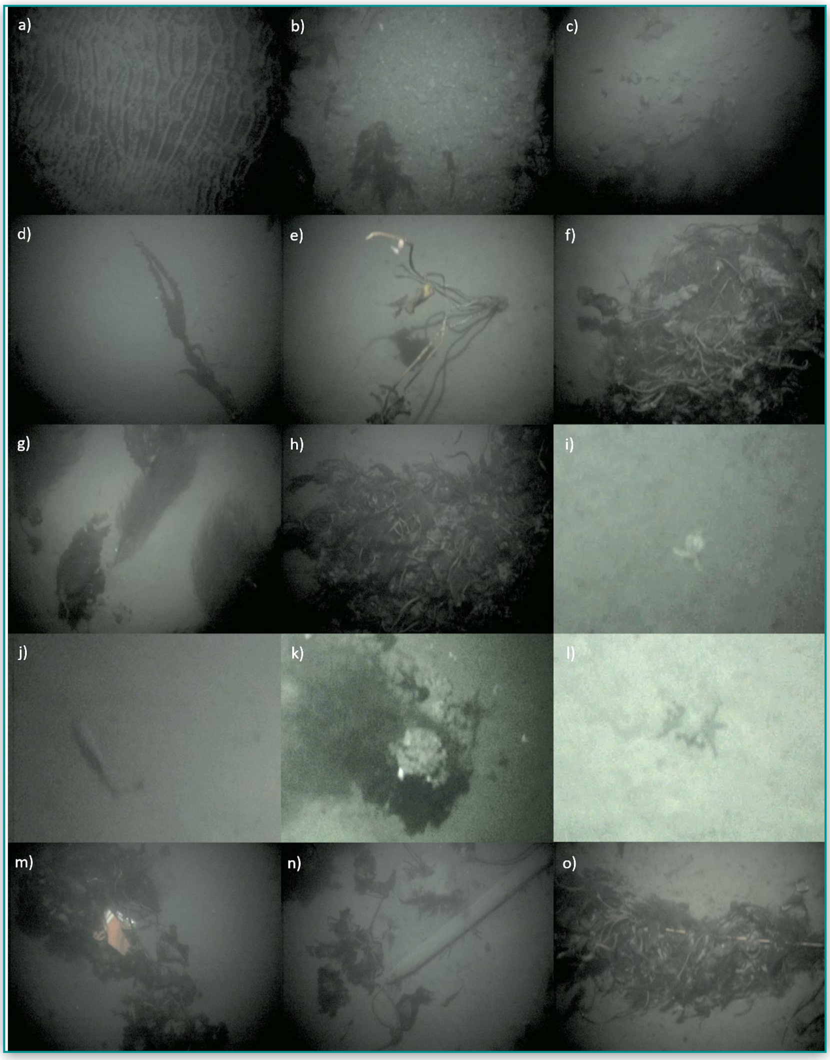


Figure 5.5. Examples of features captured by the optical camera of LAUV Fridtjof

Different examples of features captured by the optical camera of LAUV Fridtjof during the surveys of the different missions include: a) Sandy ripples. b) Pebbles and coarse sediments.

c) Sandy sediment with stones. d) Kelp lamina; probably S. latissima. e) Kelp stipes with some epiphytes. f) Path of kelp; probably S. latissima. g) Witch hair (Desmarestia aculeata). h) Path of kelp. i) Zoom in of a gastropod; probably Buccinum sp. j) Zoom in of a fish; probably Polar Cod. k) Zoom in to a rock with probably some attached Ophiuroidea on it. l) Zoom in of a crustacean; probably Hyas araneus. m) Marine litter. n) Piece of wood. o) Rope or cable surrounded by kelp.

As mentioned before, for the mission conducted on the January 13th at 4 m altitude, no usable video data was available.

For the mission conducted on January 14th at 3 m altitude, the sampled area was dominated by sandy bottom and spotted with small stones. Macroalgae were not particularly abundant and mainly aggregated in small patches. Some of these patches were concentrated around one of the pipes present in the area. Fish were spotted along this survey.

The area sampled in the mission conducted on January 15th at 2.5 m altitude was also dominated by sandy sediments and some stones. Kelp was quite abundant in this area with much bigger patches than the area sampled on January 14th at 4 m altitude. Also, fish and crabs were spotted, as well as gastropods, most likely Buccinum sp., which were sometimes quite abundant.

The region surveyed on January 18th at 2.75 m altitude was also dominated by sandy bottom, although this time, pebbles and coarse sediment were observed in extended regions. In addition, stones could be recorded. Kelp was sometimes abundant, but instead of being aggregated in big patches more isolated individuals were spread along the area. Fish and small gastropods were also observed.

Most likely, the predominant species of kelp in all the regions surveyed was Saccharina latissima. In all areas surveyed, the laminas of the kelp seemed to be lying down really close to the seabed, and sometimes they were partially buried with sediments.

Comparing the SSS to the Optical Camera

In order to verify the data from the SSS, which is based on acoustic data, “ground truth”-ing of the data had to be done by collecting direct data, in this case images.

The limited coverage between transects by the camera and the low resolution of the SSS at the extremes of the beam fan made it difficult to identify the exact features in the acoustic data. Only very clear features could be matched according to the time recorded for both datasets. Others were just pointed out as the most probable feature in relation to the camera images. (Figures 5.6 and 5.7).

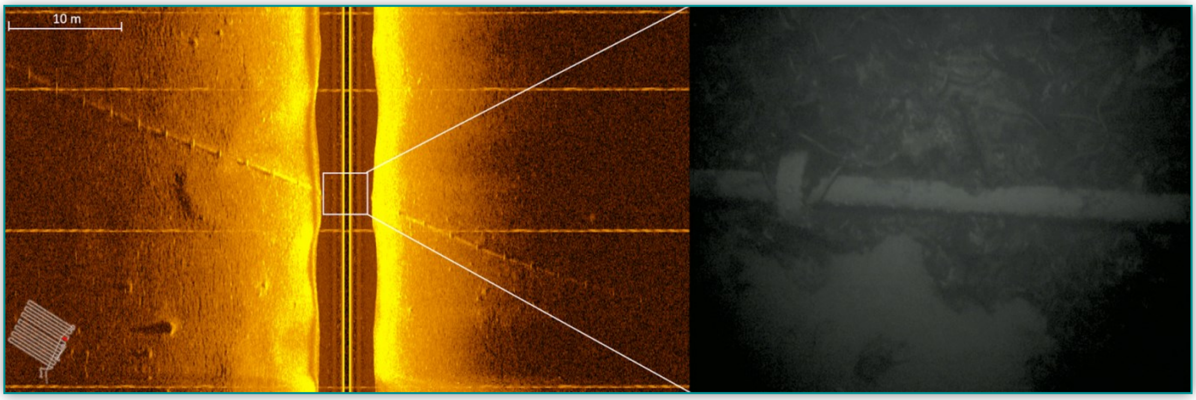


Figure 5.6. Pipe on the SSS record and the image from the camera on LAUV Fridtjof

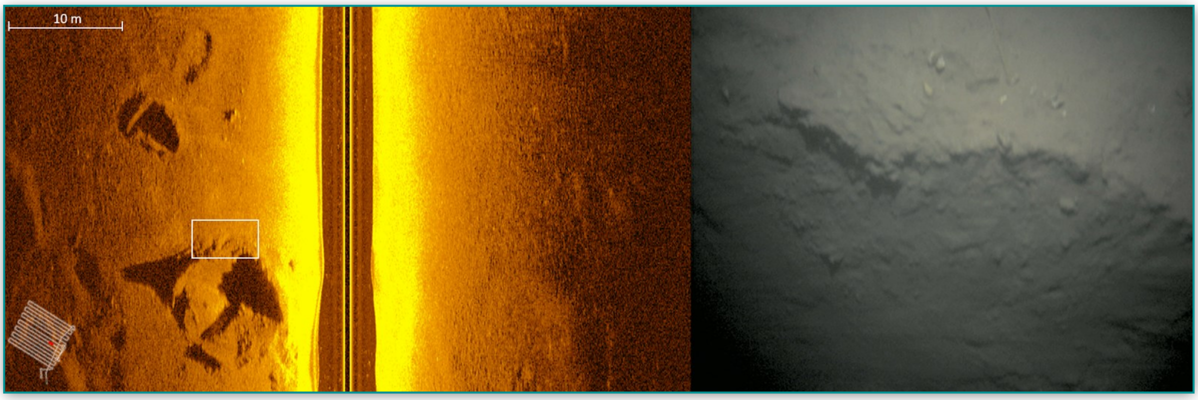


Figure 5.7. Seafloor feature on the SSS record and the camera image on LAUV Fridtjof

Results from ROVs Blueye and U-CAT

The main purpose of the ROVs was detailed exploration of specific objects of interest (OOI), including seabed habitats, which is also a part of the environmental mapping and monitoring surveys required in the petroleum industry.

After every dive, the video footage collected was retrieved from the internal storage devices and information regarding the date, dive number and video number was added. The videos were watched separately for blueye and U-CAT and the sighted organisms were identified as detailed as possible, not all down to species level. Screenshots were taken once per species to create a picture catalogue. Two species lists for BluEye and U-CAT were arranged separately for the three locations pier, beach, and Area 1. Additionally, a presence/absence list with every species of the three different habitats pelagic, benthic and epifauna was created. The number of taxa/species of each habitat at each location was compared for BluEye and U-CAT.

At the 3 locations - pier, beach and Area 1 - the ROVs U-CAT and BluEye filmed marine organisms in three habitats: pelagic, associated to the seabed and epifauna. Most of the detected taxa/species were associated to the seabed. 35 different taxa/species were identified by the videos of BluEye and 20 taxa/species by the U-CAT videos. In addition, BluEye filmed 24-and U-CAT 20 pelagic taxa/species. In contrast, 14 epifaunal taxa/species were identified by the BluEye videos and 6 by the U-CAT videos. Some examples are shown in Figure 5.8.

Figure 5.8. Red calcareous algae (order Corallinales) identified in Kongsfjorden in 2017

Results from USV Jetyak

The main goal of the Jetyak deployment was the examination of the zooplankton distribution in the water column. The data of the AZFP echograms, post noise removal, were exported and successfully used to plot the vertical distribution of zooplankton species. The test of WBAT was also performed, the aim of which is similar to that of AFZP.

The Simrad WBAT was first launched in 2015, and thus represents an acoustic profiling technology at an early stage. As a consequence, few scientific papers regarding wideband echo sounding and its capabilities have been published to date. One of the main benefits associated with wideband acoustics is the utilization of multiple frequencies simultaneously. Whereas AZFPs emit sound at a few discrete frequencies, the WBAT emits acoustic pulses in a wider range of frequencies. As multi-frequency backscatter data may potentially contain more information than data derived from a single frequency, the WBAT may improve acoustic discrimination between zooplankton taxa. However, acoustic zooplankton discrimination relies on a library of target signatures, which is currently non-existent for wideband echo sounding. Building up such a library should be considered an important next step in WBAT research and development, and could help improving the field of acoustic water column profiling.

During the fieldwork in Ny-Ålesund, the WBAT was limited to a minor role in the acoustic sampling of the water column. Only data from mission 7 of the JetYak were analysed, and significant amounts of noise were present in the dataset. The main reason for the noise was likely the WBAT deployment. Being loosely deployed from ropes at a depth of less than a metre, the instrument was subjected to extensive wave action and bubble formation. These factors likely interfered with acoustic signal transduction, producing noisy water column profiles.

Despite of the noise, distinct zooplankton layers could however be detected in the WBAT echograms. Single-target target strengths from the various layers were comparable to those from the corresponding AZFP layers, but given the current gap in knowledge regarding interpretation of wideband acoustics, no firm conclusions should be drawn. For future WBAT surveys, a stronger emphasis on data processing and interpretation should be considered.

The most significant data in relation to seabed mapping was gathered by means of a multibeam echo sounder (MBES).

Use of multibeam echo sounder

Prior to the start of the fieldwork, one of the scientific goals was a joint operation with a bottom-following AUV (Fridtjof) and the JetYak trailing its position. This would provide a bounded position reference for the AUV through an ultra short baseline (USBL), while simultaneously mapping the area with MBES.

Due to weather and technical constraints, this goal was not fulfilled. Instead, a brief survey in the harbour area was performed with MBES and side-scan sonar (SSS) mounted on the JetYak.

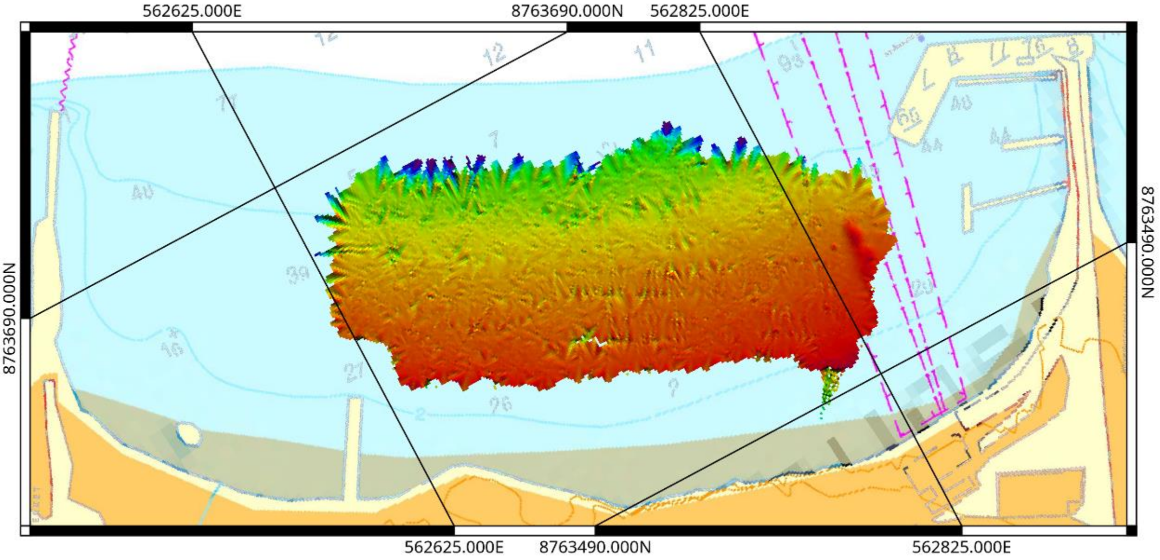


Figure 5.9. Post processed bathymetry from the multibeam sonar

The post-processed result is presented in Figure 5.8. There are still lessons to be learned from this shorter mission. The weather was near the upper limit of what the vessel could take, and the therefore illustrates the limitations of the platform with respect to data quality. The Norbit MBES is equipped with a motion reference unit (MRU), which can be used to mitigate some of the movement of the vehicle through active beam steering and post-processing. The amount of pitch and roll experienced exceeds the limits of these techniques, and artefacts appeared in the collected dataset. The magnitude of these artefacts is limited, however, due to the shallow water depths, and the bathymetry is recognisable but noisy.

6. Discussion

Chapter 6 is a discussion of the results obtained during the field campaign, with main focus on the analysis of the performance of the unmanned vehicles. The chapter highlights the main challenges encountered during the fieldwork operations in the Arctic environment and the benefits of the application of unmanned vehicles in such conditions compared to the conventional methods.

Discussion of the field campaign results

The data gathered during the field campaign provided updated information about hydrography and biology of Kongsfjorden. Although the study area is well known, the processes during the polar night represent a significant knowledge gap and the obtained results are of particular importance.

One of the interesting biological findings made during the field campaign was the discovery of the helmet jellyfish (Periphylla periphylla). It is known to occur in particularly high densities in certain Norwegian fjord systems, resulting in decreasing fish abundance. Although specimens have been found in the Barents Sea, the species has never previously been recorded in Kongsfjorden. Following the discovery, an effort was made to identify helmet jellyfish in the AZFP echograms, gathered with the JetYak. The results suggested that the species could be abundant in Kongsfjorden.

Performance of the unmanned vehicles

For the work on this thesis, main focus in the analysis of the field campaign experience was on the evaluation of the performance of the deployed vehicles in the Arctic environment during polar night. While the conducted surveys pursued biological research goals, the testing of the equipment and sensors was of particular interest for engineers. The challenges encountered while using each vehicles and relevant sensors are presented in respective sections.

LAUVs Fridtjof and Harald

For all missions with LAUV Fridtjof, navigation was inaccurate and the estimated subsurface position could not be trusted. Therefore, the results obtained from the LAUV Fridtjof surveys appeared not to be useful for the purpose of seabed mapping, which was one of the initial aims for the field campaign. However, they were suitable to estimate relative abundances of seabed features for investigated areas.

The reason for bad navigation could be that some magnetic interference was present on the survey site which affected the magnetic compass of the vehicle. One possibility could be that the airport of Ny-Ålesund (close to the study area) caused a magnetic shift of the magnetic north in the instruments. An indication that points out towards this hypothesis is that the navigation performance of LAUV Harald was much better than that of LAUV Fridtjof while the sampled areas of LAUV Harald were much further away from the shore, towards the middle section of Kongsfjorden, avoiding the local anomaly. Moreover, as noticed by the experienced participants of the field campaign, previous surveys with REMUS 100 carried out close to Longyearbyen airport also faced similar issues with the compass navigation (Fossum, 2016). Another error source for navigation could have been internal hardware failure.

The camera recordings from the LAUV Fridtjof provided valuable information in general terms. From the results, one can clearly see that the camera performance is limited by the altitude at which the AUV is navigating, in addition to poor visibility (turbidity, weak light, etc.).

The LAUV Fridtjof is equipped with 4 LEDs to illuminate the seafloor without overexposing it. In clear waters and with all 4 LEDs fully operative, the LAUV can record clear images of the sea bed from up to 5 m altitude. Unfortunately, 2 of the LEDs were not operative during the surveys. This fact limited the altitude navigation from 2.5 to 3 m. This indicates, as it would be expected, that the lighting system and the distance from the sea floor are directly related to the quality of the images.

Despite the poor illumination, the high resolution of the camera Lumenera Le165 (1376 x 1032) enabled to record a high number of pixels. Therefore, even though the visualisation of the raw images was bad at the start of the analysis, after processing the images information such as small variances in light was obtained and made the images more clear and sharp.

Due to the light limitation, the SSS had to be run at 3 m altitude, while the optimum for such operation is 5 m or more. A trade-off between clear camera images and adequate SSS recording was necessary.

LAUV Harald had no problems during calibration of the compass or during the missions, except communication drop-outs. However, adjusting the buoyancy was challenging. After adding a weight of 100 g, LAUV Harald was able to dive without difficulties. One issue concerning AUV buoyancy is that the water density may change as the vehicle moves into different water masses. If the water mass density changes because of changes in salinity, temperature or particle content, this may prevent the AUV from diving or surfacing. This is especially an issue for monitoring below the ice or close to glaciers, where changes in temperature and salinity occur. Salinity just underneath sea ice is usually higher than in the water column, which can cause problems in missions under ice.

LAUV Harald can only dive down to 100 m and did therefore not cover the entire depth range of the water column. To fully analyse the physical, biological, and chemical environment of the fjord, it could be necessary to utilise AUVs with a higher depth rating. All sensors successfully collected data during missions.

ROVs Blueye and U-CAT

The two used ROV platforms have different advantages and disadvantages. The U-CAT is a highly manoeuvrable and flexible platform due to its four fins, allowing complex movements. The biggest advantage of the fin propulsion is that the vehicle did not get entangled in kelp and could therefore swim straight through kelp forests. In one case, BluEye and U-CAT were operated close to each other and the umbilical of the BluEye got tangled in the fins of the U-CAT. Due to its simple fin geometry, this issue could be solved quickly and easily. The BluEye on the other hand, with its thrusters, is able to perform stable vertical and horizontal transects. This has proven to be useful during the investigation of the pier wall, whereas the hovering movement of the U-CAT caused it to move slightly upward and downward in the water column, making it difficult to obtain sharp and stable video footage. Another disadvantage of the fin array of the U-CAT is its sensitivity to currents. It was also recognised that the BluEye had an advantage in identifying smaller pelagic organisms compared to the U-CAT.

An often mentioned advantage of fin-propulsed vehicles over thruster-propulsed vehicles is the reduced amount of resuspended sediment from the sea floor. Accordingly, the hovering mode of the U-CAT and the upwards movement of the fins caused some resuspension of the sediment and therefore a reduced visibility, but this was moderate compared to the larger amount of sediment swirled up by the BluEye.

USV Jetyak

Prior to the start of the fieldwork, one of the scientific goals was a joint operation with a bottom- following AUV (Fridtjof) and the JetYak trailing its position. This would provide a bounded position reference for the AUV through an ultra-short baseline (USBL), while simultaneously mapping the area with an multibeam echo sounder (MBES). Due to weather and technical constraints, this goal was not fulfilled. Instead, a brief survey in the harbour area was performed with MBES and side-scan sonar (SSS) mounted on the JetYak.

There are still lessons to be learned from this shorter mission. The weather was near the upper limit of what the vessel could take, and the therefore illustrates the limitations of the platform with respect to data quality. The Norbit MBES is equipped with a motion reference unit (MRU), which can be used to mitigate some of the movement of the vehicle through active beam steering and post-processing. The amount of pitch and roll experienced exceeds the limits of these techniques, and artefacts appeared in the collected dataset. The magnitude of these artefacts is limited, however, due to the shallow water depths, and the bathymetry is recognisable but noisy. Further work is required to improve this type of platform for seabed mapping.

Integrated operations

Application of several platforms, such as AUV, ROV, USV and others, and sensors simultaneously may provide many benefits. One of them is a possibility to reduce the shortcomings of one platform – i.e. lack of coverage, persistence, communication etc. The temporal and spatial domains of the deployed vehicles are presented in Figure 6.1.

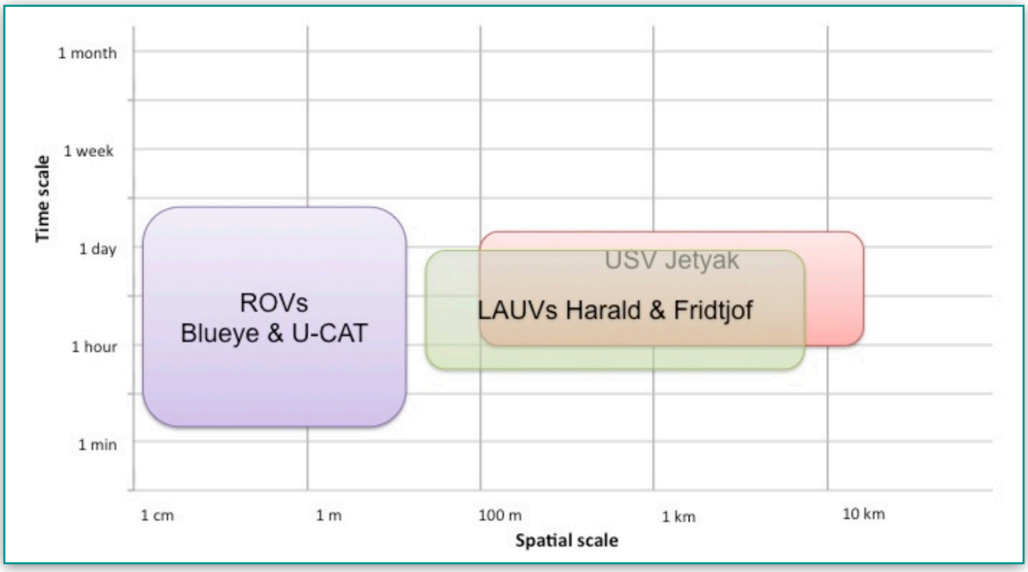


Figure 6.1. Spatial and temporal resolution of the vehicles used during the field campaign

Compared to crewed surface vessels, the programmable JetYak may, for instance, be able to follow desired track lines more accurately. Being an unmanned vehicle, the Jetyak also allows for operations in dangerous waters to a larger degree (e.g. waters associated with glaciers and sea ice). The properties of the Jetyak can also be compared with those of AUVs. Common to both platform types is their ability to run pre-programmed survey tracks. In contrast to AUVs, the JetYak is restricted to the sea surface. Consequently, the Jetyak may only be able to acquire low-resolution data from deeper waters. For shallow-water surveys the Jetyak may, however, be better suited than AUVs due to the possibility of above-water radio communication and the reduced risk of colliding with subsea obstacles. Additionally, the positional accuracy can be superior to AUVs due to the availability of global navigation satellite systems (GNSS), especially with real-time kinematic (RTK) approaches. Combining the two platforms can be a solution to improve the positional accuracy of the surveys as well as to gather the high quality data from deep waters.

In terms of spatial resolution, USVs such as the Jetyak have the capability of covering areas in the order of tens of kilometres. This is comparable to the range of AUVs, and significantly larger than the spatial coverage obtainable from fixed platforms (e.g. moorings) or ROVs. Regarding temporal resolution, processes on time scales ranging from minutes to hours may be assessed from USVs and AUVs. Although this range is small compared to the decadal range of fixed platforms, it may still be sufficient for monitoring dynamical biological systems.

ROVs are suitable platforms for monitoring the seabed and water column at a smaller spatial scale, therefore it is advisable to integrate ROVs with other platforms like AUVs and USVs to map and identify areas of interest. While AUVs and USVs provide large area coverage at a shorter time, ROVs can be applied for further, more thorough investigation of particular OOI discovered by the before mentioned platforms.

Well-planned missions do however represent an important prerequisite for multiple unmanned platforms utilization, as no researchers are on board to assess the situation. For operations in Arctic regions, the ability to run pre-programmed missions in dangerous waters makes unmanned vehicles a useful survey platform.

Implementations for a petroleum engineer

Offshore oil and gas activities require high-resolution seabed mapping data for multiple purposes: assessment of geohazards (such as landslides, fluid escape features, unstable substrates), environmental impact analysis, and environmental monitoring, including repeat monitoring of seabed habitats and ecosystems. Seabed mapping is traditionally conducted by vessels, ROVs and towed vehicles. In addition, new platforms such as AUVs are now becoming more common in petroleum industry (Pai et al., 2017).

One of the main considerations during drilling, even of a shallow site investigation borehole, is the presence of hazardous natural pore fluids, such as over-pressurised gas or gas hydrates, in the top sediment layers beneath the seabed. The implications of encountering shallow gas can be severe due to its high mobility and difficulty to control. However, it is required to obtain knowledge not only of a specific well location, but also of the larger surrounding area, since the consequences of a sudden fluid expulsion can reach the range of tens of kilometres (Hovland, 2002).

Shallow gas and gas hydrates are often associated with gas seepages and pockmarks - crater-like seabed features. In addition, the areas of active fluid flow on the seabed are characterised by increased biological activities (Hovland & Judd, 1988; Hovland, 2002). The seabed morphology is critical for assessment of geohazards, while monitoring and preserving of the biodiversity is one of requirements for sustainable exploration and production. Considering all the mentioned above, acquisition of high quality data over large areas is necessary for conducting offshore oil and gas operations. When the surveys are to be conducted in the Arctic regions, application of modern underwater robotic systems is not only time and cost efficient, but also significantly diminishes the risks to the human lives.

One of particular challenges in the Arctic is ice and icing. The field campaign took place in an ice-free fjord; therefore, no encounters with sea ice were experienced. However, the previous publications show that AUVs are capable of performing under-ice surveys and can as well be applied for ice management (Kunz et al., 2008; Wadhams & Doble, 2008; Norgren & Skjetne, 2014; Bandara et al., 2016; Barker & Whitcomb, 2016). Marine operations in the Arctic conditions are further discussed in the following section.

Operations in the Arctic during polar night

Arctic regions pose multiple challenges to scientific and industrial marine operations. Major concerns are low temperatures, ice and icing, remoteness and lack of infrastructure. Low visibility during the period of polar night aggravates these issues even further. For example, it is not possible to visually assess the presence of ice floes in the survey area prior to mission execution.

The field campaign was conducted during polar night. In the limited visibility of polar night loss of equipment is a particularly important issue. While the ROVs were connected to the surface by tethers and the position of the JetYak was known at all times by means of GPS coordinates, the AUVs were the vehicles most susceptible to loss. Both vehicles were equipped with acoustic emergency beacons, which were tested prior to every mission. However, a search party would imply the deployment of a crew on a Polarcirkel boat with a hydrophone - an operation highly dependent on weather conditions. Another consideration would be the design with emergency beacons located in the front of the vehicles, a part likely to be damaged in case of a collision. Without an emergency beacon signal and in the darkness of polar night, the successful retrieval of the vehicle would be hardly possible.

Limited visibility does not affect the unmanned vehicles under operation, but it does complicate human factors involved in launch and recovery operations, as shown in Figure 6.2. In general, launch and recovery of the vehicles were associated with most risks during the field campaign.

Launch and recovery of equipment under low visibility must be taken into account when planning offshore operations, since the polar night lasts for months in large parts of the Arctic.

The operation of underwater vehicles does not generally depend on weather conditions. However, all the vehicles required human assistance during launch and recovery. During the field campaign, all actions performed in direct proximity to water required that participants wore survival suits. Polar bear protection in remote areas was also necessary. The participants were instructed about other health related issues, for example, frost bites. In general, specific safety training is an important part of securing safety of personnel during operations in the Arctic.

Figure 6.2. Deployment of USV Jetyak and LAUV Harald
(Asgeir Sørensen)

Improper storage and handling of equipment in the Arctic, especially of instruments passing water-air boundary, may lead to serious damages. Even if the air temperature may drop below -50 °C, the temperature of the water will be close to zero. When retrieved from the water, normally flexible parts of the equipment may become fragile due to change in material properties caused by temperature gradients. During the field campaign, all the vehicles were placed in warm drying room as soon as possible after the recovery and then rinsed with fresh water.

Conclusions

All stages of offshore field development, from exploration, through development and production, and to the final decommissioning, depend greatly on assistance of underwater robotics. While ROVs represent a common and essential part of oil and gas operations, new emerging technologies are in place to provide safer and more cost-efficient solutions, and, in some cases, to access previously unreachable or unfeasible areas.

Current trends towards higher autonomy of underwater robotic systems can be particularly beneficial in oil and gas operations in the Arctic regions. Harsh weather conditions, additional environmental loads at the sea surface, including ice and icing, long distances and lack of infrastructure, especially during the long periods of polar night, are the challenges that unmanned marine vehicles can potentially resolve.

Experience gained during the field campaign, participation in which was a part of this study, showed the benefits of application of several robotic platforms, such as ROV, AUV and USV, for surveys in the Arctic during polar night. Each platform proved to have advantages for specific missions, while deployment of several different platforms during the same campaign demonstrated that such approach is beneficial both to the reduced cost and duration of the operations.

Oil and gas industry is currently under a lot of public pressure considering the environmental impacts of its activities. When proceeding further to the north, environmental mapping and monitoring will undoubtedly become of even greater importance. In addition, cost reduction is today one of the priorities as well. Efficient ways to conduct regular surveys of large areas should, therefore, be considered in the future oil and gas operations. Underwater robotics is a rapidly developing and promising field capable of solving many challenges that petroleum industry is facing.

The firsthand experience and the conducted literature review suggest that further work is required in finding better solutions for navigation of the autonomous underwater vehicles. Research in this area is currently ongoing and successful findings may lead to the significant growth of the AUV market.

To reduce the shortcomings of one platform – i.e. lack of coverage, persistence, communication etc. – several resources such as USV, ROV, and remote sensing should be considered. Also, the ability to adjust the mission execution based on sensory information is necessary for improving the data collection strategy. Some of the platforms are still sensitive to weather conditions. Increased efforts in improving the physical design for better stability of the small-scale unmanned vehicles are required.

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