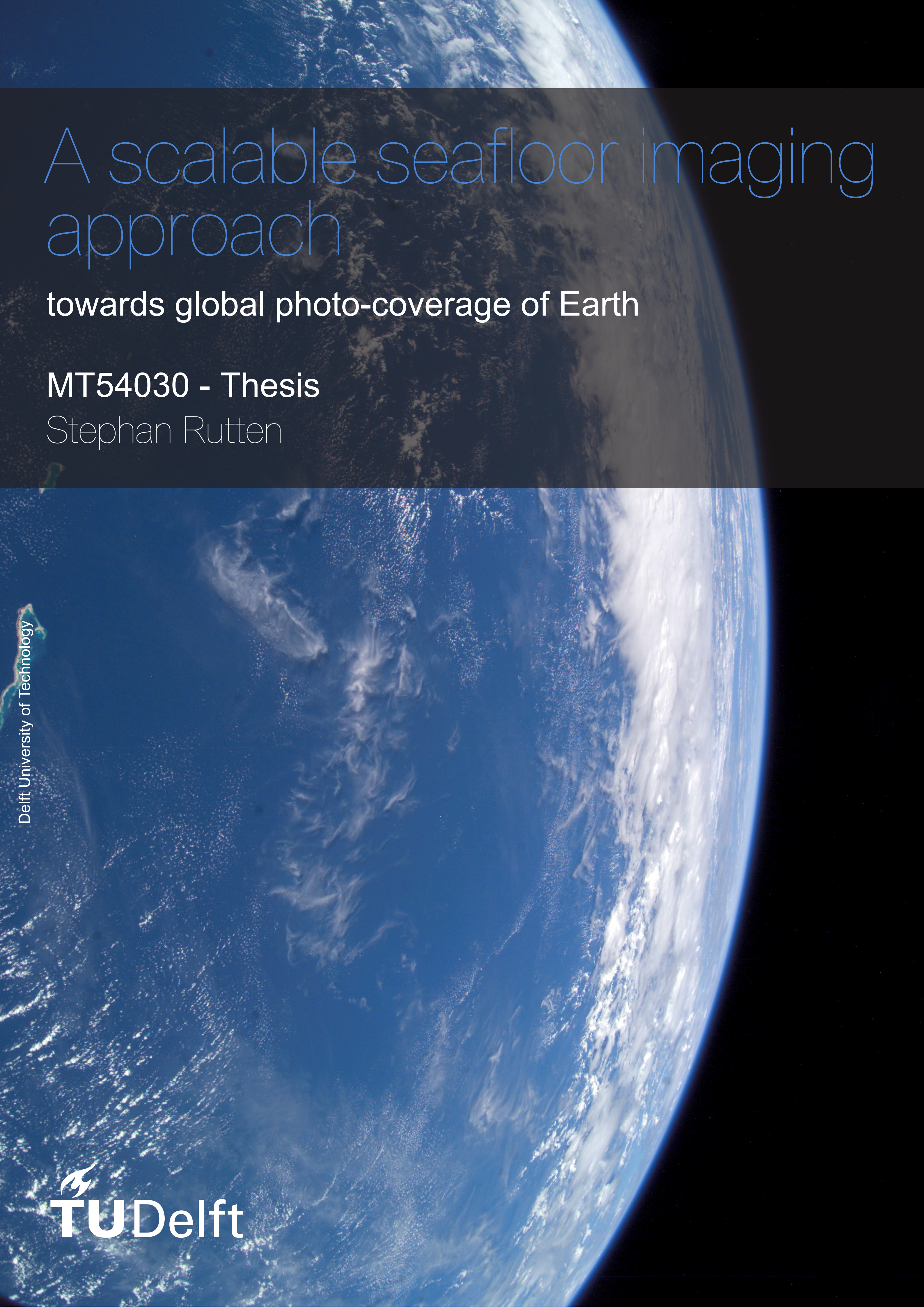

A scalable seafloor imaging approach

towards global photo-coverage of Earth

MT54030 - Thesis

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Delft University of Technology

Thesis for the degree of MSc in Marine Technology in the specialization of Ship Design

A scalable seafloor imaging approach

by

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Cover Image: The South Pacific ocean, photographed from the International Space Station during Expedition 7 in 2003, NASA

Summary

The objective of this research is to evaluate what is required to make the operation of multiple robots feasible for large scale seafloor imaging campaigns. This research also provides an early indication of the performance of such a system.

Deep water robots can cost up to $\$8$ mln. Launching and recovering a subsea robot from and to a ship, swapping its batteries and configuring its mission can take up to half a day. This requires a crew of at least five people. Due to the limited autonomy of the conventional subsea robots, combined with the aforementioned factors, means that only one robot can be deployed at the time. As a result, it takes a lot of time (years) per unit of seafloor area, and thus a lot of money.

The subsea robots' cost originates partly from its construction to withstand the hydrostatic pressure. Using oil-filled compartments with pressure tolerant electronics, the size and cost of the robots can be reduced significantly. Furthermore, it was found that by automating most of the launch and recovery tasks, the original half day process can be done in less than an hour. Finally, it is possible to localize multiple robots under water using a low-cost approach that scales well beyond tens of robots. In conclusion, these major issues blocking the use of multiple robots seem solvable.

Given that it is possible to employ multiple robots, a model was developed to analyze how much faster a 'multi-robot system' could map a certain area of seafloor. This was done in two steps.

1. First, the design of a subsea robot was captured in a parametric model, to determine the range and endurance for a specific combination of robot length, diameter and velocity. This way, using the physical parameters and design assumptions, the performance for different robot designs can be estimated.
2. The second model developed simulates the logistics of launching and recovering robots at the ship. The output of the simulation is the time required to map a certain area of seafloor.

The combination of these models provides a link between the physical subsea robot design parameters, and cost/time per area of seafloor mapped. Finally, it is computed for which subsea robot parameters the lowest the mapping cost of an area can be achieved. This is done using a brute-force approach, because the total simulation time is insignificant.

The models are validated first individually, then together in scenarios with increasing seafloor areas. Finally, the models are used to compare the proposed multi-robot system to the state of the art system, a single-robot system. A case study is done to map 1% of a region in the Pacific Ocean called the 'Clarion Clipperton Zone', which is an area comparable in size to the Netherlands. The 'multi-robot system' performs about 80 times faster, the mapping taking a mere 1.8 years compared to 201 years for the 'single-robot system'. The costs of mapping this area with the state of the art are 1.3bln, while with the proposed 'multi-robot system' they are only 18mln, against the same initial investment cost.

The implications of these results are that there is a technically feasible approach, that can be used photograph the seafloor in a much more cost-effective manner on a large scale. This while relying mostly on mature technologies, and the total system can be developed over the course of a few years. When applied to seafloor mining, it is a promising way to support a responsible seabed management strategy, that might just be in time.

Preface

This report is the result of research conducted to advance seafloor imaging systems to the next level. Although I feel I have only scratched the surface of what this subject has to offer, it was a great research project in which I could apply and combine many of the skills I have acquired during my studies.

I would like to thank Austin Kana for helping me mold my initial ideas into a defined research problem. His patient yet critical questioning have helped me to develop a better critical mindset, for which I am grateful.

In addition, I would like to thank my friends at Lobster for supporting me during the process of writing and helping me identify the fundamental questions in this research. It was great fun to diverge and converge in relevant and non-relevant topics to my graduation with you.

I hope you will enjoy reading this report.

S.H.R. Rutten
Amsterdam, July 2022

Contents

1

Problem definition

The objective of this chapter is to provide a brief background of the problem and a clear problem definition. The research objective is formulated, followed by the outline and scope of the research.

1.1. Background

Until the 1980's, there was little to no scientific data about the seafloor of the area between Mexico and Hawaii; a part of the Pacific Ocean about as large as Europe. The French national ocean research institute had done 6 boxcores[1] in a journey across. For comparison, it would be quite difficult to describe any property of continental Europe with a mere 6 soil samples. It was not until the interest in deep sea mining increased that more effort went into gathering scientific data of this part of the ocean [70].

There are many aspects to research about the subsea environment. The focus of this thesis is subsea mapping; defined here as the systematic recording of data of the benthic environment to obtain spatial distribution information of said data. Within subsea mapping, four categories of study can be distinguished;

- **Geophysics** This field of study is concerned with the properties of the substrate and deeper geological formations. This information is typically obtained using a special type of SONAR (sub-bottom profiler), which is used to listen to the reflections of different layers below the seafloor. Having this data is useful if e.g. a structure needs to be built or anchored on the seafloor. The type of foundation required for such a structure depends on the local mechanical properties of the seafloor.
- **Resource investigation** In a recently spurred rush for precious metals, people have been investigating so called 'poly-metallic nodules', fist-sized clumps of rock which contain high concentrations of manganese, copper, nickel and cobalt (Figure 1.1b). These nodules are scattered across vast abyssal plains at depths between 4000 and 6000 meters [42]. Estimating the amount and quality of resources present is done using a combination of technologies. Photographs are taken and used as a reference in combination with more efficient methods of seabed mapping using SONAR [16].
- **Ecology** Aimed at discovering and researching benthic ecosystems, this field of study also contributes to understanding how human activites are of impact on the local habitat. With human activity increasing in the deep sea, this research is gaining relevance quickly. The construction

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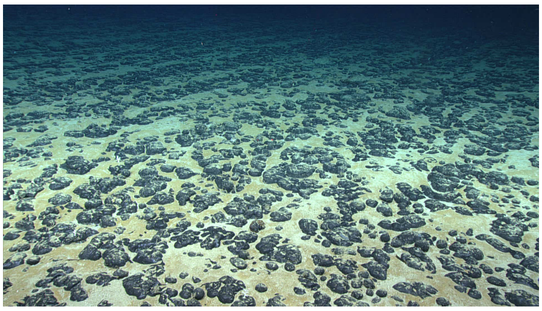
[1] Sampling method where a heavy 'box' is dropped into the seafloor and a part of the soil is scooped up for inspection on the research vessel.

of offshore assets as well as future mining activities require and Environmental Impact Assessment, of which the ecological baseline studies are a significant part. Research methods include extensive photographic seafloor imaging, the use of baited cameras and sampling.

- **Geo-oceanography** This field of research investigates how ocean basins are formed and how ocean currents behave, depending on the contours of the seabed. The seabed mapping is typically done with multi-beam SONAR and the resolution can be coarse; hundreds of meters.

All fields of study have advanced significantly over the past few decades, introducing dedicated research vessels and the use of subsea robotics for data gathering (Figure 1.1a). Now, two new factors must be considered. One, the increasing demand for precious metals spurred by abandoning fossil-fuels. Two, the urgent questions about how the oceans are impacting climate change. As a result, the need for larger scale investigations is more urgent than ever. Current research methods are already technologically advanced, but difficult to scale up to meet this need. The costs associated with a fully equipped research vessel on expedition for three months are in the millions of dollars, during which only a limited area can be researched.

(a) A subsea robot deployed from the aft of a research ship [27].



(b) A picture of the seafloor at 4500, taken in the Clarion-Clipperton Zone [74].

1.1.1. Photographic seabed mapping

While all types of seabed mapping support relevant progress in the four fields of study described, the author has most affinity with photographic seabed mapping, because:

- Photographs contain a lot of information; color, features, and if combined can also yield spatial data.
- Photographs are easily interpreted by most people. In a sense, this contributes to democratize the access to knowledge about the seafloor, much like satellite photography has done for land surfaces.
- While not economical, the data obtained from seabed photography could also be used for applications that normally require multi-beam SONAR surveys. This is not possible the other way around.

Especially for investigations involving seabed photography, the scale of operations is limited due to the rate of mapping. Where multi-beam surveys can cover swaths of several kilometers at the time, photography requires close proximity to the seabed due to the turbidity of the seawater and the attenuation of light at greater depths. A subsea device has to approach the seafloor to about 10 meters, and take pictures using artificial illumination. As a result, photographic seabed mapping takes a lot of time.

Two potential applications of seafloor photography are 1) estimating the quantity of poly-metallic nodules present on the seafloor and 2) mapping the benthic habitat. Both of these applications are encountered today in the deep sea mining industry.

1.1.2. Deep sea mining

The increasing demand and scarcity of land-based resources has caused the mining industry to investigate mining the seafloor. At approximately 4000 meter depths lie vast plains scattered with poly-metallic nodules, as seen in Figure 1.1b. These fist-sized clumps contain high concentrations of valuable metals, such as manganese, copper, nickel and cobalt. An area where these are encountered in abundance is in the Clarion Clipperton Zone[2], shown in Figure 1.2. Especially nickel and cobalt are expected to be essential for the replacement of fossil fuels, and more generally, batteries [25]. It is projected that the demand of these metals will soon outgrow their land-based supply due to the increase in the production of batteries [40].

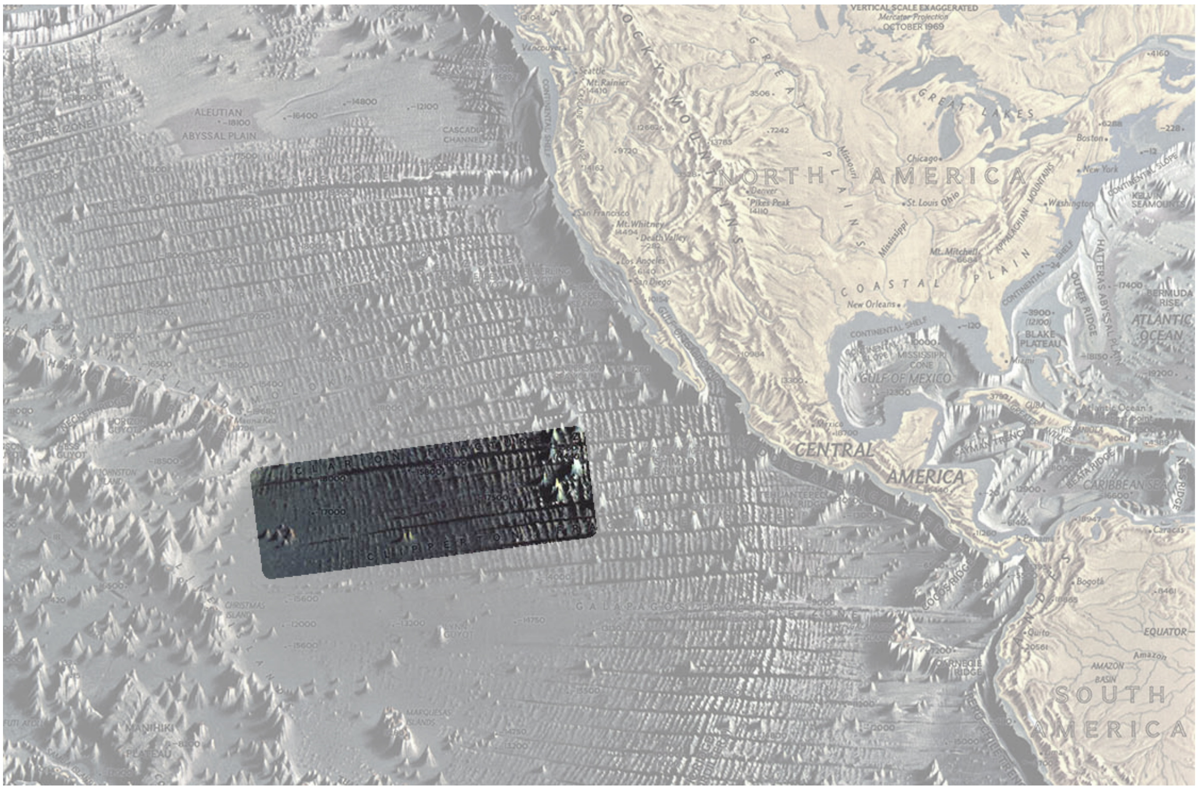


Figure 1.2: The world map showing the Eastern Pacific, with the Clarion Clipperton Zone highlighted. Adapted from [72]

Seafloor mining has not been done before at these depths, and even though pilot tests have been done, there is no consensus regarding the most viable system that can mine at commercial rates. The nodules are located on top of the seafloor, but at 4000 to 5000 meter depth, and are surrounded by very fine-grained sediment. Disturbing the seafloor in any way mixes the sediment with the water, after which it can take days to settle again. It is not feasible to filter all of the sediment out of the water, so a part of it is inevitably brought up together with the nodules to the mining vessel. Beside the technical difficulties posed by the water depth and the sediment, the costs of the mining operation will be high because of the remoteness of the location, and as a result a high rate of mineral extraction is needed to make it economically feasible. These factors increase the technological complexity of the mining system even more.

The environmental impact of the mining activities are a cause for concern to marine scientists. Scarcely anything is known about the ecosystem and geophysical processes, so it is unknown what effect a disturbance could have. Noise, mechanical destruction and most of all, the suspension of large volumes

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[2] Area in the Pacific Ocean, between Mexico and Hawaii, that has the most acute interest from the deep sea mining community.

of sediment into the sea water is expected to have a severe impact on some benthic species [20]. Moreover, the sediment plumes might persist for months and spread much further than the area that was mined. The scale of the potential impact is huge, as license areas are 75 thousand square kilometers [42].

The United Nations has mandated a committee responsible for the effective protection of the marine environment, aptly named the ’International Seabed Authority’ (ISA). The ISA is drafting regulations regarding the allowable environmental impact of commercial mining operations [13]. Potential exploitants of the area must first do research and prove that the disturbance to the environment caused by their mining process falls within the regulations. Contractors have to do an Environmental Impact Assessment (EIA), which needs to be put up for public consultation before they can apply for an exploitation license. During the exploitation phase, companies will be required to monitor the mining process closely in accordance with the regulations posed by the ISA.

In theory, this is a good system. In practice however, the ISA is having trouble drafting the regulations, because there is still insufficient data to serve as a basis for rules or even guidelines. In the meanwhile, the technological development of the mining development is progressing rapidly and in 2021, The Metals Company, together with Nauru, an island state in the Pacific, announced it aims to begin commercial mining in two years time, justified by a clause in the UNCLOS[3]. This prompted many scientists and conservationists to sound the alarm because it will take decades before the deep sea ecosystems and geophysical processes are understood to an extent that it will be possible to evaluate the impact of mining the seafloor. By now, many large tech companies have shown their support for a moratorium on irresponsibly mined deep sea metals. Either the mining industry needs to be more patient and invest more in environmental research, which might harm the advance of the energy transition because of potential shortages of battery materials, or environmental research needs to speed up, or both.

In summary, there is an urgent need for seabed mapping because of the imminent shortage of critical materials and the resulting surge in industrial activity at the seafloor. Seabed data can help understand the impact that deep sea mining has. Whether the impact is accepted or not remains to be seen. In both cases, the minig sites are of an unprecedented scale; $75000km^2$ per license.

This thesis investigates the possible scenario in which an, by today’s standards, extremely large area of seabed would need to be photographed. The outcome will help support discussions about the need of such an operation, given the costs associated with it.

1.2. Problem definition

The main problem addressed in this research is that currently it is not economically feasible to scale up seabed mapping efforts. Small to mid-size operations are possible now, but the technologies and processes used can not be applied directly to larger assignments without proportionally scaling costs as well.

To get a sense of the costs of photographic seafloor mapping, an example is provided. One scenario could be that 1% of the Clarion Clipperton Zone, has to be mapped, which in total spans $4.5 \cdot 10^6 km^2$. The flagship of the German ocean science, called the RV Sonne, has been on expedition there before, so would make a good candidate to support the mapping operation. Its operational costs are about $100k per day. Furthermore, it is assumed that is has two state-of-the-art subsea robots on board, which are alternatively deployed, such that there is a robot in the water 24/7. The robots fly at approximately 2 m/s and a swath of 5.5m can be achieved, such that its mapping speed is 11 m^2/s. For now, it is assumed that no overlap between images is required and the time of travel to and from the seafloor is negligible. This is an overly optimistic set of assumptions, but still the mapping time comes in at almost 173 years of continuous mapping, 275 days per year[4]. Of course, more ships and more

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[3] United Nations Convention on the Law of the Sea.

[4] The number of operational days is likely even less due to challenging weather conditions, crew changes and maintenance.

robots can be employed to speed up the process, but even if there were 80 ships capable of this type of operations, and a 160 of these state-of-the-art robots, the costs would remain the same, which comes down to approximately $\$4.5bln$. This is not considering the investment costs of chartering/newbuilding research vessels and subsea robots at $\$5mln+$ each.

For comparison, the current total costs of mapping about 1% of the Clarion Clipperton Zone are more than the total projected investment cost for kick-starting the global deep sea mining industry, from harvesting nodules from the seafloor to the development of shore-based processing plants [42].

This thesis is devoted to investigating how large scale seafloor imaging can become feasible, with a focus on enabling the use of more subsea robots from a single ship. This requires a decrease in the cost of subsea robots over the current state of the art, a system to streamline the handling of the robots on board the ship, and an underwater localization system that can support many robots at the time.

1.3. Research objective and outline

The goal of this thesis is to find a solution to the problem that it is currently not cost-effective to photograph large parts of the seafloor. The hypothesis is that this can be done by increasing the number of robots in the system such that higher mapping rates can be achieved and thus operating costs can be decreased. The processes executed by a multi-robot system are mostly similar compared to a single-robot system, except that multiple robots must be supported. The design of these robots, the support systems required and tradeoffs between these are investigated.

The main research question of this thesis is;

> *To what extent can seafloor imaging be made technically feasible and cost-effective at large scale by shifting from single-robot to multi-robot operations?*

To answer this question, the following of sub-questions are formulated, which are addressed in the subsequent chapters;

Chapter 2	How is seafloor imaging currently done and what are the main barriers to using multiple robots simultaneously?
Chapter 3	What system architecture can support multiple robots?
Chapter 4	What is a localization method that can support multiple Subsea Robots and meet the performance requirements, while impacting the system operations as little as possible?
Chapter 5	What is a cost-effective Subsea Robot design that enables photographic mapping of the deep seafloor?
Chapter 6	How can multiple robots be deployed effectively?
Chapter 7	How can the performance be modeled and validated at an early stage?
Chapter 8	How does the multi-robot system perform compared to a state of the art single-robot system in a real world scenario?

In Chapter 2, literature is reviewed where applicable and using private communication between industry representatives and the author. The systems used in the state of the art in seabed mapping are reviewed, and the key barriers to a multi-robot system are identified, which are used to formulate a set of design objectives. A preliminary system architecture for a new seafloor imaging system and process is defined in Chapter 3. The underwater localization subsystem is investigated in the next chapter, Chapter 4, outlining the major design tradeoffs at a high level and making some design choices where necessary. Next, Chapter 5 discusses the design of the robots, taking into consideration the imaging requirements and previous conclusions from the localization design chapter. Chapter 6 focuses on the logistics design and the supporting technology that enables subsea mapping at a much higher rate. The system design is validated in Chapter 7 by developing a model evaluate the system performance. The most important performance drivers and possible optimizations across different system components are discussed. A case study is done to validate the effectiveness and usefulness of the new subsea mapping design in Chapter 8. Finally, Chapter 9 wraps up the research and makes recommendations for future work.

1.4. Scope

The scope of this thesis is to provide a robust system- and operational concept design with validated performance estimates. The main focus in this thesis lies on investigating the technical feasibility of the physical and operational infrastructure that would be required for economically feasible large scale subsea mapping. In the light of the urgency explained in previous sections, this investigation focuses on technologies that can be implemented in the short term, i.e. a couple of years. Reliance on fundamental R&D work is avoided where possible, instead placing a preference on using proven technology in the system design considerations.

However, it is kept in mind throughout the work that parts of the solution might be further improved on or become obsolete through the emergence of new technologies, and that the design should be able to accommodate for these potential changes.

Furthermore, within the scope of investigating the short term technical feasibility of a system capable of photographing the seabed at a large scale, the individual subsystem designs are discussed, and where necessary, design choices are made, but not in detail. This requires specific knowledge of the relevant engineering domains and the designs should be specified further together with experts in those respective fields. The scope of this thesis is to provide a robust system- and operational design as a basis for further specification, with the end goal to improve the cost-effectiveness of large scale seafloor imaging.

2

State of the Art

There is already a significant demand for seafloor imaging. Subsea mapping in general has been around for decades and the global hydrographic survey market was estimated to have reached a value of $ 3.4 bln in 2020 [30] [31]. This chapter provides an overview of the technology and equipment that is currently used to photograph parts of the seafloor for mapping purposes.

The objective of this chapter is to answer the question;

> *How is seafloor imaging currently done and what are the main barriers to using multiple robots simultaneously?*

First, an overview of the stakeholders relevant to this project is provided in Section 2.1. The state of the art is described generally, after which the use of autonomous robots is investigated in more detail in Section 2.2. Finally, a thorough analysis of the identified barriers is presented in 2.3.

2.1. Stakeholders

The focus in this thesis is on the stakeholders that are involved in the operation of the seafloor imaging system. The stakeholders in the design, manufacturing and testing of subsea mapping systems are not investigated, as the main interest lies in the improvement of the operational performance over current seafloor imaging methods or systems.

For the seafloor imaging in deep water there are two main stakeholders identified; ocean researchers and deep sea mining contractors.

Ocean researchers Scientists and support staff are usually employed by a national research institute (non profit) with a scientific research agenda. Often, these institutes collaborate internationally with each other to share the costs of expeditions and get the greatest value of the time spent at sea. These research expeditions have been done for decades, and scientists are dependent on the equipment that is available (or developed by the research institutes) for carrying out their research. Their primary needs are;

- Lower cost for subsea mapping
- Reliable and safe equipment
- Video data of the sea floor, with some estimate of the location of the footage
- Other data about the water chemistry, temperature, etc.

Mining companies Companies that are interested in the potential of deep sea mining are developing machines for the extraction and processing of the ore material from the sea floor. This is guaranteed to have an environmental impact, and the International Seabed Authority (ISA) requires transparency and guarantees about the extent of this impact. An Environmental Impact Assessment has to be carried out, of which an important part is setting an Environmental Baseline. This requires large swaths of sea floor to be mapped in several ways; visually, chemically, biologically. During future commercial mining operations it is likely that active monitoring will be required in addition to pre-mining expeditions. The primary needs of mining companies are:

- Lower cost for subsea mapping
- Reliable and safe equipment
- Larger scale subsea mapping operations
- Video data of the sea floor, with an accurate estimate of the location of the footage
- Other data about the water chemistry, temperature, etc.

TU Delft The university is interested in advancing scientific research and publishing research that will contribute to society. Their primary needs are;

- Work of academic quality
- Bridging gaps between disciplines, in this case Marine Technology and Cognitive Robotics.

Lobster Robotics Lobster is a startup that is developing a low-cost subsea robot. They are interested in the context in which multiple of these robots are deployed and what technologies are required to enable and support this. Their primary needs are;

- Insight in current subsea mapping operations
- Insight and actionable measures that need to be taken to enable large scale subsea mapping

Miscellaneous stakeholders There are other applications than the ones mentioned above which could benefit from a economically viable system for large scale seafloor imaging. Governments require detailed maps of waters in their territory to be made and kept up to date for defense applications. Salvage and archaeology sectors will have more insight in the conditions of potentially interesting sites.

Conflicting interests A possible conflict between the needs of the ocean researchers and the mining companies is the end use of the data. Ocean researchers will want to use it to protect the environment, while mining companies look to exploit it for profit, with environmental conservation as a secondary priority. The way in which a better subsea mapping system is used is important to keep in mind throughout its lifecycle, from concept design to end of life.

Another possible conflict of needs might arise between the TU Delft and Lobster Robotics; the needs of Lobster Robotics are more result and commercially oriented, while TU Delft demands academic quality both in process and result and general open access science for the broader good.

The stakeholder's needs for other types of data than camera data will not be discussed in this thesis as it is not in scope.

2.2. State of the Art

This section starts with a general introduction of operations at sea and is followed by an overview of types of subsea robots. Finally, a more thorough analysis of operations with Autonomous Underwater Vehicles (AUVs) is provided.

Offshore subsea research is performed from either specialized research vessels or general Offshore Supply Vessels, which can be fitted for a number of usecases. These vessels are typically 60-100m long and as a result cost up to $100k per day, depending mostly on the number of crew on board. The reason that such large ships are used is because of the rough weather conditions encountered offshore [18]. Expeditions are scheduled for up to three months and have a program of work covering 24 hours per day during the entire period [51].

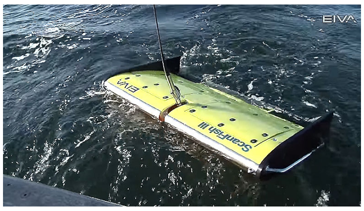
2.2.1. Types of robots

There are a number of different kinds of robots that are used in subsea research. A brief overview of their application, advantages and disadvantages follows.

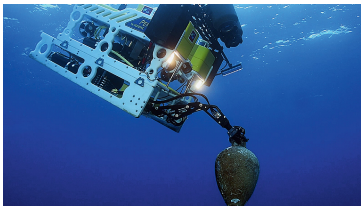
Remotely Operated Vehicles ROVs (Figure 2.1c) are commonly used in subsea research. An ROV is built up on a frame on which a number of thrusters, recording equipment, lights, sensors for navigation and stationkeeping as well as special payloads can be mounted. Deep water ROVs can weigh up to several tonnes. They are attached to the ship via a cable which provides it with a data link and power supply. ROVs give researchers a live link to what is happening subsea. If something interesting or unexpected is seen on the video streamed from the ROV to the ship, crew can choose to investigate this further immediately. Furthermore, ROVs are often equipped with manipulators that can be used to take samples. The craft are frequently used in maintenance and repair activities in the offshore energy sector.

Autonomous Underwater Vehicles AUVs (Figure 2.1a) are still not common in subsea research, and most the development still comes from the military perspective [3]. The past decade has seen more commercial interest in these craft however. AUVs are large, streamlined devices, reminiscent of torpedoes, and designed for endurance. They carry various types of SONAR devices, cameras, navigation sensors, communication and positioning devices and recovery provisions. Depending on the target depth and payload configuration, the mass varies between 800 - 2000 kg for deep water (more than 300m) AUVs. They are generally propelled by a single thruster that is mounted at the back of the AUV, and steered using movable flaps, located along the aft. As the name implies, these apparatus are untethered and follow a pre-programmed path, using beacons placed in the field beforehand as a navigation reference. AUVs are used to collect large quantities of spatial information about the seabed. [4]

(a) An AUV deployed from a ship. [21]



(b) An image of a remotely operated towed vehicle by EIVA. [63]



(c) An image of an ROV recovering an archaeological artifact. [46]

Towed robots Another type of subsea robot is towed behind the ship, and is like an 'upside down kite' which is equipped with sensors that measure seabed properties [43], like shown in Figure 2.1b. This saves the initial investment cost and know-how required to operate the advanced robots mentioned before, but has to be towed continuously by the ship.

Miscellaneous devices In addition to the survey work done using AUVs and ROVs, so called 'box-cores' are taken, sediment samples which are collected by dropping a large metal box into the ocean floor, collected about $1m^3$ of sediment for analysis at the surface. Some researchers also work with landing platforms (called 'landers'), which are usually deployed for longer periods of time and measure the chemical composition of the seafloor and can act as 'wildlife cameras'; taking pictures when movement is detected. These are stationary and can be deployed for much longer times than mobile platforms, up to several years. Activities involving a subsea robot in general can take up days of ship time, because the handling of the device is a manual and, depending on the sea state, laborious operation.

2.2.2. AUV features and operation

The focus of this research is with the AUV type robots, because these are exceptionally suitable for mapping large areas of seafloor. ROVs are tethered and thereby limited in range and number, the same applies to towed robots. Further discussions in this chapter will focus only on AUVs.

Three deep sea (6000m rated) AUVs have been selected to provide insight in the current state of the art, shown in Table 2.1 and Figure 2.2.

	Hugin 6000	**SeaRaptor**	**Remus 6000**
Manufacturer	Kongsberg Maritime	Teledyne Marine	Hydroid (Kongsberg Maritime subsidiary)
Length [m]	6.2	5.5	3.94
Diameter [m]	0.875	0.63	0.67
Weight [kg]	1850	1000 - 1200*	863
Approx. cost [$]	8000	5000	5000
Battery capacity [kWh]	60	13 - 16*	11
Nominal speed [m/s]	2.06	1.54	2.1
Source of information	[49] [28]	[65]	[59]
Image	Figure 2.2a	Figure 2.2b	Figure 2.2c

Table 2.1: Three market leading AUV types. Note that two are manufactured by Kongsberg Maritime. * configuration dependent

For visual subsea mapping, the AUVs will be equipped with a camera system and a strobed light, synchronized to the shutter of the camera. The AUV will fly between 5 - 10m above the seafloor, depending on the visibility under water [70]. The pictures are taken with overlap along the track and across the track so that they can be 'stitched' together in post-processing to form a 2D map of the ocean floor. Depending on the application, the location of any features or objects need to be known with some accuracy, generally between 0.5-5m. Thus, the location of the AUV needs to be known when a picture is taken. This is a challenging field of engineering and is usually achieved with both on-board navigation sensors and external acoustic reference networks. This network is comprised of spatially distributed beacons which the AUV can use to determine its position relative to the global coordinate system [37].

2.2.3. Regular operations

The process of operating an AUV is the following:

1. Pre-launch preparations includes checks of the mechanical components, sensor calibration, emergency systems and mission configuration. One or two crew members are required for doing these

checks.

2. Launching the AUV is done using a crane or other lifting device, to bring the AUV from the deck level to the water, which generally takes only a few minutes [18].
3. The ship may then create some distance between it and the robot as the latter prepares for diving. Most AUVs are quite streamlined and self propelled, but their maximum pitch angle is limited, and as such they cannot make a vertical descent but have to spiral down to the sea floor.
4. The AUV begins its mission once arrived at the sea floor. The HUGIN class AUVs have endurances spanning multiple days depending on the configuration, with a cruise speed between 2 and 4 m/s. Even though AUVs are untethered robots, operators still require the ship to stay in the area to supervise the robot remotely and intervene if something goes wrong [70]. In such a case, when the autonomous programming of the robot cannot deal with the situation, it comes floating back to the surface where there is sufficient bandwidth to get new instructions.
5. After it has completed its mission the robot ascends to the surface. Usually, the exact location where it surfaces is not known ahead of time, but is transmitted by the robot via satellite or radio communication after it has surfaced. The ship is moved within a couple hundred meters in the vicinity [18], and manoeuvred close to the robot once the operators have spotted it.
6. The recovery operation then consists of either having the robot dock in some sort of contraption, or grappling onto the robot and towing it back to the deck. The latter is most common and a manual process which requires skillful cooperation between the AUV operators and the bridge.
7. The AUV is then moved to a work space where the batteries can be either swapped or charged. During this time, the data is extracted as well, via a physical link or using a removable storage unit. Charging the larger AUVs can take anywhere up to 5-8 hours, and swapping can be done in 1.5 hours with a fully trained team of up to 5 engineers in the case of the HUGIN series AUVs [18]. The AUV is then ready for its next deployment, starting from step 1 again.

The handling process steps for the Hugin 6000 are summarized in Table 2.2. These parameters are likely similar for the other types of deep sea AUVs.

Handling activity	**Duration [h]**	**Source**
Pre-launch preparations	1-1.5	[18]
Launch	0.08	[18]
Surfacing of the robot up to visual detection of the operator	0.5	[70]
Recovery	0.5-1.5	[18] [58]
Charging/battery swap and data transfer	5-8 for charging 1.5 for swapping	[29] [18]

Table 2.2: Different handling activities and their estimated duration.

Note that the handling steps altogether can take a minimum of 3.75 and a maximum of 11.75 hours. This means that for a ship that costs $\$100k$ per day to operate, the handling time alone costs $\$16k - \$49k$ in between every deployment, during which no seabed mapping is done.

(a) The Hugin 6000 AUV [28]. **(b)** The SeaRaptor AUV [65]. **(c)** The REMUS 6000 AUV [32].

Figure 2.2: An overview of three types of deep sea AUVs.

2.2.4. Irregular operations

There are situations in which operators need to interrupt the autonomous operations of the robot, which fall outside of the regular AUV operating process:

1. It can happen that the AUV has some sort of internal malfunction, causing it to become unresponsive.
2. Another case might be that the AUV collides with the sea floor. With the sensor suite typically used, AUVs can handle only a certain terrain slope, and will otherwise collide, causing damage or even loss of mobility of the craft.
3. A third situation can arise when an AUV gets stuck in either vegetation or so called ’ghost nets’, fishing gear that has been lost at sea and clumped together. This could result in the loss of the vehicle altogether.

Manufacturers and operators have several mitigating measures to choose from:

1. The AUV is designed to be slightly neutrally buoyant, such that it will slowly float up to the surface. During this ascent, the AUV can drift far away from its last known position, and is thus provided with satellite communication equipment.
2. To avoid collision, a minimum flying altitude of usually at least 5 meters is required, although this differs between different types of AUVs and the local conditions.
3. When an AUV gets stuck in such debris, its naturally slightly buoyant design might not be enough for it to reach the surface again, and a recovery operation has to be done by the operator. The AUV must be located, which can be done by an acoustic distress signal which the AUV emits. This signal has a limited range (kms), so the ship should stay close during the AUV during operations.

If the operator would leave the AUV unsupervised, it could take days until they would find that the AUV is missing. By then, the AUV could be anywhere due to ocean currents and chances of recovery become exceedingly slim. Operators thus choose to actively monitoring the AUV operations.

Offshore contractor Allseas indicated that this was one of their main reasons for using ROVs instead of AUVs for survey work, because there is a direct communication and physical link between the ship and the robot, making it much harder to lose the robot [58]. Malfunction of an AUV or ROV would either way result in an interruption in the operations, which can cost up to $100k per day and additionally threaten the deadline of the work agreed upon with the client. Then, the chance of recovering the ROV quickly is much greater because it stays attached to the ship. For an AUV, there is even a chance that it is not recovered at all.

2.2.5. High cost

It does not help that the AUVs described are deemed expensive, even by industry [8]. The market leading models are the HUGIN series by Norwegian defense contractor Kongsberg Maritime and the REMUS series by US-based Hydroid (a subsidiary of Kongsberg Maritime). These devices make use of many technologies developed over several decades by Norwegian military-funded spin-offs, and as a result achieve unparalleled performance in terms of data quality and reliability. They cost between $5mln and $10mln, depending on the battery capacity and payload configuration [3]. When the cost of the specialized crew (5-6 people) along with the rental price of such an AUV is compared to the total costs of operation, it accounts for 15% - 25% of the total operational costs of an expedition [58] [18].

It is because of this cost and the laborious operations of the launch and recovery that it is rare for operators to have more than 1 AUV active at the same time[1]. This results in a limited effective mapping speed per ship and thus leads to longer expeditions, leading to high costs. For areas that are limited in size, this is acceptable. Single-robot operations require limited dedicated infrastructure and are fairly simple in execution. But if larger areas are to be mapped for future applications, the limited mapping speed will be a significant problem. Adding a few more AUVs to the operation will increase the mapping speed but also the cost; more crew is required, not to mention the significant additional investment.

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[1] There is one exception, a company called Ocean Infinity, which has a track record of performing operations with up to 9 of these AUVs simultaneously, but it must be noted that there are indications that this company is used to save money by using tax breaks from shipwreck salvage, and thus cannot be held as an example for typical deep sea research.

2.3. Barriers analysis

As discussed in the previous section, there are a number of barriers that need to be addressed before a multi-robot system can be used;

- High capital costs of Subsea Robots
- Laborious and time consuming handling (L&R, charging)
- Localization does not scale

Each barrier, if not addressed, increases the cost per mapped area significantly, especially for larger areas. In this section, a simple model is developed to quantify the effect on the cost per mapped area. The effects of each barrier and their underlying shortcomings are investigated.

2.3.1. Cost estimate

It is difficult to quantitatively compare the 'cost' of a data-gathering system. Initial or investment costs play a role, but also cost per day. If one system is much quicker in gathering data and as a result takes a shorter amount of time to complete a certain area, then cost per day is not a valid base of comparison. Then 'cost per information' seems more appropriate. In the scope of this work, this boils down to the costs per area photographed, as recommended by [33].

In order to come to a model for calculating this cost per square meter, a number of assumptions must be made.

Time frame *Time spent outside the handling and operation of the robot does not count towards the mapping cost;* If the entire chain of events before and after the actual surveying is examined, it is not trivial where the surveying begins and where it ends. For example, months of planning go into the expedition before a ship even leaves the harbor. Within the scope of this work however, the cost per square meter is identified as an interesting parameter to express the cost of the *physical* mapping system. Ship time is the main expense of a survey operation. For a fair comparison between different mapping campaigns, it makes sense to decouple the cost of mapping from the distance to shore. Going further offshore would otherwise increase the cost of mapping, while the performance of the mapping system has no effect on the travel speed (cost) of the ship. Therefore, including the travel time would not accurately reflect the mapping cost. Similarly, prior to deployment, some sort of navigation reference needs to be set up[2] for the robot to be able to relate the data captured to a position. For simplicity, the operational aspect of setting up the infrastructure for navigation of the robot is omitted in this analysis.

Data value *The value of the captured data is uniform across different systems;* It will be assumed that photographic data gathered across different mapping systems will be of approximately equal value. This way, the performance of two different system can be compared based on cost, without having to quantify the value of the data. The value of two different images of the same stretch of seafloor could vary based on the resolution, sharpness, lighting circumstances and color sensitivity.

Supervision *The full ship's running costs during the robot's mission count towards the mapping cost;* It is assumed that the ship cannot be used for other value-added activities during the actual mapping activities, and as such, the entire duration of the robots deployment is counted towards the cost of mapping. In reality, it is likely that activities such as box-coring could take place while the robot is performing its mission, provided that the ship stays in close proximity for monitoring the robot. It is difficult to say however whether other activities would be preferred but cannot be scheduled due to the required supervision of the robot. For simplicity, this factor will not be included in the cost modelling.

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[2] Refer to Chapter 4 for an elaborate analysis of this aspect.

With these assumptions in place, the time it takes for the robot to conduct its operations must be established. First, the absolute mapping speed of the robot and its dive/ascent time is determined. The mapping speed is based on the swath and the cruise speed. The swath is the width of the strip of seafloor that the robot 'sees', and the cruise speed is the average speed of the robot. Also see Figure 2.3.

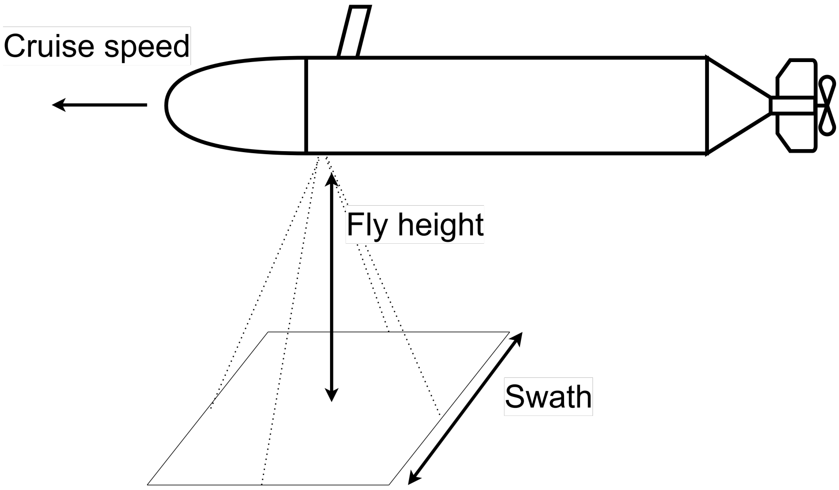


Figure 2.3: Determining the mapping speed of the robot.

Then, together with its endurance and the L&R time, the total time for the operation is found. The time it takes during which the robot is mapping can be determined as well now. From this, the total mapped area can be determined, which together with the OPEX of the ship and the equipment leads to the mapping cost per area.

This process is summarized in Figure 2.4.

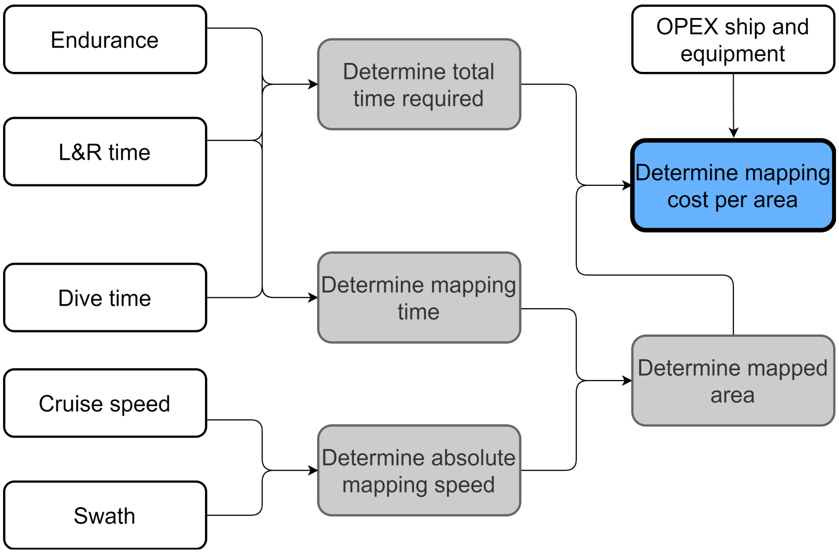


Figure 2.4: Model for determining cost per mapped area.

The data in Table 2.3 was provided to the author mostly in private communications (each source indicated in Table 2.3) as a rough estimate of the required parameters. For each parameter, the average value of the different sources was used.

Most current deep sea mapping expeditions seem to be done using the Kongsberg HUGIN series AUV [50][18]. The vessels from which these are operated differ, but are generally at least 60m long because they have to go offshore. A 2019 expedition to map parts of the seafloor in the Pacific was undertaken using a ship called 'Maersk Launcher', an offshore supply ship of 90m long [16].

Parameter	Data	Units	Source
Cruise speed	1.80	m/s	[50]
Swath	5.5	m	[16] (was deduced from proportions in figure)
L&R time	7200	s	[58] [18] [70]
Descend + ascend time	21600	s	[18] [22]
Endurance	216000	s	[50]
OPEX ship	0.93	\$/s	[8]
OPEX equipment	0.29	\$/s	[8]

Table 2.3: The parameters of a typical current state of the art scenario.

The resulting cost of mapping with the state of the art is approximately $0.15\ \$/m^2$. That is about $\$900$ for a soccer field, $\$15mln$ for the city of Den Haag, and $\$710mln$ for the Doggersbank. For comparison, the cost of commercial satellite imagery is on average $\$2 \cdot 10^{-5}/m^2$ [14]. The costs for mapping these same areas using satellite photography would be $\$0.12$ for the soccer field, $\$1963$ for Den Haag, and $\$94,700$ for the Doggersbank. The latter of course would not provide as much information as the photos taken underwater.

Sensitivity analysis The figures in Table 2.3 depend on system configuration, the environmental parameters as well as operational factors.

- The optimal cruise speed of the robot depends on its propulsion power and payload power. This range is quite narrow, between 1 m/s and 2 m/s. Increasing it would diminish endurance because of the increased resistance, and decreasing it by much would reduce the area covered per battery charge.
- The fly height is limited by the imaging system used, the same applies to the swath. Depending on the water clarity, the fly height (and corresponding swath) could be increased to about 10 meters. However, generally 5-6 meters is chosen as it has a better chance to get the data of acceptable quality. In general AUVs may only fly above 5 meters, because they have too limited manoeuvrability to avoid collision with a sloping seafloor.
- Launch time is dominated by pre-flight checks and initialization, which can take up to an hour.
- The dive and ascent time depends on the pitch angle of the robot, which is 50 degrees at most [22]. This yields a dive or ascent time of about 1.2 hours for 6000m depth. However, a field operator at Fugro indicated they average at about 30 minutes per 1000m, which would bring the total dive or ascend time to 3 hours, more than double [18]. This large discrepancy between the theoretical value and the reported value for dive/ascend time is odd, and the reported value will be assumed to be most accurate, rather than the value from the specifications.
- The time it takes to do recovery is most variable, ranging from 30 minutes to 1.5 hours, depending on the sea state, the skill of the recovery operator and the manoeuvrability of the vessel [18].
- The endurance of the robot depends on its cruise speed and the amount of batteries it carries. Assuming one of the latest models is used, the HUGIN Superior [29], battery life can be expected to be about 60 hours at a cruise speed of 1.8 m/s [58]. The exact endurance depends on what payloads are active.
- The operational expenses (OPEX) of the ship depend on its size and crew. Typically, this is between \$60k and \$100k for offshore ships. Assuming there is a full research and supporting crew on board, \$100k is a reasonable estimate. The OPEX of the equipment is based on the rental price of the AUV and the 5-6 person crew of engineers and surveyors that comes with it [58]. This figure probably depends on the duration of the expedition as well as any special requirements for the expedition, that might require extra crew.

In conclusion, the highest uncertainty encountered in the different parameters is in the time it takes to do recovery (factor 3), although this leads to only a 5% difference in mapping cost per area. The difference in the cost of operating the ship has a much larger effect; a proportional difference in mapping cost between \$60k and \$100k.

2.4. Investigation of barriers

The model is now applied to quantify the extent of costs that the barriers pose.

Capital cost A reduction in the capital cost of the robot decreases the cost per mapped area. The rental price of the equipment includes both the crew of 5-6 engineers [18] and some margin for the AUV itself. Decreasing the cost of the AUV to nil decreases the mapping cost per area by approximately 8-10%.

A number of cost-saving measures are:

- Removing features on the AUV that are not required for visual mapping. The HUGIN Superior marketed across different sectors and described as being ”designed to be the most capable AUV” [29]. The additional payloads, such as hydrographic SONARs, sub-bottomprofilers, etc, make up the bulk of the costs and can be omitted for visual mapping [75].
- Instead of using pressure vessels to protect the internal electronics against the hydrostatic pressure, electronics can be made ’pressure tolerant’, removing the need for pressure vessels, feedthroughs and a significant amount of buoyancy material altogether.

Once the robots are lower cost, larger scale production will drive down costs even further. These considerations are developed further in Chapter 5.

Laborious handling The term ’handling’ is defined here as all actions that take place above the water surface. A list of these activities is provided in Table 2.2, along with the estimated duration of each step. Particularly the time it takes to get a visual on the robot and recovering it are subject to great variability, due to weather conditions, sea state, the vessel’s manoeuvrability and the operator’s skill. The variability results in a 5% cost difference to the mapping cost. Reducing the handling time to 0 altogether reduces the mapping cost by 9%.

There are a few considerations on how the handling time can be reduced:

- It is likely that the charging or battery swap takes less time with a smaller robot, but a smaller robot will have to be handled more often than a larger robot because it will have a lesser endurance.
- It seems that one of the major factors in the challenging handling is the size of the robots. This results in the requirement for heavy equipment, more people to operate this equipment, and more safety precautions need to be taken. If size can be reduced, physical handling might become faster.
- The electric vehicle market also faces the challenge of quickly charging large batteries without swapping. Insights from this sector could be applied to charge AUVs quicker, so that swapping is not required anymore, saving crew.
- Reducing the reliance on the skill and communication of the operators for the recovery process would enable more flexible deployment and possibly less crew on board, saving cost.

These considerations are developed further in Chapter 6.

Underwater localization This barrier is not related to the cost-effectiveness directly, rather it is a hard requirement that the images taken can be referenced to a global coordinate system. Due to limitations of current technology and the acoustic channel, it is not possible to localize more than a few AUVs at the same time [62]. This is a barrier to a true multi-robot system, as the main advantage of such a system is having many robots mapping in parallel. If this is limited to 10s of robots, the potential remains limited. A more detailed discussion on underwater localization methods is provided in Chapter 4.

2.4.1. Requirements and objectives

The current state of the art in visual seafloor mapping uses a single, advanced AUV with great endurance and top-of-the-market navigation equipment. A future multi-robot system needs to fulfill the same requirements as the current single-robot system. Based off the usecases for seafloor imaging described in Chapter 1, the following requirements were gathered from stakeholders in both industry [8] and research [70]:

R1 provide images of the seafloor of a resolution of at least 1 pixel/cm
R2 provide position of images with an accuracy of 0.5m or better
R3 operate up to a depth of 6000m
R4 deliver the data to the ship

In addition to these high-level system requirements, a number of barriers are defined that must solved to make a multi-robot system technically feasible. Based on the shortcomings that were discussed and analyzed in the this chapter, the following barriers are identified:

1. Deep sea rated AUVs are deemed expensive by the stakeholders and cost up to $\$5$mln . Even the investment in a single craft is a significant hurdle.
2. Launching and recovering an AUV, swapping its batteries and configuring its mission can take up to half a day and requires a crew of five people. This is mostly manual labor, and having more robots would require more crew. Crew wages are the main cost driver in offshore operations.
3. Current underwater localization technologies can support only a limited number AUVs because of bandwidth limitations.

It is clear that these barriers need to be overcome. The degree to which they are can be captured in design objectives. These objectives serve to have some quantified goal to measure design solutions against, and they are not hard requirements.

1. The current investment cost of an AUV system is assumed to be about $\$5$mln. While this is a significant hurdle, it is one that has been overcome before. From [75], the cost saving measures described in this Chapter could result in a 50x cost reduction, which would bring down the cost of individual robots to approximately $\$100k$. For the same total investment cost, the multi-robot system can consist of approximately 50 robots.
2. The underwater localization system that will be required will need to be able to localize at least 50 robots simultaneously. As the localization technology is likely integrated in the robots to a degree that it will be difficult to upgrade later, the design objective is set to localize 100 robots simultaneously.
3. The handling time should be much shorter than the current state of the art. During handling, the robot cannot do seafloor mapping, so this period should be minimized.

Summarizing, the operational objectives are:

O1 Reduce capital cost of AUVs to $C_{AUV} < \$100k$
O2 Localize 100 robots simultaneously
O3 Reduce handling time $HT < 11.75h$

These four top level requirements and three design objectives will be referred to in further discussions about the system and component design. Many of the proposed multi-robot seafloor imaging system's objectives overlap with those of the current state of the art approaches. The main difference is the objective of scale; the system developed in this thesis should be applicable to much larger scale operations while remaining both economically and technically feasible.

2.5. Conclusion

This chapter started off with the research question *”How is seafloor imaging currently done and what are the main barriers to using multiple robots simultaneously?”* To answer this question, a brief stakeholder analysis was done and the solution they use investigated.

It was established that there are two major stakeholders; non-profit research institutes who seek to advance marine science, and for-profit mining companies that seek to make the mineral resources that the seabed holds available to the global markets. A fundamental conflict arises already; the first seeks to protect the environment that is the subject of their studies, while the latter's priority is to set up an economically viable operation.

Seafloor mapping projects are undertaken using an Autonomous Underwater Vehicle (AUV) which is operated from a ship. The AUV is prepared, launched and monitored through an acoustic link during operations. The AUV flies about 5-10m above the seafloor and takes pictures, which are 'geo-referenced' using the location estimate from an acoustic transponder network that has to be set up beforehand. When the battery of the AUV starts running out, it returns to the surface, where it is spotted and recovered to the ship. The data is extracted and the batteries are swapped or charged, after which it is ready for the next deployment.

Three barriers to using multiple robots for subsea mapping were identified:

1. Deep sea rated AUVs are deemed expensive by the stakeholders and cost up to $\$5$ mln. Even the investment in a single craft is a significant hurdle.
2. Launching and recovering an AUV, swapping its batteries and configuring its mission can take up to half a day and requires a crew of five people. This is mostly manual labor, and having more robots would require more crew. Crew wages are the main cost driver in offshore operations.
3. Current underwater localization technologies can support only a few AUVs because of bandwidth limitations.

Furthermore, four system requirements were found which cover almost every subsea mapping need, including usecases in deep sea mining. Based on the barriers, three design objectives were formulated to better quantify the needs in a multi-robot system.

R1 provide footage of the sea floor of a resolution of at least 1 pixel/cm
R2 provide position of images with an accuracy of 0.5m or better
R3 operate up to a depth of 6000m
R4 deliver the data to the ship

O1 reduce capital cost of AUVs to $C_{AUV} < \$100k$
O2 localize 100 robots simultaneously
O3 reduce handling time $HT < 11.75h$

The next chapter builds further on the requirements and explores the system architecture necessary to deploy multiple robots.

3

System design

Having established the state of the art and the barriers to a multi-robot system, this chapter investigates what a suitable system architecture is. The addition of more robots to the ’seafloor imaging system’ will introduce more complexity compared to the conventional ’single-robot system’. The term ’seafloor imaging system’ refers here to ’the entirety of technological solutions that make seafloor imaging possible’. The research vessel, any dedicated onboard equipment, the subsea robots and the systems onboard the subsea robots together make up the seafloor imaging system. The research question is as follows;

> *What system architecture can support multiple robots?*

In this chapter, a system architecture is derived from the requirements and functional objectives of the seafloor imaging system. This approach is chosen rather than re-examining the current, single-robot, system architecture for two reasons:

1. Asserting a certain system architecture as representative to the state of the art could introduce a bias that is reproduced in the new design.
2. It could be that the system architecture resulting from this chapter is very similar to what is currently in use. Still, there would be added value, because determining the system architecture from the bottom-up provides a much better insight in underlying tradeoffs.

In Section 3.1, the requirements and functions are analyzed and assigned to subsystems, resulting in a system architecture design. The next section, Section 3.2, alludes to how the system is deployed in an operational setting. In Section 3.3, it is discussed that because of using multiple robots, certain operational ’modes’ can be classified. These modes are defined and discussed.

3.1. System architecture

The scope of this thesis is to investigate a multi-robot system that can be realized within a *couple of years* from now. While a fully autonomous ship would be an interesting design option to lower operational cost, this is deemed unrealistic on this timescale. The system designed here will not be fully automatic and it is likely that various adjustments and upgrades will be done in the first couple of years of operation. Therefore, a conventional, crewed ship is required. Furthermore, it is assumed that the seafloor imaging system is operated from a ’regular’ offshore support vessel, i.e. no special facilities like a moon-pool or dynamic positioning system are required.

The system architecture is developed to help conceptualize the system and the context in which it will be operating at an early stage. The goal is not to come to the most optimal system design, but merely to illustrate a possible system architecture and lay the groundwork for further analysis.

3.1.1. Functions

The high level system functions can be specified based on some initial considerations. Some considerations of physical nature are:

1. The photos can only be taken close (<20m) to the seafloor, so a separate device from the ship is needed.
2. **R2** demands the images to be geo-referenced. GNSS[1] only works up to the water surface, under water a different localization system is needed.

And some of economical nature:

1. The great depth and distance these subsea devices will cover make a physical link between them and the ship infeasible. The tethers are expensive and could get tangled, the risk of which increases for every device added.
2. Transferring the acquired image data to the surface is not feasible wirelessly. There will be large amounts of data, and compared to above-water signal carriers, underwater communication has a very limited bandwidth, so wireless data transfer would take too much time.
3. When the devices surface, above-water signal carriers could be used. However, wireless broadband is generally not available offshore, so data transfer would rely on either physical contact with the research vessel or use of satellite communication. The latter is both expensive (\$$5.000$ per month) and too limited in bandwidth (350 Mbps) [69]. Then, the remaining option is to make direct physical contact with the vessel.
4. Creating this physical contact can be done under water, using some sort of docking system. But, considering the mapping system system will be new in a lot of aspects, having physical access to the subsea robots and data transfer systems will be of great advantage for troubleshooting, repairs and upgrades. Recovering the subsea devices to the deck of the ship has the added advantage that anything above water is far less likely to break down.
5. Similar considerations apply for the energy storage and transfer of the subsea device. The ship can provide both when there is physical contact.

The need to come close to the seafloor to capture images requires artificial lighting[2]. The fact that the images cannot be directly transferred to the ship or some land-based data storage also implies that some form of storage on the subsea device is needed. Furthermore, the need to localize the images can only be satisfied by combining an underwater position estimate, in reference to some point on the surface, and a global position estimate of said surface point. Finally, the subsea device needs to dive to the seafloor, fly over the seafloor and return to the surface, where it needs to be recovered to the ship through the splash-zone[3]. This discussion is summarized in Figure 3.1.

---

[1] Global Navigation Satellite System, such as GPS, Galileo and GLONASS.

[2] Natural light is mostly absent from 300m or deeper, and **R3** specifies that the seafloor imaging system must operate up to a depth of 6000m.

[3] The region where air transitions to water. This is considered a difficult region because of the widely fluctuating wave forces combined with the buoyancy of the object traveling through it creates an unpredictable load to carry.

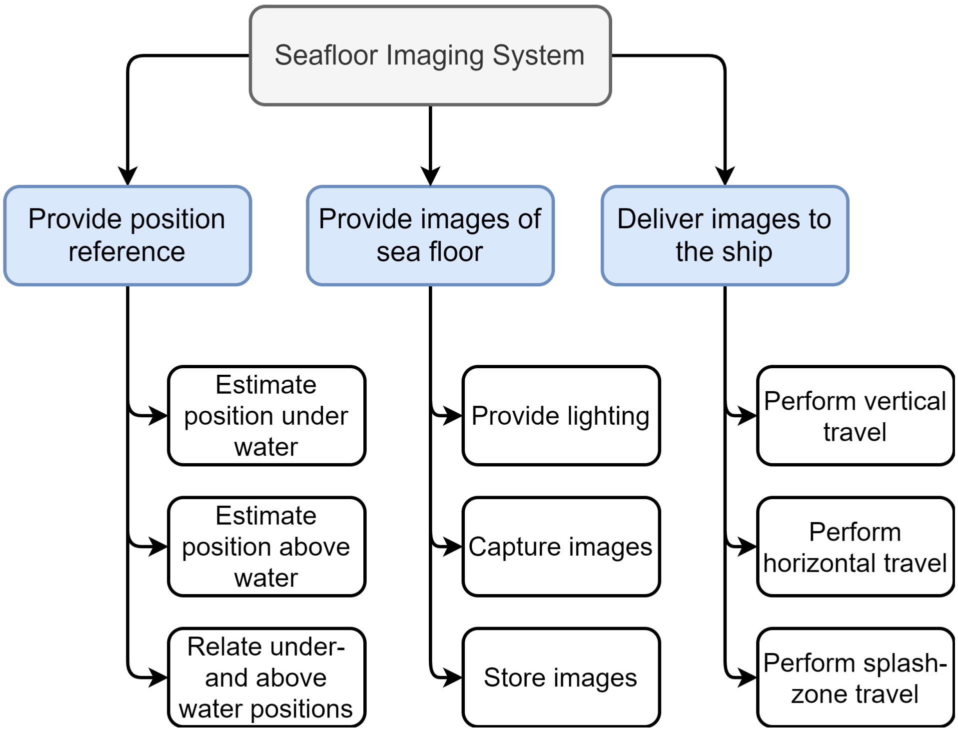


Figure 3.1: The functions of the seafloor imaging systems are broken down in three categories. Each category is further captured in three subfunctions.

3.1.2. Subsystems

The previous discussion already alluded to possible subsystem definitions. Five subsystems encompassing the total seafloor imaging system are discussed in more detail in the next few paragraphs. Note that there are different ways to demarcate subsystems, so there are other combinations possible than discussed here.

Camera system The Camera System captures images of the seafloor. Included in the Camera System is illumination, which may require significant power depending on the sensor technology, the lighting efficiency, the altitude above the seafloor, and the water quality. The Camera System is part of the device going underwater, it is consciously defined as its own subsystem. The tradeoffs governing its design differ enough from those of the carrier that it can be considered its own subsystem.

(a) A custom launch and recovery system [38]. **(b)** A HUGIN AUV deck of a ship [49].

Figure 3.2: Two examples of subsystems.

Subsea Robot The Subsea Robot transports the Camera System to the right place above the seafloor. It also provides power and storage of images for the Camera System, and facilitates the geo-referencing of the images. The Subsea Robot is launched and recovered to the ship for every mission. In the current state of the art, this could for example be a Hugin AUV (Figure 3.2b). It is assumed in this work that all Subsea Robots have the same functionality. While heterogeneity introduces interesting design options, it complicates the system and is not necessary for a proof of concept.

Handling system Its function is to facilitate the logistics of the Subsea Robots on board the ship. The Handling System includes a launch and recovery system and is used to charge the Subsea Robots as well as transfer the captured images to the ship's data storage. In current practices, the Handling System scope is limited to the launch and recovery system (see Figure 3.2a), because all other interactions with the Subsea Robot can easily be done manually. When more robots are added to the system however, a greater degree of automation is needed.

Localization system The Localization System is used to estimate the position of the Subsea Robots relative to the global reference frame. The design of this subsystem is non-trivial and involves many different considerations, of which a more detailed discussion is provided in Chapter 4.

Governance system The Governance System is a tool that helps the operators manage the multitude of different processes in the seafloor imaging system. Weather conditions might change, or a different mapping strategy must be used after reviewing some of the captured images. The Governance System allows operators to make these changes without specifying the mission profiles for every Subsea Robot individually.

Table 3.1 provides an overview of the mapping from functions to subsystems. Note that the greatest number of different functions are fulfilled in the Subsea Robot.

3.1.3. Selection

Some of the subsystems and their interactions are investigated in the research, and some are not. The subsystems and interactions of interest are the Localization System, the Handling System and the Subsea Robots. Figure 3.3 provides an overview of the five subsystems and their interactions, described here:

	Governance system	Handling system	Subsea robot	Camera system	Localization system
Provide position reference					
Relate under- and above water position estimates	×				
Estimate positions under water			×		×
Estimate position above water	×				
Capture images of seafloor					
Provide lighting				×	
Capture images				×	
Store images			×		
Deliver images to the ship					
Perform splash-zone transport		×			
Perform vertical transport			×		
Perform horizontal transport			×		

Table 3.1: The relation between subsystems and functions of the seafloor imaging system

- The Governance System receives position estimates of the Subsea Robots from the Localization system. It manages when the Handling System needs to recover which Subsea Robot.
- The Handling System has a physical interface with the Subsea Robots; it provides power during charging and receives the images that the Subsea Robots have captured.
- The Subsea Robots either actively or passively provide a position estimate to the Localization System, and command the Camera System to take pictures when the seafloor is close enough.
- The Camera System transfers the data it captures to the Subsea Robot.

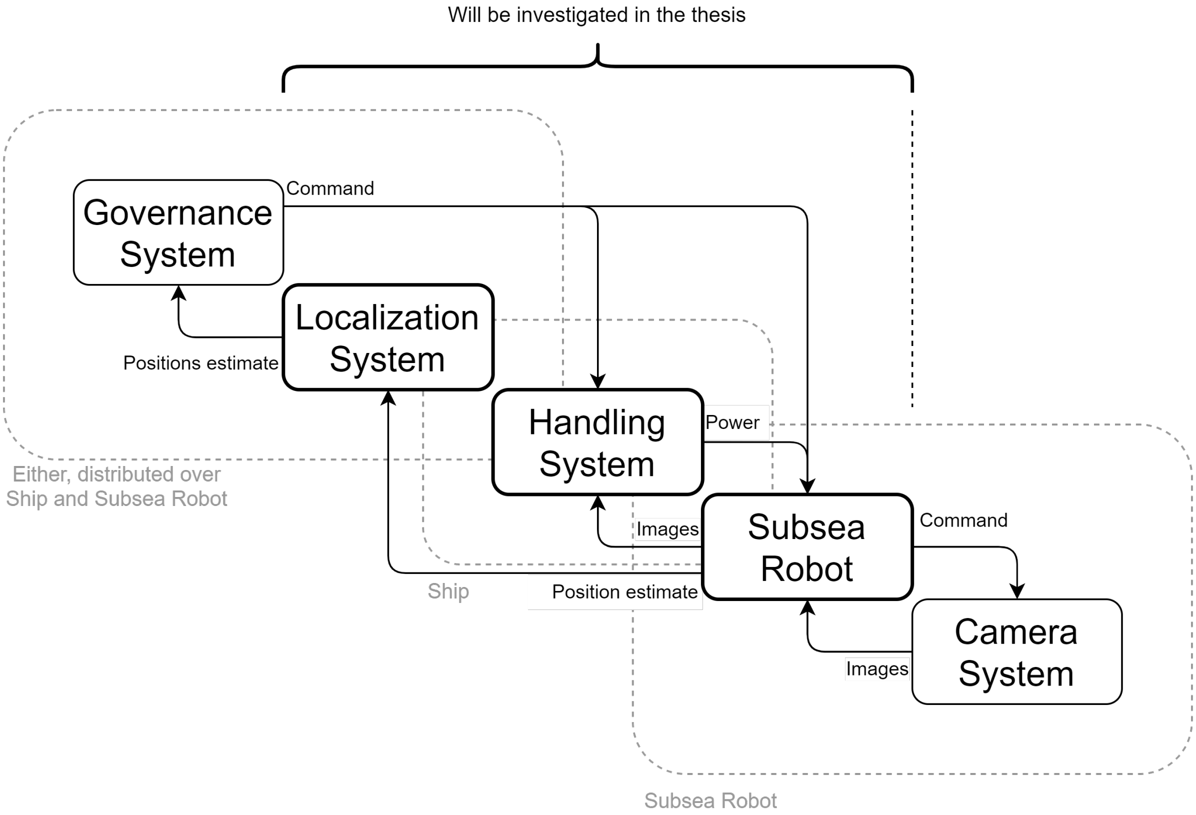


Figure 3.3: The different interfaces between the subsystems.

The two systems that will not be explored further at this stage are the Governance System and the Camera System, because:

- The Governance System highly depends on rest of the system's architecture, as well as the operator's exact needs. Furthermore, this subsystem likely has little to no hardware component, and might even be spread out over other subsystems.
- The Camera System delivers images of the seafloor to the Subsea Robot. It is integrated in the Subsea Robot and receives power and commands directly from its host. There are no other interfaces between it and the rest of the system. State of the art systems have sufficient performance, so some market research is done to determine the interface requirements with the Subsea Robots.

3.2. Concept of Operations

The purpose of the concept of operations is to visualize how the system works, from port to sea floor. The steps indicated at the start of each paragraph correspond to the steps in Figure 3.4.

Step 0-1 The operation of the system starts when the ships loads all of the equipment in port and is prepared for the journey. It sets course to its destination. Once in close proximity, the subsea operations can begin.

Step 1-2 The Localization System is enabled. Then the Subsea Robots are deployed using the Handling System. The Localization System keeps track of the positions of the Subsea Robots and the Governance System provides an interface to the operators.

Step 2-3 Once the Subsea Robots arrive at the sea floor, the designated area is photographed.

Step 3-4 When the Subsea Robots have completed their imaging assignment, they will ascend and return to the ship, facilitated by the Localization System. The Subsea Robots are recovered to the ship, recharged, and the data transferred to the ship by the Handling System. During this period, new robots can already be deployed. This cycle repeats as a continuous process.

Step 4-5 Once the research goals are achieved, all Subsea Robots are recovered and the ship returns to port. On-shore, the acquired data is processed and prepared for further studies.

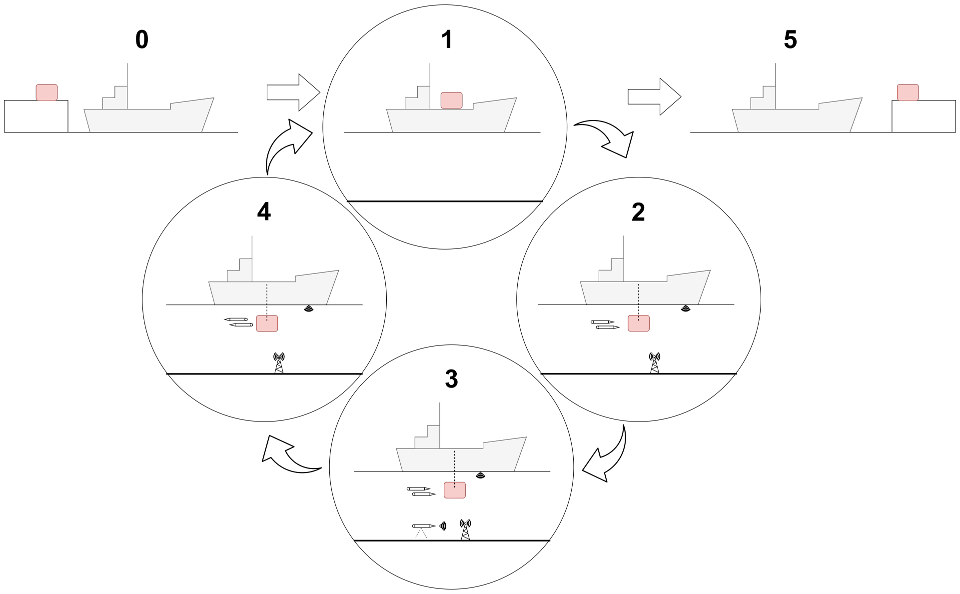


Figure 3.4: Lifecycle of the seafloor imaging system.

3.3. Operational modes

The previous section describes the operational stages of the seafloor imaging system. However, depending on the design of the system and the specifics of the scenario, Step 1-4 of the operational lifecycle lead to different behaviors of the seafloor imaging system. This section describes a method to distinguish four different modes of operation. These modes will later be used to classify and validate the results of the simulation developed in Chapter 7.

The operations of the system can be represented by Figure 3.5.

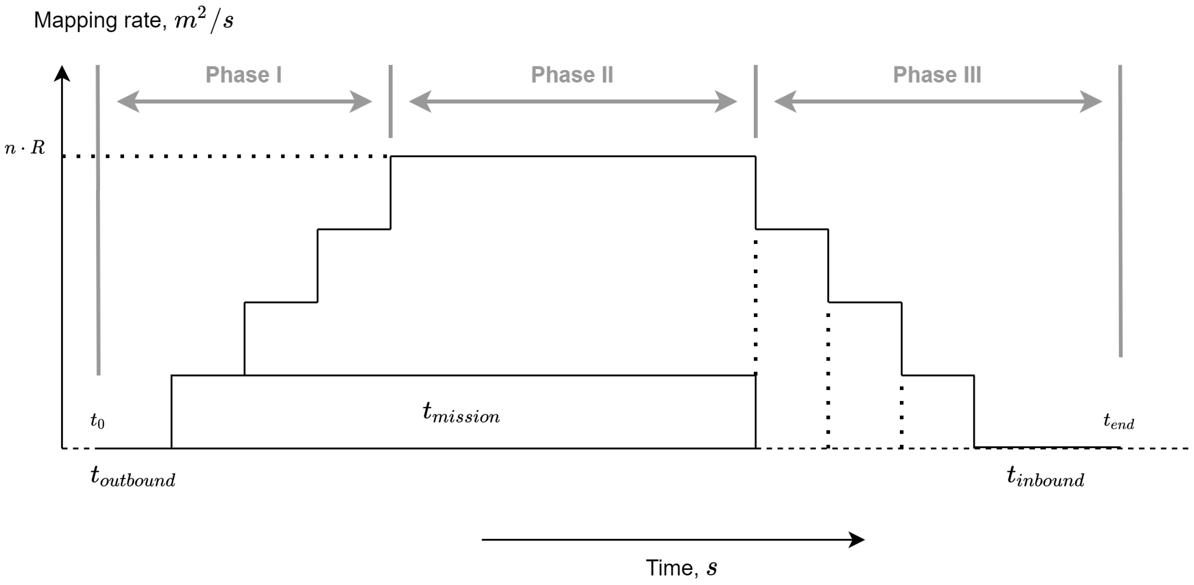


Figure 3.5: A schematic diagram representing the mapping rate of the seafloor imaging system as a function of time.

Three phases can be identified in this diagram:

Phase I The increments in mapping speed on the vertical axis represent Subsea Robots entering the mission state after being launched from the ship. The intervals between the launch of different robots is the duration of the longest process step in the launch process, defined here as $t_{max,o}$.

Phase II The Subsea Robots are mapping the seafloor and the Handling System is not recovering or launching new Subsea Robots.

Phase III Once the mission duration has passed, the Subsea Robots are recovered again, marked by the incremental decrease in overall mapping speed, until all robots have been recovered.

Phase I and Phase III are only separated when the mission time is longer than the cumulative interval between launches. In other words, the system behavior in Figure 3.5 only occurs under certain conditions.

3.3.1. Mode parameters

The first condition can be expressed as;

$$t_{mission} \geq (n-1) \cdot t_{max,o} \tag{3.1}$$

$$P_1 = \frac{t_{mission}}{t_{max,o}} + 1 \geq n \tag{3.2}$$

The second condition is that there are enough Subsea Robots in the system such that every Subsea Robot only has to do a mission once to map the entire area. If the number of Subsea Robots and their range are insufficient to cover the objective area, the system behavior will be different. In this case, it is possible for Phase I and III to start overlapping, and to have multiple occurrences of Phase II. This condition is met when;

$$\frac{A_{objective}}{range_{robot} \cdot swath} > n \tag{3.3}$$

$$P_2 > n \tag{3.4}$$

Table 3.2 provides an overview of the different modes and the corresponding parameters.

	$P_1 \geq n$	$P_1 < n$
$P_2 \leq n$	Mode 1	Mode 2[4]
$P_2 > n$	Mode 3	Mode 4

Table 3.2: Four system modes are defined, based on the comparison of two parameters to the number of robots in the system.

3.3.2. Examples

Within each mode, the behavior as visualized in diagrams like Figure 3.5 can still vary depending on the specific process parameters. Some simple examples are provided here.

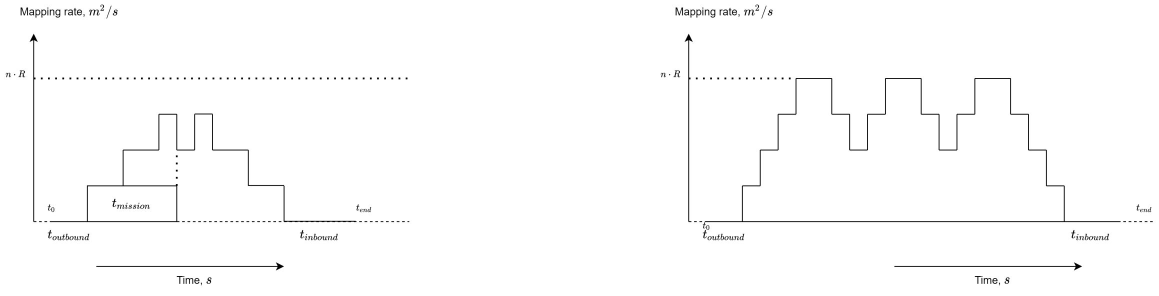
---

[4] It is assumed that $t_{mission} >> t_{outbound}$.

Mode 1 Figure 3.5 is an example of a Mode 1 operation. Phase I and III do not overlap and the area can be mapped using a single batch of robots. In other words; $P_1 \geq n$ and $P_2 \leq n$.

Mode 2 If $P_1 < n$ and $P_2 \leq n$, the system is defined to operate in Mode 2, of which an example is provided in Figure 3.6a. This means that before all robots are launched, the first robot deployed has already finished, in other words, Phase I and III overlap.

Mode 3 An example of what this could look like is provided in Figure 3.6b. There are several flat peaks in the graph, indicating a Phase II, where the Handling System is inactive because all Subsea Robots are performing a mission. Phase I and III overlap in two instances after the first batch. Note that the ratios between the peaks and valleys in the graph depend on the properties of the Handling System.



(a) An example where Phase I and III overlap, but the area can be mapped with a single batch of robots, resulting in a Mode 2 operation.

(b) A situation where $P_2 < n \leq P_1$, resulting in a Mode 3 operation.

Figure 3.6: Two examples of a Mode 2 and Mode 3 operation.

Mode 4 A Mode 4 operation has multiple peaks, but not necessarily flat peaks where a Phase II behavior occurs. From the experiments done in the development of the simulation in Chapter 7 it has been proven difficult to find a representative example for this mode.

The Modes and Phases that were defined will be used throughout this work to describe the system behavior.

3.4. Conclusion

This chapter started with the question *”What system architecture can support multiple robots?”* The functions of the seafloor imaging system were derived and allocated to five subsystems, where the highlighted subsystems will be investigated further in this thesis;

1. Governance System
2. **Localization System**
3. **Handling System**
4. **Subsea Robot**
5. Camera System

These subsystems interact as follows; once the research vessel is at the desired location, the Handling System deploys the Subsea Robots. The robots dive to the seafloor, while their location is continuously determined by the Localization System (directly from the ship or previously deployed auxiliary devices). When a robot arrives at the sea floor it uses its Camera System to start photographing. When the robots return to the surface, they are recovered to the research vessel again by the Handling System and prepared for the next deployment. The Governance system manages the other subsystems and provides an interface for the operators.

Of the subsystems described, only the Localization system, the Handling system and the Subsea Robot are investigated further in this thesis. Their designs are challenging because they share many interfaces and dependencies, while the other two are more linear in design. These three subsystems are also key in investigating the technological and economical feasibility of the envisioned mapping system.

It is assumed in this work that all Subsea Robots have the same functionality. While heterogeneity introduces interesting design options, it complicates the system and is not necessary for a proof of concept.

Due to the presence of multiple robots in the seafloor imaging system, the operational behavior can be different, depending on the Subsea Robot and Handling System design parameters. Three phases and four modes of operation were defined. These are used to categorize behaviors of the system and facilitate discussions on different results in the design study.

4

Localization System design

Underwater localization is a challenging topic. Conventional localization technology like GNSS rely on electromagnetic waves as a signal carrier, which experience significant attenuation underwater. In seawater, which is conductive, these methods are nearly unusable, as their range is greatly diminished. Only around the visible spectrum and for greater wavelengths does the absorption coefficient of electromagnetic waves in seawater diminish, as evident from Figure 4.1.

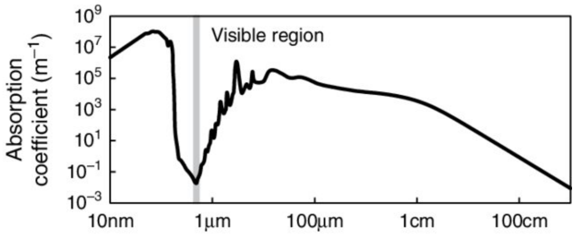


Figure 4.1: The visible region knows the smallest absorption coefficients [36].

These parts of the spectrum can be used to send signals up to several hundreds of meters, but this is not enough to readily satisfy the requirement of operating up to 6000m (requirement **R3**). Provided that the standard methods of surface localization cannot be used [45], other methods have to be employed, which will be discussed in this chapter.

The objective of this chapter is to provide an answer to the following question:

> *What is a localization method that can support multiple Subsea Robots and meet the performance requirements, while impacting the system operations as little as possible?*

This chapter does relates to design objective **O2** posed in Chapter 2, and is an investigation of the technical feasibility of multi-robot operations under requirement **R2**, to provide position information with an accuracy of 0.5m for the images that are captured by the Subsea Robots.

This chapter begins with a brief definition of terms, an overview of the localization problem and continues with a review of the literature, covering various design options. Some options can be readily eliminated, others result in tradeoffs, which are presented and discussed as well. Finally, a suitable localization method is selected and the chapter is concluded with a brief summary.

4.1. Introduction

This section presents some background information essential to the subjects of the rest of the chapter.

4.1.1. Definitions

Navigation, positioning and localization are defined differently by different authors. In this work,

- *positioning* is defined as determining the distance and angle to a certain (nearby) reference,
- *navigation* is defined as determining a route between the current position and the desired position, and
- *localization* is defined as determining the distance and angle in a global reference frame.

Furthermore, two separate localization problems are identified; above water and under water. Above water, localizing is relatively straightforward; determining the coordinates in the global reference frame using off the shelf GNSS technology. Subsurface, no such option is readily available, and requires a more in-depth study.

4.1.2. Types of localization

There are a number of sensors and methods that can be used to position and localize a robot under water. These are combined to achieve the highest accuracy position estimate with a sufficient update rate. Preferably, the error on the position estimate is bounded, such that the localization method does not affect the duration of the mission or deteriorate over time. [37] [45]

Figure 4.2 provides an overview of options for underwater localization.

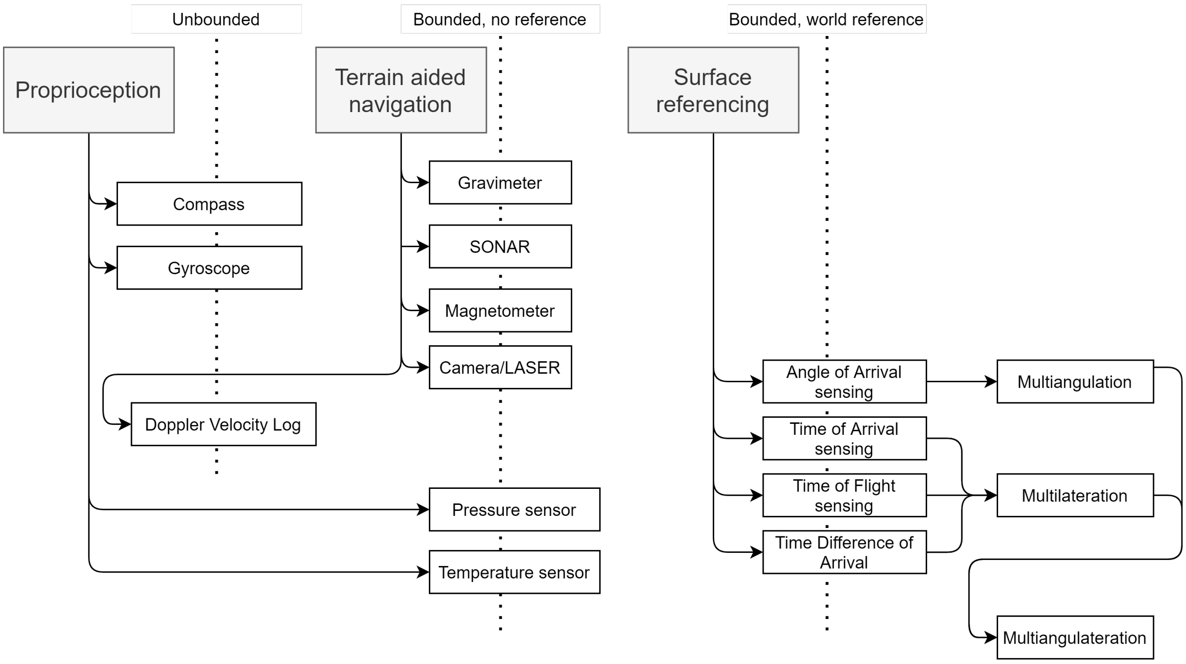


Figure 4.2: An overview of different localization methods, modified from Fig 1. in [55]. Three classes of localization are indicated, and per class the sensors can have different types of errors.

The leftmost column contain localization methods that have an unbounded error; the error grows over time or travelled distance. The middle column shows methods that have a bounded error, but whose results are in a local reference frame, generally relative to the robot. These can be used for positioning and some local navigation, but not for localization. The rightmost column provides the absolute localization methods, which return a position estimate in the global reference frame [55].

Furthermore, there are three categories of sensor types or sensing techniques in the figure;

- *proprioception*, the sense of self-movement or body position,
- *terrain aided navigation*, which in this case uses the seafloor as a stable reference, and
- *surface referencing*, which references the position of the robot to a surface vessel. The surface vessel is assumed to always have a near-perfect global position estimate, and as such, the global position of the robot can also be determined.

It is also possible to obtain a global bounded reference by using knowledge of the seafloor, for example; its shape, the magnetic field, certain recognizable points such as shipwrecks, etc. This option is not further explored here because it requires prior knowledge of these properties of the seafloor. For most of the operations of the system, such knowledge will not be available.

The methods under ’proprioception’ and ’terrain aided navigation’ in Figure 4.2 have been implemented and combined in various ways in the past decade of AUV design [55] [5]. These methods are not investigated further in this work because they are solved for individual robots and do not impose significant challenges on a multi-robot system, whereas the surface referencing methods that were developed prior know pose significant limitations when increasing the number of robots in the system.

4.1.3. Obtaining a bounded horizontal reference

The main challenge that remains is to obtain a bounded reference in the horizontal plane. A pressure sensor already provides a bounded vertical reference from the start of the mission of the Subsea Robot, but the ’terrain aided navigation’ methods only work once the Subsea Robot is close to the seafloor. In the duration of travel between the surface and the seafloor, any global XY position estimate will accumulate an unacceptable error [19].

By reasoning there are two options;

1. continuously correct any accumulated error, or
2. obtain a single global reference point once near the seafloor and use bounded-error terrain aided navigation methods from there.

In addition, it is possible to have an intermediary between the Subsea Robot and the surface vessel, such as a subsea station or another Subsea Robot. However, this introduces additional system complexity and more single points of failure to the system.

Option 2 has a similar drawback. If the terrain aided navigation fails at some point, the global position reference will also be lost. For example, an optical terrain relative navigation system will stop working when visibility deteriorates. In this case, the global position is also lost, and needs to be updated. In this situation, option 1 is used.

In conclusion, an architecture based on a direct link between the Subsea Robot and the surface, that continually updates the Subsea Robot’s global position estimate, is the most robust design option.

4.2. Acoustic localization

As discussed at the beginning of the section, using electromagnetic waves under water is not feasible. Instead, almost all subsea signalling and communication is done using acoustic waves. Acoustic waves have a much lower attenuation in seawater. There are a number of drawbacks however:

- *limited bandwidth:* the acoustic channel is noisy and limited by the rapid attenuation for higher frequencies.
- *attenuation:* despite requiring much less power than when using an electromagnetic wave as a signal carrier under water, the required power is still significant.
- *reflections:* near the surface or seafloor, multi-path errors can distort the signal. In the watercolumn, there are various layers of different water density, and at the interface of those layers, the signal can be partially reflected if the angle of incidence is too large. This limits the horizontal range of acoustic systems [23].

Furthermore, the technology behind creating and interpreting acoustic signals is relatively complex. For example, a typical underwater acoustic transmitter and receiver system already requires knowledge of analog electronics, digital electronics, material science, wave physics, antenna design and mechanical engineering to design. First, a digital electric signal is converted to an analog signal, which is fed into a high voltage transformer which drives a transducer, generally fabricated with a piezo-electric material. The transducer then converts the electrical energy into mechanical energy. The signal travels with approximately 1500 m/s through the water and reaches the receiver, which is essentially the same as the transmitter but works the other way around. The mechanical energy of the acoustic wave is transformed to electrical energy by the transducer, which is converted to a digital signal. This technology is the foundation upon which underwater signalling is built [68].

State of the art localization systems can generally be classified as either the LBL (long baseline) or USBL (ultra-short baseline) type. The name refers to the distance between the receivers, which can be hundreds of meters for LBL and centimeters for USBL. Both are based on an interrogation-reponse cycle. The interrogator transmits a signal, which is detected by the receiver, after which the receiver responds with another signal. The interrogator then determines the time between transmission and arrival, resulting in the two way travel time (TWTT). Using an estimate of the speed of sound profile of the water column, the distance to the responder can then be estimated [55].

LBL In LBL systems, the interrogator is the subsea vehicle which interrogates several widely spaced beacons, which are placed either on the surface or the seafloor, prior to the mission. The positions relative to each other, or the absolute positions of the individual responders, are known by the interrogator. The subsea vehicle then interrogates the beacons one by one, and estimates the ranges to the beacons using the TWTT and knowledge about the sound velocity of the water. Using a multilateration algorithm it determines its own position relative to the beacons. If it knows the global positions of the beacons, then it can also determine its own global position from this information. [37]

USBL In USBL systems, the interrogation is usually done from a surface vessel, which has a transceiver. The subsea device has a responder. In addition to determining the TWTT of the signal, the interrogator's receiver consists of an array of transducers, such that by using a technique called phase-differencing, the Direction of Arrival (DoA) of the response can be determined. This instantly yields the relative position of the robot to the ship, without the need for interrogating multiple targets like in LBL. [37]

Each method has its own advantages and disadvantages. For example, USBL is generally only used for short-range applications, because its angular selectivity decreases proportionally to the distance to the target. Furthermore, only the topside unit has the information about the position of the subsea vehicle, which is fine for monitoring the operations but does not enable the subsea vehicle to make autonomous navigation decisions. On the other side, USBL is much easier to deploy because there is no need to set up and initialize a beacon network prior to operations, like in LBL. LBL can achieve much higher accuracy though, and the position information is with the subsea vehicle.

If, on top of the signal used to determine the two way travel time (TWTT) or the direction of arrival (DoA) information is modulated, the localization information is in principle available to all actors in the system.

In USBL, the interrogator can include the robot's estimated global position from the previous cycle in the interrogation signal. In LBL, the responding beacons can include their global position in the response signal, such that no prior knowledge of the beacons' (relative) positions are required. Additionally, this enables the possibility of mobile beacons.

There are some crucial issues with implementing either of these systems in a multi-robot system. USBL and LBL both need at least interrogation/response cycle per subsea vehicle to provide a position estimate.

For example, when a surface vessel wants to determine the position of a subsea vehicle which is at 6000m depth, assuming an average sound velocity of 1500 m/s, it will take roughly 4 seconds for the signal to reach the subsea vehicle, and another 4 seconds for the surface vessel to receive the response. Only then the next robot can be interrogated. This is called a Time Division Multiple Access (TDMA) scheme, because multiple nodes can be interrogated by spacing the access to each node in time.

When considering multiple robots, the time between position fixes can become significant. The error accumulation on the position estimate might become unacceptable in between transmissions. Alternatively, a Frequency Division Multiple Access (FDMA) scheme could be applied. In this scheme, the nodes are interrogated simultaneously but over different frequency bands. Some commercially available systems support this scheme, but even then only 10 or so responders can be addressed at the time.

In conclusion, most currently commercially available systems lack the capability of providing localization for larger numbers of Subsea Robots. This is because they rely on an interrogation/response cycle. However, there are methods to localize without this dependency.

4.2.1. Silent localization schemes

As discussed, the limited bandwidth of the acoustic channel, combined with the requirement for a two-way signal, limits the scalability of current underwater localization. Several publications propose using so called 'silent localization schemes', where the topside vessel sends a single signal, which is registered by the subsea vehicle. The Time of Travel (ToT) to the topside vessel can be determined by the subsea vehicle if they have synchronized clocks. They are said to operate on an absolute (shared) time base in this case. [37] [55]

Rypkema et al [62] propose a 'silent inverted USBL localization scheme', where the surface vessel signals at continuous intervals, and the subsea vehicle uses the absolute time base to determine the distance and DoA measurements to determine angle to the vessel. The global position estimate can be computed for the data gathered by the subsea vehicle by using the relative position estimate of the subsea vehicle and the global position estimates of the surface vessel.

Simetti et al [67] propose a system where two or more beacons are deployed, each with an accurate internal clock, which emit signals at given times, such that a subsea vehicle, equipped with just a receiver and an internal clock, can determine its own position relative to the beacons at every transmission using a multilateration algorithm. If the beacons are located at the surface, they can simultaneously get a global position estimate of their own position using GNSS. Similar to the approach in the previous paragraph, the global position of the subsea vehicle can be determined post-mission. Alternatively, the position estimates of the beacons is modulated in their transmission such that the subsea vehicle immediately knows its own global position.

Having more beacons gives operational and algorithmic complexity, and thus Eustice et al [19] employ a 'virtual' or 'synthesized' silent LBL method, where a single, mobile beacon provides regular broadcasts. Multiple different relative bearings to the subsea vehicle are required to obtain a position estimate. Both carry synchronized clocks. In addition, this method relies on high performance proprioception and terrain aided navigation on the subsea vehicle to 'fill in the gaps' between the acoustic broadcasts.

There is an alternative to using an absolute time base for silent localization. Cheng et al [12] propose a method where the Time Differences of Arrival (TDoAs) between different beacons are measured by the subsea vehicle to determine the range differences. Multiple surface beacons are in place. The first beacon starts with a broadcast. Upon receiving this broadcast, the next beacon broadcasts a signal, modulating in its broadcast the delay between the time it received the previous broadcast and the time of sending the current broadcast. This goes on until the last beacon has broadcasted. The subsea vehicle received all broadcasts and can determine with this the distance between the beacons and its position relative to the beacon network. This does require the modulation of some information in the broadcasts of the beacons, and demodulation of this signal at the subsea vehicle, but does not require accurate, synchronized clocks. The disadvantage here is again that it takes a number of broadcasts from the beacon network before the subsea vehicle can determine its position. In between transmissions, its position error drift must not become too large, and thus sufficiently performant proprioception and terrain aided navigation are required.

In the ‘synthetic’ scheme, there is just one beacon that fulfills the functions of both the lead beacon and the others by swiftly changing its surface position after every broadcast. Every broadcast must include its own global position at that time, obtained from GNSS. Mourya et al [48] expand on this concept by proposing a robust location estimator including an appropriate model of the measurement errors. Furthermore, three practical schemes of static and mobile anchor deployment are proposed, as well as an overview of the estimator options combined with the deployment schemes to get a situation-dependent optimal choice.

Table 4.1 provides an overview of the different silent localization methods discussed so far. The implications of the methods for the design of the subsea vehicle and the surface vessel are discussed below.

	Eustice et al	Rypkema et al	Cheng et al
Localization method?	Multilateration	Triangulateration	Multilateration
Subsea vehicle equipment?	Synchronized clock, DVL/INS suite, multilateration location estimator algorithm	Synchronized clock, receiver array, beamforming electronics and algorithms	Receiver, demodulation capability, DVL/INS suite, multilateration location estimator algorithm
Surface vessel equipment?	Synchronized clock, transmitter, highly mobile	Synchronized clock, transmitter	One or more mobile GNSS-enabled transceiver(s) with modem capability
Absolute time-base	required	required	not required
Range estimate	required	required	required
Angle estimate	not required	required	not required
Good dead-reckoning	required	not required	required
Modem capability[1]	not required	not required	required
Stationary surface vessel	not required	not required[2]	not required[3]

Table 4.1: An overview of three sources’ proposed solutions, compared along a number of axes.

Absolute time base Pre-2011, temperature compensated chrystal oscillator (TXCO) technology was the best miniature clock available, based on chip technology. After 2011, the Chip Scale Atomic Clock (CSAC) was commercialized, which is more accurate. When the clock’s accuracy is multiplied with the sound velocity of water, the best possible accuracy of the clock-based localization system can be determined. This is 18.75cm for TXCO and 1.5nm for CSAC. The CSAC packages require a pressure

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[1] for relative localization of the surface vessel to the subsea vehicle. For global localization, every method needs modem capability.

[2] But it can be stationary as well.

[3] But they can be if multiple surface vessels (more than 4) are deployed.

vessel with a minimum internal diameter of about 5cm and a length of 10cm. It has an average power consumption of 115 mW. The clocks have to be time-synchronized before operation, but also frequency synchronized, called 'disciplining' [53]. The GNSS frequencies must be used for this routine. This can take up to an hour because of the short term noise in the GNSS signal. The clock is also sensitive to temperature variations, for example during the dive and ascent of the subsea vehicle. Additional calibration or post-processing might be required.

Acoustic transceiving The subsea vehicle will need an acoustic receiver in any case. The design aspects have been discussed in earlier in Section 4.2. The transmitter, which will be mounted on the surface vessel, might need to have a relatively high power output in order for its signal to reach subsea vehicles at 6000m depth. The surface vessel can be equipped with substantial power sources, so this should not be a problem. Cavitation might be a problem at the transducer face though, because of the relatively low environmental pressure at the surface.

Direction of Arrival estimates In the case of Rypkema et al's approach, a method to estimate the DoA of the signal is required at the subsea vehicle. The angular selectivity of the transducer array must be significant. Assuming a maximum horizontal spacing between the surface vessel and the subsea vehicle, with a baseline between the transducers of 0.5m[4], the azimuth angle resolution must be at least $arctan(0.5/4000) \approx 0.007deg$ and the zenith angle resolution must be at least $arctan(0.5/6000) \approx 0.004deg$, which are two orders of magnitude, respectively, higher than the current state of the art [37]. If the distance and depth estimate of the subsea vehicle are sufficiently accurate, only the azimuth angle is required.

Inter-transmission navigation In between position fixes provided by the acoustic localization system, the position estimate of the subsea vehicle must not accumulate an error too large. Inertial Navigation Systems, generally composed of accelerometers and gyroscopes in all axes, have a relatively high drift [5]. A Doppler Velocity Log can provide a velocity estimate of the subsea vehicle, leading to a drift of typically 0.5% for an integrated DVL/INS navigation system. DVLs are expensive, power intensive and physically large devices however, and only work near the seafloor. Mid-water column, the DVL will not function. Arguably, during that phase of the mission, the accuracy of the localization system is also less important.

Modem capability Modulating and demodulating information into a carrier is essential for either Cheng et al's or Mourya et al's localization method. The subsea vehicle only needs demodulating capabilities though. The same receiving transducer can be used for all acoustic receiving, but additional electronics and signal processing is required. This slightly increases the size and complexity of the system.

Stationary surface vessel The requirement for a stationary surface vessel implies that it needs a dynamic positioning (DP) system, which can be expensive and has limited performance as weather and wave conditions deteriorate. The main vessel from which the system is deployed will likely already have a DP system, but using the main vessel as a beacon will restrict its other mission tasks. Ideally, the ship is free to pursue other activities during the operation of the mapping system. Even if an unmanned surface vessel is used, several have to be deployed in order for all methods to work. On the other hand, if the localization method supports a mobile surface vessel, only one has to be deployed.

A general note is that improving the system's reliability by eliminating components and interactions might decrease overall performance. If inter-robot communication & localization is possible, either the performance of the entire localization subsystem within the mapping system will be improved, or

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[4] This is significantly larger than any current systems.

the cost/performance ratio of the individual components can be decreased while still achieving similar overall localization performance.

4.2.2. Design options evaluation

Three design options for the localization subsystem and their implications were explored in the last subsection. With this knowledge, they can be evaluated against the subsystem requirements as well as other system design considerations.

These are a number of requirements that guarantee that the Localization System will be able to effectively support the seafloor imaging system's requirement with regards to accuracy;

1. The subsystem must guarantee an accuracy of 0.5m for gathered data.
2. The subsystem must provide localization in real-time.
3. The subsystem must be able to localize at least 100 Subsea Robots simultaneously.
4. The subsystem must be able to localize Subsea Robots up to a depth of 6000m and a horizontal distance of 4000m

Additionally, some practical design considerations include;

1. As little additional infrastructure introduced as possible
2. Low power system on the Subsea Robot
3. Physically small system on the Subsea Robot
4. As little additional handling steps or complexity introduced as possible

As discussed, Rypkema et al's method relies on DoA estimates, whose required selectivity is two orders of magnitude higher than the current state of the art can provide. Therefore, their localization method is probably infeasible.

Eustice et al's and Cheng et al's methods remain. From Table 4.1, the differences are the need for an absolute time base and the need for modem capability. From a localization perspective, modem capability is an additional cost and complexity driver. But from an operational perspective, modem capability is already required for the control of the mapping system, for example to send a 'stop' command in case the weather conditions suddenly deteriorate and the ship has to move. In that sense, re-using this capability for localization is more attractive than relying on an additional system. The synchronized clocks in the Subsea Robots that are required to localize using an absolute time base would require synchronization prior to launch from the ship, and take up additional space in the Subsea Robot.

In conclusion, Cheng et al's method of silent underwater localization seems like the best design direction, given the current considerations. For further investigation in the design of the localization system, a number of tradeoffs must be considered;

- The system's positioning accuracy vs the maximum (horizontal) distance between the surface vessel and the subsea vehicle
- The maximum (horizontal) distance between the surface vessel and the subsea vehicle vs the power and sensitivity requirements of the acoustic transmitters/receivers on board the surface vessel and subsea vehicles.

Additionally, more in-depth investigations in the following aspects of the system are required to further quantify and compare the available design options;

- The reliability and performance of the total position estimation algorithm with varying integrated navigation and acoustic localization performances;
- Noise and robustness of the communication system, both for the localization and any mission-related commands;
- Topside GNSS receiver requirements and transmitter requirements, as well as the design for the state estimation and powertrain of the surface vessel.
- The effect of adding inter-robot communication for better state estimation and the possible relaxation of performance requirements for sensors & processing presently required in the Subsea Robots.

Furthermore, some design choices for a supporting surface vessel can already be deduced. A highly mobile surface vessel is required, having both a GNSS receiver and an underwater transmitter with modulation capability. It will likely need to exchange state estimation with the main ship, so will need some sort of radio link. Physically, it will need to be launched & recovered, recharged or -fueled, and possibly repaired on the main ship as well. The surface vessel could be unmanned, even autonomous, such that the crew of the main ship can focus their attention to other tasks. It should be investigated whether it is possible to use an aerial drone to fulfill the role of the surface vessel. It would easier to handle, could likely change position more quickly and can be much smaller than a ship that would have to execute the same tasks.

4.3. Conclusion

This chapter started with the question: *”What is a localization method that can support multiple Subsea Robots and meet the performance requirements, while impacting the system operations as little as possible?”*

Underwater localization is challenging because of the unbounded position estimate error in the horizontal plane. Creating artificial references on the seabed is labor intensive and therefore unattractive. Conventional acoustic localization methods can not support enough Subsea Robots due to limitations in bandwidth. Silent acoustic localization schemes however do not have bandwidth limitations, and can support many Subsea Robots at the time. A brief literature review was done to reveal that silent localization can be done with or without an absolute time base. Cheng et al propose a TDoA approach that does not require synchronized clocks, which seems like the most favorable design option in this initial investigation. This choice is based on a lot of tradeoffs that must be investigated further. The implementation of the design and the algorithms used for state estimation must also be investigated further. For now, a clear solution direction for the localization subsystem is identified, from which physical requirements for other subsystems can be derived for modeling in Chapter 7. The research sub-question posed at the beginning of the chapter is answered only partially, because to quantify the performance of the Localization System, more specifically the accuracy of the position estimate, a more detailed design study must be done.

5

Subsea Robot design

The first design objective (**O1**) identified in Chapter 2 states that the cost of the AUVs used for deep sea imaging must be decreased by at least an order of magnitude, such that the number of robots in the system can be increased by an order of magnitude while keeping the investment cost approximately the same. Additionally, the requirements **R1** (high resolution), **R3** (operate up to 6000m deep) and partially **R4** (deliver data to ship) are primarily dependent on the design of the Subsea Robot.

This chapter revolves around the following question;

> *What is a cost-effective Subsea Robot design that enables photographic mapping of the deep sea floor?*

The design of the Camera system and the Subsea Robot are specified further. The Camera system design is explored at a high level to discover the implications for the design of the Subsea Robot, which must be specified to a certain degree in order to build a parametric model in Chapter 7 for use in the optimization of the entire seafloor imaging system.

Section 5.1 provides an analysis of the general AUV design methods and cost reduction strategies. In Section 5.2, the requirements that the Camera System poses on the Subsea Robot design are investigated. Finally, Section 5.3 discusses the subsystems of the Subsea Robot and integrates the requirements from Section 5.2 and Chapter 4.

5.1. AUV design

The objective of the AUV or Subsea Robot is to deliver the payload to the right locations above the sea floor and return with the captured data. Its design is essential to the fulfillment of the system requirements **R1** (image quality), **R3** (operate up to 6000m deep) and **R4** (deliver data to ship). Additionally, an important shortcoming in the current state of the art, blocking economically feasible, large scale seafloor imaging, is the high cost of deep-water AUVs. The first design objective of the multi-robot seafloor imaging system is **O1**: *Reduce capital cost of a single AUV to less than* $\$100k$.

There are numerous AUV designs and publications about AUV designs. There a different approaches to the design process, but usually the body shape is determined first, based on the type of work the AUV is intended for. That being said, there is no universal 'recipe' for an AUV design; it depends entirely upon its intended purpose and for whom. This section discusses some general design aspects first, then explains the essence of pressure tolerant construction. Some discussion on capability reduction as a cost-saving measure is provided, after which a conclusion for the cost of a suitable Subsea Robot design, based on these principles, is given.

5.1.1. General design

AUVs are optimized for long ranges and tend to be streamlined, with a long parallel midsection (like a torpedo) to house batteries, sensors and navigation equipment [4].

Other options include biomimicing hulls, multi-hull designs, and others. The most common form factor of the body of the AUV is torpedo-style, because of its balance between both streamline and ease of manufacturing. It is also easier to model hydronamically than the other body shapes. The overall number of external appendages to the body should be minimized to keep the drag forces low and increase the endurance of the device for its size [4].

Most AUV designs incorporate some sort of modularity in their construction to facilitate repairs and flexibility of operations. For example, so that payloads can be swapped out by users between missions to gather different kinds of data [75]. This design feature (and its corresponding physical overhead) will not be accounted for in any subsequent modeling.

The AUV needs an energy source for propulsion, navigation and mission activities. Batteries, fuel cells, nuclear energy and internal combustion engines, as well as wave energy and solar are possible energy sources [24]. Lithium batteries have one of the highest energy densities, simple interaction requirements, are rechargeable and are commercially available. Some manufacturers opt for more advanced systems to achieve better performance, like the HUGIN series AUVs, which use a hybrid fuel-cell system [49].

AUVs are used in a variety of applications, and as a result, almost all AUV designs are tailored to providing a multitude of sensing options. There are two strategies to provide these capabilities in an AUV; either by integrating the various sensors in the vehicle by default, or by providing some sort of modularity, requiring the operator to physically re-configure the AUV in between applications. Both strategies involve additional cost and complexity.

5.1.2. Pressure tolerant construction

In conventional AUV technology, significant space in the vehicle is taken up by pressure housings, seals, feedthroughs and buoyancy material. There are few materials that are lighter than water but that will not collapse under pressure[1]. One of them is called syntactic foam, consisting of miniature pressure vessels that contain a gas, and are thus lighter than water while pressure resistant. This material comes in different strength and quality grades, and are machined to the required shape and size. Generally, the greater the depth rating of these materials, the higher their density, and thus the more is needed for the AUV. Typical syntactic foam densities for 6000m rated applications lie between $550 - 700kg/m^3$ and cost between $200\$ - 700\$$ per kilogram of buoyancy [75]. The size and cost of AUVs is affected significantly by the use of pressure vessels and the required syntactic foam, as become apparent from Figure 5.1. While the state of the art AUVs are integrated more tightly than shown in this figure, the ratios of buoyancy foam and pressure vessels to electronics and sensors is similar.

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[1] The hydrostatic pressure increases by roughly 1 bar for every 10 meters of seawater.

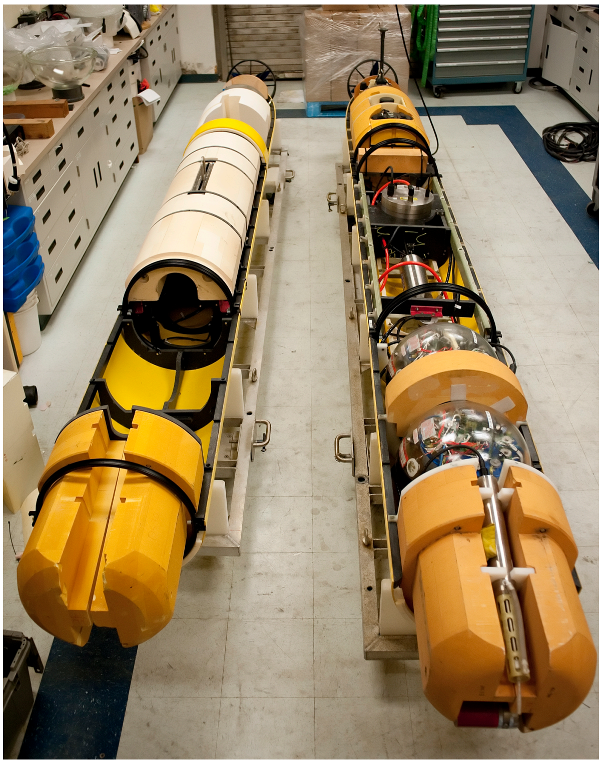

Figure 5.1: This photo of the insides of a 6000m-capable seafloor imaging AUV shows the space required for buoyancy material and pressure hulls [15]

It is possible to circumvent the use of pressure vessels, by designing electronics and other subsystems in such a way that they are inherently resistant to high pressure. The electronics and subsystems can then be housed in thin-walled enclosures, which are filled with a non-compressible fluid to protect them from sea water. With this approach, electronics enclosures do not have to resist pressure differences, and can thus be thin and of lightweight materials, while the feedthroughs can also be much simpler. Because the overall construction is much lighter, less syntactic foam is required to achieve near-neutral buoyancy of the AUV. This in turn results in an overall possibility for size reduction compared to conventional deep sea technology, while saving costs.

5.1.3. Capability reduction

AUVs are used in a variety of applications and manufacturers maximize the applicability of their AUVs by including many different capabilities. Different types of SONARs, obstacle avoidance systems and high performance navigation systems are almost standard in most high-end AUVs. However, seabed imaging requires only basic navigation and a Camera System. By removing everything else, the Subsea Robot becomes unsuitable for other applications. In the current AUV market, where AUVs are a significant investment for most operators, this is undesirable, likely one of the reasons why manufacturers do not choose this route.

The capital cost can also be reduced by decreasing the quality of the essential parts somewhat, which will naturally result in worse performance for individual robots. According to the data sheet of the HUGIN Superior, it is ”designed to be the most capable AUV” [29], and sports a variety of payloads to geophysical, hydrographic, environmental and defense applications. The first step in cost reduction would be feature reduction and keep only what is necessary for visual mapping. Reducing the the battery capacity results in a reduction in endurance, but also in cost. To keep mapping costs per area constant by adding a second robot, the endurance of each robot can be reduced by a maximum of 68%. This is a significant result because having more robots together will achieve the same cost-effectiveness against a lower investment cost.

5.1.4. Conclusion

Pressure tolerant design, combined with capability reduction as cost saving measures can likely reduce the cost of Subsea Robots below $\$100k$, as design objective **O1** requires. A detailed cost analysis should be done to confirm and provide a quantified basis to this initial study.

5.2. Camera System design

The main objective of the subsea mapping is to photograph the seafloor. This section discusses how the Camera System works and how its specifications affect the design of the Subsea Robot.

The global requirement for the image quality (**R1**) states that a resolution of at least 1 pixel per centimeter should be achieved. Modern image sensors easily have enough pixels to surpass this requirement, even if the swath exceeds 20 meters.

The seafloor must be illuminated with a light source from the Subsea Robot. The light emanates from the light source, travels to the seafloor, reflects back towards the robot and a fraction is captured by the lens which projects it on the image sensor in the Camera system. The available power for illumination is an important parameter in the Camera System design. It affects the following aspects;

+ Swath
+ Cruise velocity
- Mission duration

With a brighter light, the Subsea Robot can fly higher above the seabed, capturing a larger swath. Similarly, with a brighter light, the required exposure time is shorter, and the Subsea Robot can move at a higher velocity without causing motion blur in the images. Finally, a brighter light requires more power, which reduces the length of the mission. In summary, there is a tradeoff between the mapping rate and the mission duration, governed mainly by the power of the lights in the Camera System.

Modelling the optical path to find the relation between the cruise velocity and the required payload power is complex. Figure 5.2 shows that the light power diminishes due to multiple effects; spherical spreading, attenuation, spillover and the reflectivity of the seafloor. This will be addressed later in the section. First, the swath and cruise speed requirements are examined.

The swath is found in literature and private communication to be approximately equal to the fly altitude, which is between 5 and 10 m, depending on the water quality. To find the mapping rate, the cruise velocity must be determined as well.

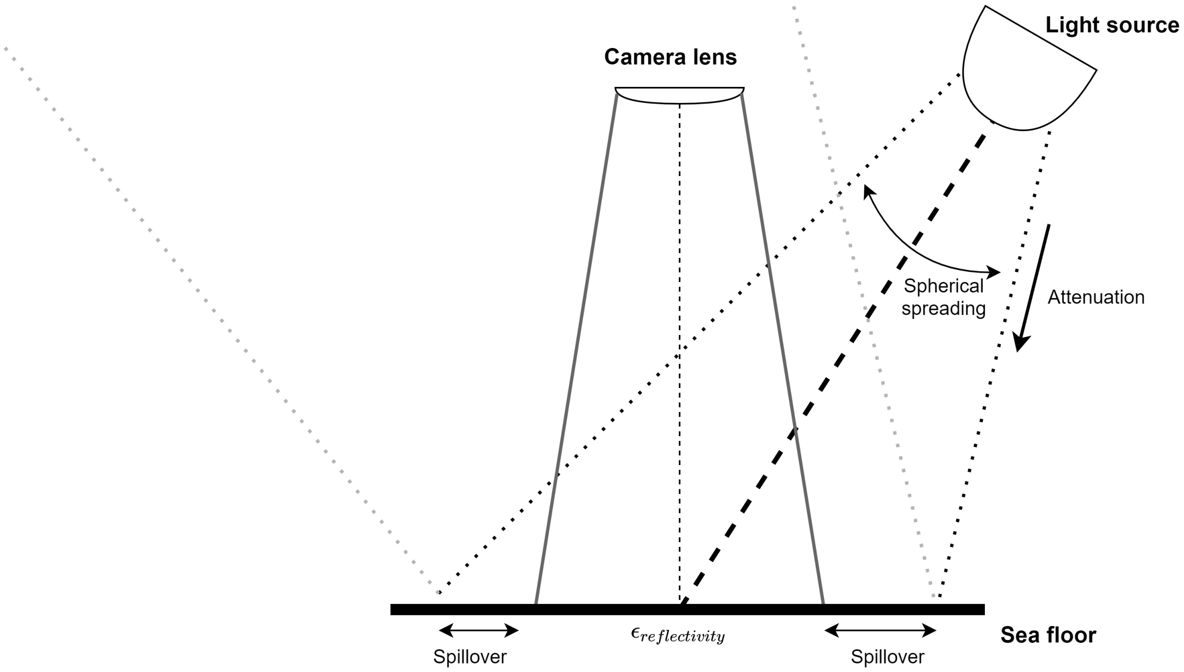

Figure 5.2: Losses occur in the optical path due to both geometric and physical effects.

There are two possible parameters that could pose an upper boundary to the cruise velocity when it comes to the Camera System. The first is the point from where the camera imaging rate is insufficient to achieve the desired coverage, and the other one is when motion blur starts to occur. These two are explored below and the lowest upper bound determined.

The imaging rate should at least allow for a 100% coverage of the area traversed. Furthermore, to stitch the images together to form a map, at least a 75% along-track overlap and 33% across-track overlap is used [39]. A representative of Fugro reported that they keep at least a 70% along-track. Figure 5.3 provides a visualization of the along-track overlap.

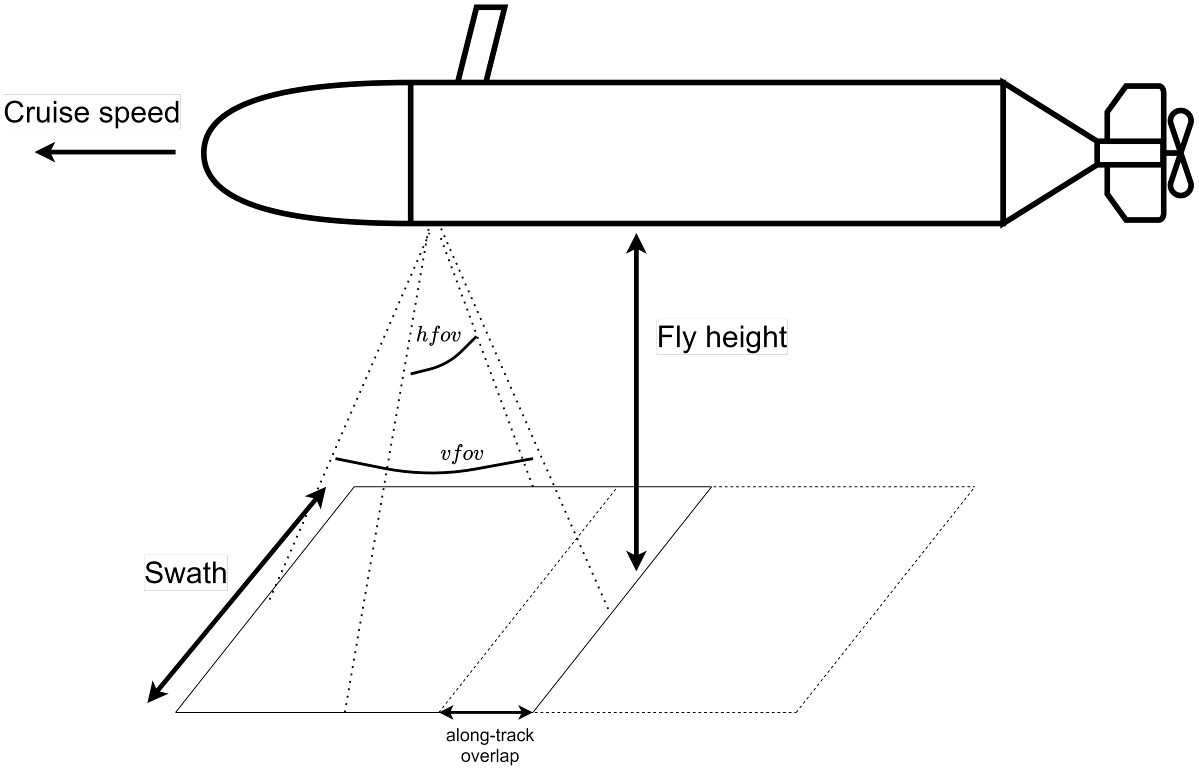

Figure 5.3: The imaging rate depends on the vehicle speed, the fly height, the image footprint and the required overlap between each image.

To find the required image capture interval, the along-track overlap can be expressed using the following relation, according to [39];

$$o_{along} < \frac{f-d}{f} = 1 - \frac{vt}{2h \tan\frac{\alpha}{2}} \tag{5.1}$$

The maximum cruise velocity resulting from the desired coverage is then;

$$v_{max,1} < (1 - o_{along})\, 2h \tan\frac{\alpha}{2} H_{camera} H_{camera} \qquad = \frac{1}{t_{capture}} \tag{5.2}$$

The maximum cruise velocity to avoid motion blur can be determined in a similar manner. To avoid motion blur, the Subsea Robot may not move more than half the project pixel length on the seafloor. Again, following [39];

$$f_{pixel} = \frac{p}{l} h \tag{5.3}$$

The 'along-track overlap' must be less than 50% of the pixel footprint, thus;

$$d_{exposure} < \frac{f_{pixel}}{2} \tag{5.4}$$

$$v_{max,2} < \frac{p}{2lt_{exposure}} h \tag{5.5}$$

Possibly, the maximum cruise velocity determined by having sufficient coverage is smaller than that of having no motion blur.

$$v_{max,1} < v_{max,2} \left(1 - o_{along}\right) 2h \tan\frac{\alpha}{2} H_{camera} \qquad < \frac{p}{2lt_{exposure}} h \tag{5.6}$$

which simplifies to

$$t_{exposure} < \frac{p}{4lH_{camera} \tan\frac{\alpha}{2} \left(1 - o_{along}\right)} \tag{5.7}$$

The dominant velocity constraint is not a function of fly-height but of camera properties and overlap requirements. [39] describes a deep sea mapping system using a DSLR camera at an approximate cruise velocity of 1.75 m/s. The exposure time and image capture interval are related linearly to the maximum cruise velocity. Since then, solid state mirrorless cameras have become the norm and provide much better performance when it comes to the image capture interval. Furthermore, the mirrorless cameras are equipped with the latest image sensor technology, which has been rapidly advancing for the last two decades.

Within the scope of this thesis, it is assumed that the improvements to camera technology since the publication of the aforementioned paper pushes the cruise velocity constraint to 10+ m/s, where it becomes irrelevant. The increased propulsion power at this speed diminishes range beyond what is required for economical operations, and the Camera System will thus not impose a constraint on this parameter.

Further specification of this subsystem would require a model along the lines of the following description;

1. The designer selects a number of high performing image sensors with large pixel sizes and a low photon per pixel requirement to achieve a sufficiently high signal to noise ratio;
2. Using the dark noise, the readout noise and the quantum efficiency of the specific sensor, the luminosity can be determined;
3. With the pixel size and the cruise velocity, the maximum exposure time can be found and from this, combined with the luminosity, the required radiance in $\frac{W}{m^2}$ can be determined;
4. This is fed into a model of the optical channel, using assumptions about the lens properties, the water properties and the seabed reflectivity;
5. From this, the required radiance at the light source on the Subsea Robot can be determined;
6. Using the specifics of the technology behind the light source, the required electrical power can be found.
7. The above steps have to be done for several wavelengths in the visible spectrum, as the image sensor, optical channel and light source all behave differently at different wavelengths.

Using the above model outline, the cruise velocity can be connected to the payload power, which can be used in the parametric model of the Subsea Robot for global optimization of the subsea mapping system.

The Subsea Robot model requires an estimate for the dimensions and the average power. SubC Imaging's 1Cam is rated to 6000m depth and a good representative for the camera part of the Camera System. SubC Imaging also offers lights, also in a pressure housing. However, it is possible to use LEDs under high pressure, and a PBOF housing could be used instead of a pressure housing. The same applies to the driver electronics [7]. Because of this, it is assumed that the only significantly large element in the Camera System is the camera in its housing, with a submerged mass of $2.2kg$ and a maximum diameter of $101mm$ [47].

The camera has a recording power of $8W$. The LED power depends on the flash duration. The Tilefish system developed for Kongsberg AUVs has an average power consumption of $15W$ [73]. A slightly less efficient system is assumed here to be around $30W$.

5.3. Subsea Robot subsystem design

Subsea Robots need at least a propulsion system, a battery system and a navigation system. Generally, a localization and/or recovery system is included, along with a processing unit and a payload of some sort. See Figure5.4 for an overview.

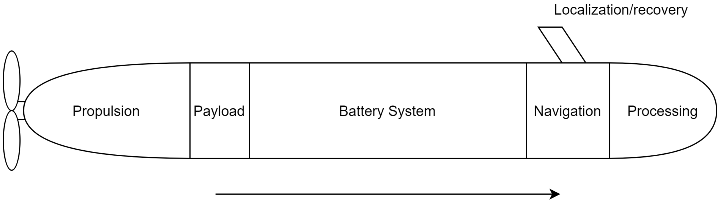

Figure 5.4: This schematic diagram of a potential design for the Subsea Robot would likely not match its physical configuration, which might be more convoluted in pursuit of more efficient integration.

This section elaborates on the assumptions for each of these subsystems. The Subsea Robot subsystems are assumed to fit in cylindrical hull sections such that the total robot can be described using the lengths and power estimates of each subsystem.

Propulsion In this work, it is assumed that a single thruster is located at the tail of the robot. The robot can maneuver using movable flaps located along the aft, such that three degrees of freedom are achieved. A typical propulsive efficiency of such a system is 50% [60]. The propulsion power depends on the shape and dimensions of the AUV. The shape and length of the aft portion of the AUV depends on the propeller size and corresponding motor torque. An included angle of about 30 degrees strikes a good balance between propeller size and motor torque for direct drive electric motors [60]. As such, the length of the propulsion module is equal to;

$$L_{prop} = \frac{D_{robot}}{2\tan 15^{\circ}} \approx 1.87 D_{robot} \tag{5.8}$$

It is assumed that any driver electronics and syntactic foam fits within this space.

Battery system A battery system consists of individual battery cells, a battery controller and syntactic foam. Usually, lithium cells are preferred over other battery chemistries, because of their high energy density. The length of the battery system is determined last in the model in Section 7.1. With the length, the available volume for battery cells is determined using the density of syntactic foam and some overhead percentage for electronics and thermals;

$$V_{cells} = V_{battery}\eta_{integration} \cdot \frac{\rho_{robot} - \rho_{syn.foam}}{\rho_{cells} - \rho_{syn.foam}} \tag{5.9}$$

The energy capacity of the cells can then be determined using their volumetric energy density, $C_{cells} = V_{cells} \cdot \rho_{volumetric}$.

Navigation system As indicated in Section 4, the Navigation System of the Subsea Robot needs to at least fill in the gaps between the position fixes provided by the localization system. For this, an Inertial Navigation System (INS) combined with a Doppler Velocity Log (DVL) provides sufficient performance. To get an estimate of the size and power demand of the navigation system, a brief market analysis with regards to the DVL will be done. It is assumed that the size and power consumption of the INS is negligible.

A selection of the commercially available 6000m rated DVLs is shown in Table 5.1.

	Teledyne Tasman	Teledyne Pathfinder 600KHz	Nortek DVL500
Depth rating	6000m	6000m (OEM)	6000m
AVG power	5.4W	3.4W	3.0W
Min. hull dia	260mm	n.a.	275mm
Weight in water	4.4kg	n.a.	3.1kg

Table 5.1: Information obtained from Lobster. [75]

The commercial price of these products lies between €$20k$ – €$30k$. Of the three options, the Teledyne Pathfinder is only provided as OEM for 6000m rating [54]. Of the other two, the Nortek DVL500 is the smallest [17]. This DVL will be used in further discussions about the Subsea Robot design. With a weight in water of 3.1kg, the required volume of syntactic foam is;

$$-m_{DVL}g + \rho_{syn.foam}V_{syn.foam}g = B \tag{5.10}$$

$$\text{where} \tag{5.11}$$

$$V_{syn.foam} = A_{frontal}x^2L_{syn.foam} \tag{5.12}$$

$$\tag{5.13}$$

Assuming the syntactic foam is added in a cylinder-shape with x% of the diameter of the AUV, the equation can be further specified to

$$L_{syn.foam} = \frac{B + m_{DVL}g}{\rho_{syn.foam}A_{frontal}x^2g} \tag{5.14}$$

resulting in a module length of

$$L_{nav} = L_{syn.foam} + D_{DVL} \tag{5.15}$$

Localization system The requirements for the localization system were derived in Chapter 4. The acoustic receiver will consist of a hydrophone, syntactic foam and processing electronics. The processing electronics are assumed to take up negligible space compared to the syntactic foam and the hydrophone. The sensitivity and bandwidth required for the hydrophone have to be determined in further research, as well as the processing electronics' requirements. As a rough estimate, it will be assumed that OceanSonics' icListen products are used. The size of the 6000m rated package is about 350 ml with a mass of approximately 1kg and a diameter of 48mm. [34]

Reusing equation 5.14;

$$L_{syn.foam} = \frac{B + m_{hydro}g}{\rho_{syn.foam}A_{frontal}x^2g} \tag{5.16}$$

where

$$m_{hydro} = m_{hydro,air} - \rho_{water} V_{hydro} \tag{5.17}$$

yielding a module length of

$$L_{loc} = L_{syn.foam} + D_{hydro} \tag{5.18}$$

Processing unit The processing unit is generally embedded in another subsystem, like the navigation system. It is assumed that this fits in the forebody of the AUV, which is assumed to be hemispherical.

$$L_{proc} = \frac{D_{robot}}{2} \tag{5.19}$$

Payload In the case of a photo-survey, at least a camera and light system are required. The requirements for the payload were derived in Section 5.2.

$$L_{syn.foam} = \frac{B + m_{cam} g}{\rho_{syn.foam} A_{frontal} x^2 g} \tag{5.20}$$

yielding a total module length of

$$L_{pay} = L_{syn.foam} + D_{cam} \tag{5.21}$$

Overview The total length of the Subsea Robot can be determined by combining all subsystems;

$$L_{robot} = L_{prop} + L_{pay} + L_{bat} + L_{nav} + L_{loc} \tag{5.22}$$

The craft has a static power consumption of

$$P_{hotel} = P_{pay} + P_{nav} + P_{loc} + P_{proc} \tag{5.23}$$

and a dynamic power consumption of P_{prop}.

There are many design variables to AUV design. A rough yet realistic model of a complete AUV representing the Subsea Robot is sufficient for the scope of this thesis. It must be noted that the assumptions for the weight and mass are based off of the pressure tolerant approach. The six essential subsystems were identified and modeled as modular hull sections, such that each subsystem can be described with just its length and power consumption. The propulsion, payload, battery, navigation, localization and processing subsystem are dimensioned based on a combination of empirical design rules from previous work and some market research into specific components. This results in a complete description of the robot's size and power consumption, which forms the basis of the parametric Subsea Robot model developed in Section 7.1.

5.4. Conclusion

This chapter started with the question *"What is a cost-effective Subsea Robot design that enables photographic mapping of the deep sea floor?"*.

In the first section, the shape of the body and general design considerations are discussed. In the theme of cost reduction, using pressure balanced, oil filled systems, the size and cost of the Subsea Robot design can be greatly reduced, compared to the current state of the art.

Specifying the Camera System in detail requires a complex model of, among others, the optical channel between the camera and the light source, and is outside the scope of this thesis. However, using a publication on a similar system, it can be ruled out with sufficient certainty that the Camera System will pose a velocity constraint on the Subsea Robot. The swath can be obtained from literature as well as private communication to be between $5 - 10m$, and an off the shelf pressure housed camera is used to provide ballpark figures for the size and power consumption of a deep sea capable Camera System.

The Subsea Robot consists of six essential subsystems, which are a battery, propulsion, navigation, localization/recovery, processing and finally a payload system. These can all be modeled as a contribution to the length and the power of the Subsea Robot by taking into account the specific equipment that is required in each of the subsystems and calculating the required volume of syntactic foam.

No fundamental obstacles to develop the Subsea Robots that satisfy the system requirements **R1** (high resolution), **R3** (operate up to 6000m deep) and partially **R4** (deliver data to ship) were encountered. Most capabilities have already been proven or at least can be asserted technically feasible within a relatively short development window. Naturally, a more thorough investigation is required to come to the final designs and quantify the performance more precisely.

This concludes the definition of the most important physical components. The operational processes are defined in the next chapter.

6

Operations

With a system architecture in place (Chapter 3), and the high cost of AUVs addressed by a different robot design in Chapter 5, this chapter focuses on the handling process on board of the ship. Design objective **O3** is to reduce the handling time to less than 12 hours, which is the current worst case scenario with the state of the art. In addition, there is the technical feasibility of a system capable of processing multiple robots to discuss. The logistics of operating a system with more than a 100 active autonomous Subsea Robots warrant an investigation of their own. The handling process is defined and analyzed. The Handling System is designed and each of its components discussed to form a insight in the different design options and tradeoffs. A concept design is proposed based on this discussion and specified further. With this chapter, the following research question is answered;

> *How can multiple robots be deployed effectively?*

In Section 6.1, the handling process definition and analysis are provided, followed by Section 6.2 and 6.3, which discuss the charging and data transfer design spaces. Section 6.4 then outlines the architecture of the Handling System, allocating functionality to subsystems. The following subsections each discuss a particular subsystems and the underlying tradeoffs. Finally, Section 6.5 summarizes the specifications of the proposed Handling System concept design. A brief conclusion is provided in Section 6.6.

6.1. Introduction

In this work, handling is defined as everything that happens above the water surface. The main objective of the handling system is to get the robots into and out of the water as quickly as possible.

The Localization System designed in the previous chapter requires the deployment of several surface vessels equipped with beacons. This is not considered in the following discussion, because these handling steps do not need to happen frequently. In that sense, they are 'normal' overboard operations, which do not require specific consideration in this proof of concept design phase. The handling of the robots however needs to happen constantly and quickly, and as such warrants a deeper investigation.

Section 2.3 already briefly touches on the different phases in the handling process. Chronologically, the process consists of these steps;

1. Pre-launch operations
2. Launch

3. Recovery
4. Data transfer
5. Recharging

Several factors impact the magnitude and variation in the time it takes to execute these steps. Specifically, the skill of the operators, the design of the robots and the sea state and/or other weather conditions. The impact of each factor to the handling process steps is indicated in Table 6.1

Step	**Duration [h]**	**Impact of sea state**	**Impact of robot design**	**Impact of operator skill**	**Parallelize?**	
					Currently?	Feasible?
Pre-launch operations	1-1.5	low	high	low	no	yes
Launch	0.08	medium	high	medium	no	not trivial
Recovery	0.5-1.5	high	medium	high	no	not trivial
Data/power transfer	1.5-8	low	high	medium	no	yes

Table 6.1: The handling process properties' qualitative evaluations were determined based on discussions with industry experts. [70] [18] [58]

The two process steps that happen on the ship can be more easily parallelized and are also less dependent on the operator skill or the sea state. If the robot design allows, quick and parallelized execution of these steps should be relatively simple. On the other hand, the steps that occur in the splash zone, between the ship and the ocean, are more complicated. Parallelizing these steps would be more difficult. Still, to facilitate the scaling of the mapping system, a number of objectives can be set:

- Ease strong dependencies on operator skill
  - Results in simpler and more predictable work
  - Less operators saves cost, as crew cost is one of the major cost drivers for offshore operations
- Be less reliant on a calm sea
  - A larger operating window increases the cost effectiveness of the system
- The handling system has a capacity of more than a hundred Subsea Robots

These objectives help guide system design choices further in this section.

6.2. Power transfer

In one of the current state of the art systems, namely the HUGIN AUV series, swapping the batteries instead of charging them on the AUV can save up to 6.5 hours in the total handling time [29]. Battery swapping is thus much quicker than charging but requires;

- an easily disconnectable battery subsystem in the Subsea Robot
- Additional batteries
- A small crew of operators or specific automation
- Swapping still requires a charging solution to charge the swapped battery

Charging is much simpler in that regard because it only requires the charging solution, and not the additional swapping infrastructure. To better understand the tradeoff between swapping and charging, the performance, handling and cost aspects of both options will be discussed in the next two subsections.

6.2.1. Charging

There are roughly three methods of charging; constant voltage, constant current and a mixed phase. The fastest method is mixed: first a period of constant current and then a period of constant voltage, called CC/CV charging. [52]

The charging rate is generally expressed in C. For example, charging a 5000mAh battery at $1C$ means that the charging current is 5A and the time for a full recharge is about 1 hour. Charging at $2C$ would mean charging at 10A and achieving a fully charged battery in about half an hour. The charging rate depends on the battery type/chemistry. The most high performance batteries now are LiPo or Li-ion, whose charge rate is generally 1C (1 times the rated current) [1]. A higher charging rate is possible, but will decrease the lifetime of the battery cells quicker. Conversely, if a lower charging rate is used, for example $0.8C$, the battery cells will degrade slower and result in a longer lifetime.

Cells designed for power output can be charged/discharged quicker than cells designed for energy capacity. It is the latter that are most suitable for the Subsea Robots' operational requirements.

Fast charging methods The charge curve of most types of lithium ion cells is such that the last 30% of the charging until fully charged goes at a significantly slower rate. For the fastest charging rate, only the first 70% should be charged.

Additionally, cells can be pre-heated to prevent lithium plating, where metallic lithium is formed at the anode. Results show that pre-heating to $50 - 60^{\circ}C$ can reduce the effect of plating by a lot. The cells should quickly be cooled afterwards to prevent damage due to spending longer times at elevated temperatures. [10].

Connecting to the charger Before charging can start, the Subsea Robot's battery needs to be connected to the ship's charging system first. There are two options; by making physical contact or without making physical contact. The advantages and disadvantages are displayed in Table 6.2 for both performance and handling aspects.

	Contact free	**Contact**
Performance	Lower power transfer	High power transfer
	Higher losses	Efficient power transfer
	Complex technology	Simple technology
Handling	No wear on interface	Interface will wear out
	Corrosion resistant	Additional corrosion protection required
	No mating force	Mating force required

Table 6.2: The indications in this table are based on the author's own experience in AUV design and industry experience.

Ignoring power losses[1], the tradeoff is between more laborious handling or longer charging time when considering contact vs contact free charging interfaces.

Given that any additional handling operations require either a manual or automated solution, which respectively increased crew headcount or decreased system reliability, reducing the handling requirements seem most favorable option. A physical contact based solution must address the risk of wear,

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[1] Assuming that the ship has plenty of power and any overheating of components can be dealt with

corrosion and take into account that there will be a certain mating force to overcome during the connecting and disconnecting of the charger.

In summary, the following design consideration for charging apply.

Specifically for the Subsea Robot design:

- The battery capacity could exceed the required capacity up to a factor of $\approx 1/0.7 \approx 1.43$ to facilitate faster charging. No additional capacity or less than a factor of 1.43 is possible, but will lead to a longer charging time
- The battery system of the Subsea Robot could include a heating/cooling system to facilitate faster charging at $> 1C$. It might be possible to have the heating/cooling system external to the Subsea Robot, on the ship

and general considerations:

- Charging can be done faster ($> 0.8C$), at the cost of battery lifetime, increasing system maintenance cost and downtime. The larger ecological footprint due to the extra materials required to keep the system running is also a factor.
- The Subsea Robots' battery chemistry can be chosen to facilitate either faster charging (higher power density) or higher energy density (and resulting in longer charge times). Additionally, the cost and lifetimes of different chemistries should be considered.

After the discussion on the swapping design option, the different design considerations will be compared to come to a design choice.

6.2.2. Swapping

As indicated at the start of this subsection, battery swapping is faster than charging but it requires additional complexity:

- an easily disconnectable battery subsystem in the Subsea Robot
- additional batteries
- a small crew of operators or specific automation

Each of these additional factors will be discussed below.

Disconnectable battery system The main challenges for making a disconnectable battery system are

- Having a quickly disconnectable yet high power capacity link between the battery and the rest of the robot
- Dealing with the effects of salt water; corrosion and short circuiting
- Keeping the mass and space overhead of the connection limited

The first two considerations can be dealt with at the expense of the third; especially if a contactless connection is chosen. Commercially available options suffer from limited power transfer efficiency and bulkiness [75].

Physical contact connectors have a more modest overhead, a lower complexity and a better power efficiency. There are roughly three options when it comes to physical mating:

	Mating force	Mating complexity	Overhead
pressure shielded	medium	medium	high
wet-mate/flooded	high	low	medium
pressure balanced oil filled (PBOF)	small	high	small

Table 6.3: While a wet-mate solution has a high mating force, the complexity is low, favorable for repetitive processing, both manual and automatic.

For the pressure shielded option, the operator has to open some sort of pressure housing, either by means of loosening fasteners or a screw shroud of some sort. The wet-mate/flooded design option is simply pushing or pulling the connector. It must be noted that for the pressure balanced oil filled (PBOF) solution, the oil would have to be spilled and refilled every time the battery is disconnected [64].

The wet-mate/flooded option has the lowest mating complexity, but a high mating force and medium overhead. However, compared to the mating effort of the PBOF solution and the overhead of the pressure shielded, it seems the best solution.

Additional batteries For the discharged battery of a robot to be swapped with a charged one, there need to be more battery systems than Subsea Robots in the system. In the worst case, if all robots are deployed and recovered at the same time, an additional 100% batteries are needed. In the best case, if 50% or less of the robots are deployed at the time, no extra batteries would be needed (batteries of the unused Subsea Robots could be swapped with those of the Subsea Robots in use). The number of spare batteries depends on the endurance of the Subsea Robots and the operational strategy.

A battery system likely represents between 60-80% of the mass of the robot, as well as at least 50% of the cost. This should be kept in mind when considering swapping as a design option.

The swapping process The swapping can be done manually by crew members, or by some automated system.

Depending on the size of the robot, the battery might have to be split in several parts to facilitate safe handling by humans. The connecting overhead of each battery module will add to the total size and cost of the robot. If an automated system would be used, this size constraint may be less relevant. The complexity and reliability of an automatic system is something to consider though. A hybrid solution would entail a co-bot type system; the human operator takes care of the ‘complex’ positioning and timing, while the robot only does the heavy lifting.

Charging the swapped battery The charging time is of less relevance with the swapping solution; the engineering complexity in making a high-energy, fast charging system may be bought off simply by having more spare batteries. Slower charging could mean a more performant battery system for the robot, no need for extra capacity and no need for a heating/cooling system. In addition, the lifetime of the batteries can be extended by charging even slower. Even though more batteries are required up front, the climate impact may be smaller due to the much greater lifetime when slow charging is applied. The slowest charging rate depends on the maximum number of extra batteries available, the endurance of the robots and the operational strategy.

6.2.3. Swapping-charging tradeoff conclusion

The main sub-tradeoffs in this design choice are listed in Table 6.4.

Aspect	Charging	Swapping
Performance	Up to 43% larger capacity needed for faster charging and possibly heating/cooling system for faster charging	Wet-mateable battery section(s)
Handling	Contact-free charging port vs Wet-mate charging port	Manual vs fully automated vs co-bot
Performance vs handling	Lower performance & longer handling time vs simple and easy to automate	Higher performance & shorter handling time vs more complex process, more difficult to automate
Cost	Additional battery capacity per robot Heating/cooling system	Additional batteries Wet-mate interfaces Support infrastructure

Table 6.4: Table providing an overview of the different tradeoffs for swapping vs charging.

The initial mapping system design philosophy is that despite them having lesser performance, having more Subsea Robots increases overall mapping speed most effectively. The bottlenecks for scale are then handling capacity and overall cost. Both these factors are better addressed by a charging solution rather than a swapping solution. If less robots per ship are used, likely the swapping solution outweighs the charging solution, because the overall turnaround is faster and less automation is required because the handling capacity is not as critical as with having many robots.

6.3. Data transfer

Before and after a mission, data needs to be transferred to and from the Subsea Robot. Before the mission, the mission profile and additional settings must be uploaded to the Subsea Robot. Afterwards, logs and the acquired payload data must be downloaded from the Subsea Robot to the ship. This can be done wirelessly or not; using a physical link, transfer speeds of multiple GB/s can be achieved. The options for wireless technology are more complex. Using commercial off the shelf wireless watertight connectors, about 12 MB/s can be achieved [44]. Using modern WiFi 6 technology, a maximum speed of 1.2 GB/s can be achieved [77].

It is possible to already make a rough estimate of the required data transfer time. Assuming the Subsea Robot takes pictures of about 16MP at 3Hz, without compression or stitching, over 3500 GB is accumulated after a mapping time of 20 hours [47]. With Wifi6, this results in a transfer time of about an hour [77]. If the Subsea Robot can already stitch the images together, for example during the ascent phase or live during captures, the data size can be reduced by more than 70%[2], leading to a similar decrease in transfer time.

The data transfer time seems to be in the same order of magnitude of the charging time of the Subsea Robots. The charging and data transfer designs should be investigated in more detailed to find out which one is the bottleneck.

It might even be possible to start transferring data from the moment that the Subsea Robot is recovered from the water.

6.4. System design

The handling system has to fulfill a number of functions, listed in the first column of Table 6.5. An initial suggestion for a set of subsystems is provided in the first row of the same table.

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[2] Due to having an along track overlap of 70%, as discussed in Chapter 5

	Outside/deck		Workshop		Storage
	Launch system	Recovery system	Power system	Data interface	Storage system
Transfer data between robots and ship				×	
Transfer power from ship to robots			×		×
Transport robot from ship to water	×				
Transport robot from water to ship		×			
Store robots for later use					×
Unstore robots for immediate use					×

Table 6.5: A description of how the required functions can be mapped to individual subsystems.

Essentially, three different types of spaces are required; one for overboard handling, one for short-term handling and one for long(er) term handling. These are the Deck, the Workshop and the Storage respectively. On the Deck, the launch and recovery takes place. The Workshop is where crew can manually inspect the Subsea Robots as they go out or come in to or from the Deck. A number of automatic checks can also be done here, and malfunctioning Subsea Robots can be set aside for further troubleshooting. The Storage holds most of the Subsea Robots, and has charging and data transfer facilities as well.

Before continuing with the system design, it must be determined if and where these spaces are located on the ship. To determine a suitable architecture of the system, some general design choices will be discussed.

L&R from the ship or from an unmanned platform? The launch and/or recovery of the Subsea Robots could be done from the ship, but also from another unmanned platform. For example, a small mobile vessel that positions itself over the Subsea Robots once they are at the surface to recover them.

The advantages of using an unmanned, secondary vessel;

- because unmanned vessels are smaller and more maneuverable than the main ship, L&R might be easier;
- the wave induced motions of the unmanned vessel are more similar to Subsea Robot (compared to ship), which might ease the recovery process even further;
- if the recovery can be done independently from the ship, the crew is more flexible in planning other operations.

Disadvantages include;

- there will be an additional system that has to be launched and recovered in order to perform subsea mapping;
- when something breaks on the unmanned vessel, or something else goes wrong, it is much more difficult to access for troubleshooting and repairs than when it would be on the ship;
- if the unmanned vessel malfunctions for longer periods, a backup method would be required to recover any Subsea Robots still in operation. This would likely occur from the ship, so there will already be some sort of recovery system in place on the ship;

- if the unmanned vessel is significant in size, an accidental collision with the ship will pose a serious safety hazard.

In conclusion, launching and recovering the Subsea Robots from an unmanned vessel could make the process easier and allow for more flexible deployments, but introduces additional system complexity and introduces an additional single point of failure. The L&R should happen from the ship itself.

L&R from the back or the side of the ship? Most modern research ships have both deck space available for overboard operations in the aft and the sides of the ship. Both locations could be an option to place the L&R system that handles the Subsea Robots.

The advantages of using the aft of the ship include;

- the ship will be positioned with the bow into the waves or wind if possible, so there will be less hindrance for the L&R process from the weather conditions;
- There is plenty of space at the back of the ship, where the side might be constrained by the superstructure of the ship.

Disadvantages include;

- The Subsea Robots will have to come close to the ship's aft thrusters, which might pose a hazard;
- Other equipment that has to go overboard will follow the same considerations, so will compete with the mapping system's equipment for the aft space.

Despite the disadvantages, using the aft seems like the better choice because there will be less interference with waves/wind during the L&R process, of which it was identified that it is strongly affected by the sea state.

The position on the ship where most of the handling process' steps will be executed is now determined. Figure 6.1 provides a rough overview of the handling systems.

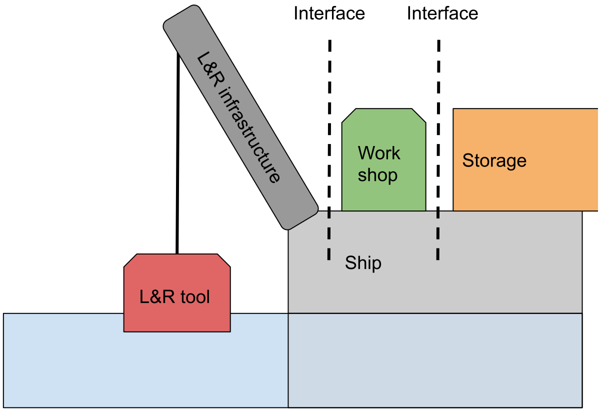
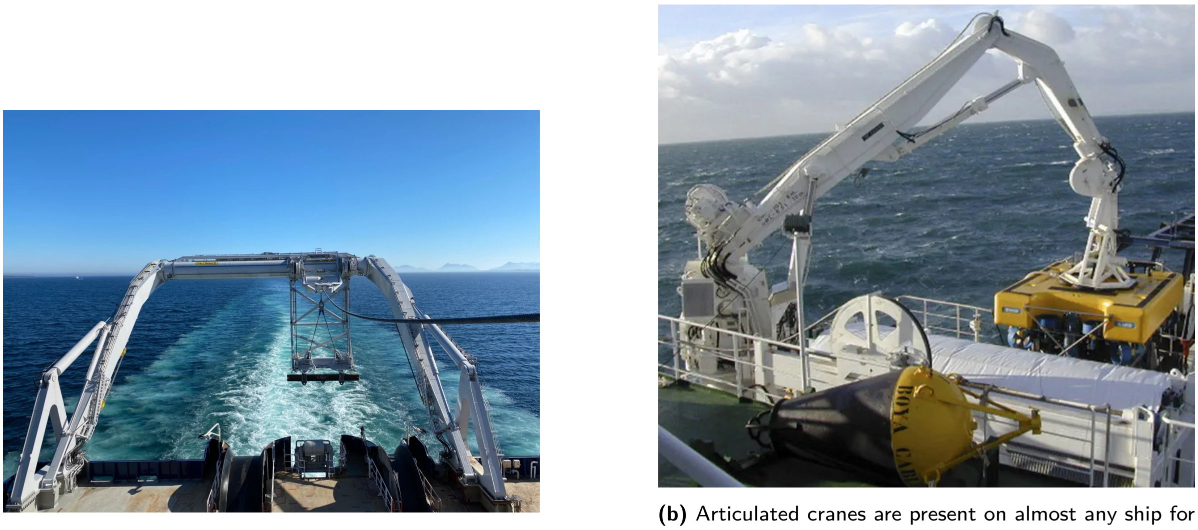


Figure 6.1: A side view of the Handling System.

In the next couple of subsections, the design of each subsystem will be discussed and specified further. Each subsection is concluded by a list of modelling parameters needed to develop a model of the complete handling process.

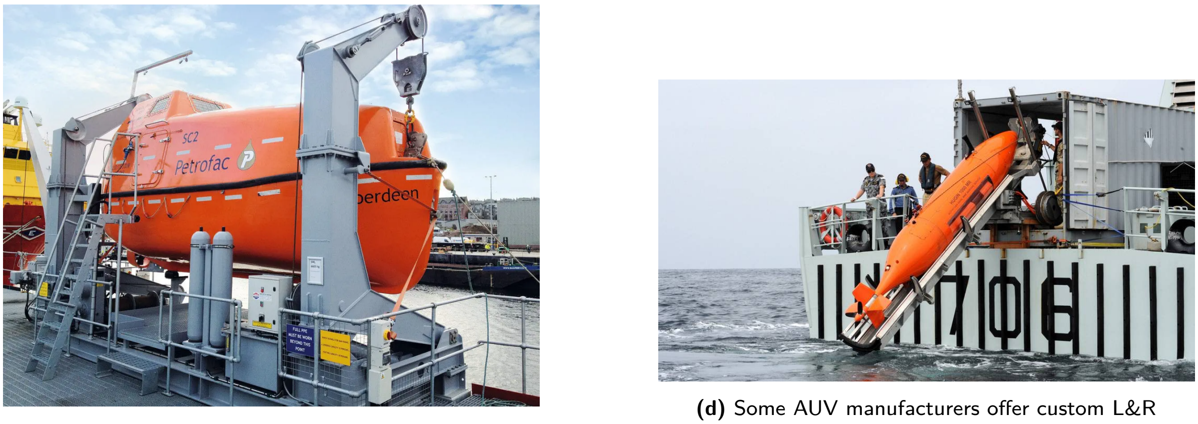
6.4.1. L&R facilities on the ship

There are multiple ways to do overboard operations on a ship. Four are displayed in Figure 6.2; the A-frame, the articulated crane, the davit and custom solutions, in this case a slide specifically for AUVs. The davit in Subfigure 6.2c is only suitable for placing at the side of the ship, so this option is not suitable. The custom slide in Subfigure 6.2d can be placed anywhere, but cannot be used for anything else than launching or recovering the Subsea Robots. On the other hand, to use the device, operators do not have to be exceptionally skilled. The articulated crane in Subfigure 6.2b requires more care in operation, but is highly flexible; it can serve other applications as well. Finally, the A-frame in Subfigure 6.2a can be mounted at the aft and side of the ship, has limited degrees of freedom so should be relatively easy to operate and can also be used for multiple usecases. Between the A-frame and the articulated crane, the A-frame seems like an easier solution that can be motion compensated easier as well. In conclusion, the A-frame positioned at the aft will be chosen to support the Launch and Recovery operations on the ship.



(a) An example of an A-frame on a ship [2].

(b) Articulated cranes are present on almost any ship for cargo transfer in port [66].



(c) A typical Davit construction [57].

(d) Some AUV manufacturers offer custom L&R solutions [56].

Figure 6.2: Four possible options to launch and recover the Subsea Robot from the ship. Note that Figure (a) and (d) might be able to support multiple L&R operations simultaneously.

6.4.2. L&R Tool

The launch and recovery process steps will be done using the L&R Tool subsystem. The L&R Tool should be compatible with the other subsystems, and as such has at least the following requirements;

1. The L&R tool can be operated from the A-frame
2. The recovery procedure must be possible with minimum robot control authority (3DOF, x translation, velocity dependent yaw and pitch)

Furthermore, it would be nice to have the following qualities;

1. The recovery process takes less than 1 hour
2. The recovery process does not require human operators
3. The L&R tool should be usable up to sea state 5

The L&R Tool needs to execute two main functions; launching and recovering. The launch process is relatively simple; the robot is transported from the deck to the water surface where it will trigger its mission and dive.

The recovery process is a little more involved. Once the robots are done with their mission, they will return to the ship for pickup. This is quite a challenging part, as neither the ship nor the robot will ever be completely still due to wind and wave movements. This means that both have to adjust to each other's position and movement constantly in order to interface safely.

There are two distinct design options for the recovery process; either it happens at the surface or somewhere underwater.

At the surface:

+ The Subsea Robots are passively stable, as they are naturally buoyant, and will remain at the surface despite wave movements
- The Subsea Robots have no control authority
- The wave-induced motions will be largest here
- Communication will be intermittent due to partial submergence

At least 10m below the surface:

- The Subsea Robots are not passively stable
+ The Subsea Robots have maximum control authority
+ Wave-induced motions are strongly reduced
+ Communication will be stable if acoustic carriers are used

The Subsea Robots and the ship can only be controlled in certain directions, and their wave-induced motions differ quite a lot. This dynamics mismatch and the limited control options mean that under the influence of waves, both systems will respond differently and do not have the control authority to fully correct this asymmetric response. The recovery can be done with proper timing by the operator, but will remain difficult and unreliable to pull off.

Moving the operation to below the waves, where their movement has less effect on the robot, and where the robot has more control authority, this dynamics mismatch is not solved nor is the limited control authority of the overall system; but now at least one of the components can be controlled predictably, significantly easing the complexity of the docking problem.

Now either the robot can actively try to overcome the dynamics asymmetry by anticipating the L&R Tool's movements and acting accordingly, or more control authority can be added to the L&R Tool to limit the wave induced disturbances. The latter can be done using an active heave compensation system, removing most of the L&R Tool's unwanted movement through the water.

Then, both system components have been stabilized and ‘normal’ docking control schemes can be applied. Docking remains a difficult problem, but the system architecture is relatively agnostic to the exact implementation, so this cam be investigated in other works.

6.4.3. Workshop design

The Workshop must facilitate operators to manually check the incoming and outgoing Subsea Robots, as well as support a number of automatic checks to speed up the process. The Workshop must have facilities to remove a malfunctioning Subsea Robot from the active system for further troubleshooting or repairs. In short, the functions include;

- Provide crew access for manual inspection post/pre mission checks
- Provide automatic post/pre mission checks
- Have a method of moving incoming and outgoing Subsea Robots
- Interface with the Storage
- Interface with the L&R tool

Because it is deemed a better option to choose charging rather than swapping, the charging can take place in the Storage subsystem to save space in the Workshop.

The Workshop should be in a sheltered space such that weather conditions do not affect the effectivity of the crew operating the Workshop. It can either be built in a standard 20’ or maybe even in a 10’ shipping container.

Subsea Robots could be moved through the Workshop using a dolly or cart, either on rails or freely movable. Alternatively, a fixed roller conveyor line could be used. The latter has the advantage that only the Subsea Robots move, requiring less force. This can also be automated more easily using existing infrastructure used in factories.

6.4.4. Storage design

To store up to a 100 robots on a ship requires a large space. Preferably, this space is shielded from weather and the elements, much like the Workshop. Likewise, a convenient solution is to use a standard size shipping container, because it can be placed on any ship of sufficient size, and every ship or harbor has the facilities to place it on deck. A full size container (40’) is too large for most research vessels, 20’ is a better standard to work with.

The Storage must provide the following functions;

- Store over a 100 Subsea Robots
- Provide charging facilities for the Subsea Robots
- Provide data transfer facilities for the Subsea Robots
- Provide crew access for maintenance or troubleshooting
- Interface with the Workshop

To provide crew access for maintenance or troubleshooting, at least one walkway is required, of at least 700mm wide. Given the internal dimensions of the shipping container, either two walkways and four rows of Subsea Robots with a diameter less than 230mm are possible, or one walkway and two rows with a maximum width of 475mm are possible.

Subsea Robots could be stored vertically, implying a robot length of at most the height of the container, which is 2.39m. Alternatively, they could be stored horizontally, placing the length constraint at the internal length of the container, which is 5.9m.

Additionally, the Subsea Robots should be secured in place once they are placed in the Storage, to prevent damage due to ship movements.

The loading or unloading a Subsea Robot from or to the Storage could likely be automated relatively easy by taking inspiration from warehouse automation. The Storage will be a closed environment where safety can be monitored closely.

The Storage container should have climate control for to maintain the temperature of the Subsea Robots between $10°C$ and $20°C$, even in arctic or tropical environments. Prolonged exposure to higher temperatures will decrease battery life and cold conditions during charging will as well. Additionally, excessive moisture, originating from the recovered Subsea Robots, should be extracted from the atmosphere. Commercial off the shelf solutions are available, called reefer containers. A thermal buffer should be installed at the interface between the Storage and the Workshop to maintain a constant temperature in the Storage.

6.4.5. Interfaces between spaces

An incoming Subsea Robot should be queued in between its current station and the next station until the next station is free to accept it. Similarly, for outbound Subsea Robots, the system should wait for a signal that the next station is available to receive the Subsea Robot.

6.5. Resulting system design

With the discussed system architecture, the handling process can be defined in more detail. Figure 6.3 provides an diagram defining the different steps.

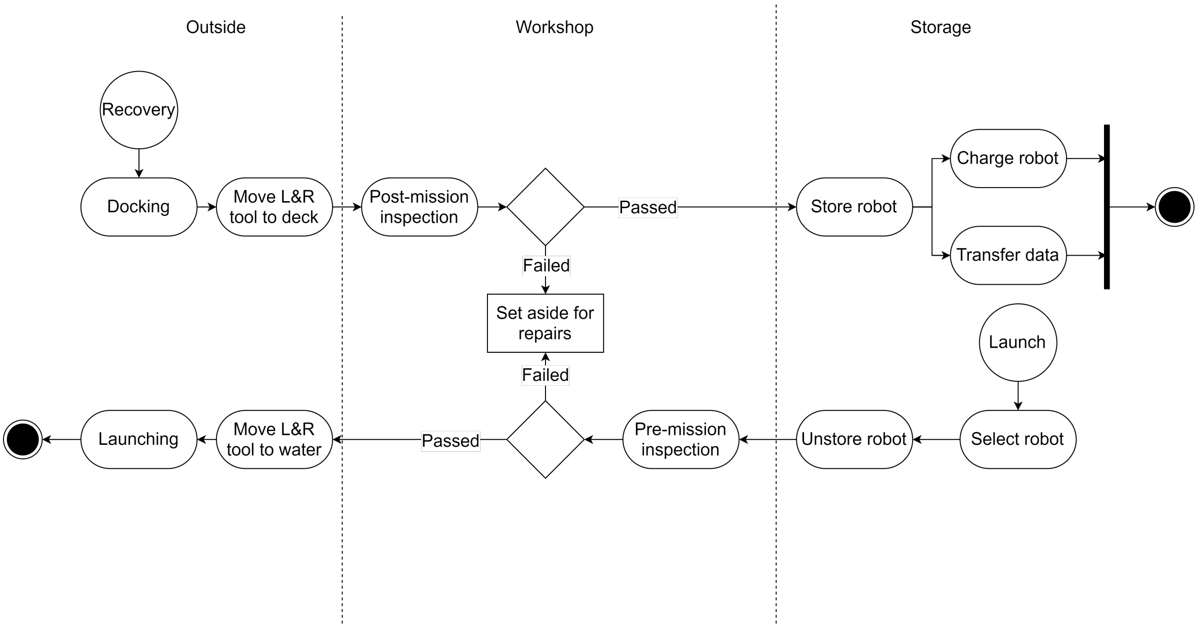


Figure 6.3: The different process elements are split up in an Inbound and Outbound chain.

In the diagram, the Recovery process comes first. The Subsea Robot docks in the L&R tool and is moved to the deck. In the Workshop, a post-mission inspection is done, partly automatically, and partly by a human operator. If it fails the check, it is set aside for further troubleshooting or repairs. If it passed, it is offered to the Storage, where it is automatically stored in a storage slot. There it is charged and simultaneously its data is downloaded to the ship. It is then ready for its next deployment. Once a new deployment is requested, the Subsea Robot is removed from its storage slot and handed over to the Workshop. It is once again inspected and its mission is configured. Should it not pass the inspection, it is set aside for later troubleshooting or repairs. Otherwise, it is passed to the L&R tool, which moves it to the water surface and launches it. The Subsea Robot starts its mission.

The design choices made in the Handling System imply some additional features in the Subsea Robot;

- The Subsea Robot must have a physical connection for charging;
- The Subsea Robot must have WiFi functionality to provide a data transfer rate of at least 1 GB/s
- The Subsea Robot must be able to dock on its inbuilt localization system

Additionally, there are a number of additional features to the Subsea Robot that could promote the charging speed, but these will not be further explored in this work.

6.6. Conclusion

In this chapter, the question *”How can multiple robots be deployed effectively?”* was investigated. The Handling process is dependent both on external factors, such as the weather conditions and operator skill level, as internal factors, such as the presence of specific features in the Subsea Robot design. A Handling System architecture and concept design is proposed to minimize the influence of external factors on its performance, and a number of additional non-invasive features to the design of the Subsea Robot are proposed.

The handling of the surface elements of the Localization System is not considered for now, because can be considered ’normal’ overboard operations, where the handling of the robots however needs to happen constantly and quickly.

The Handling System consists of a Storage, a Workshop and a L&R System. The Subsea Robots are normally stored and charged in the Storage, inspected and configured in the Workshop, and, if need be, repaired, and finally launched or recovered in the L&R system. The Storage and Workshop are built into standard shipping containers, and the L&R system relies on an A-frame that is mounted on the aft of the ship. This results in a flexible Handling System which can be adapted to local conditions if need be.

This chapter concludes the design part of this thesis. The next chapter develops a model of both the Subsea Robot and the Handling system to gain insight in the different tradeoffs and performances under various scenarios.

7

Performance

The main research question in this thesis applies to both the technical feasibility of a multi-robot seafloor imaging system and the cost-effectiveness of such operations. The previous chapters elaborated on the design of the different components that enable the seafloor imaging system to operate at large scale. The system architecture and the design choices are validated by investigating the system performance to evaluate the cost of operations. This can be compared with the cost estimate of the state of the art provided in 2.

This chapter is aimed;

- to validate the cost-effectiveness of the seafloor imaging system design over the current state of the art;
- to discover important performance drivers in the system design;
- to help make high level design tradeoffs at an early stage in the design process.

The question that is answered at the end of the chapter is;

> *How can the performance be modeled and validated at an early stage?*

The most important performance indicator is the specific mapping cost. Secondary are the number of robots in the system, the mapping rate of the system over time, and the total cost per mapped area.

To this end, a model is developed of the mapping process that determines the total mapping cost for a specific mapping scenario, for different system design parameters, including various Subsea Robot designs.

The mapping process is modeled using a discrete event simulation, where every event is an action at system level (Figure 7.1). The handling system flow is modeled, but the interaction with the handling system, inter-robot coordination and any other logistics are not modeled. While these are important to take into account in later stages of the design, they are not expected to limit the performance of the imaging system significantly. Rather, the on-board logistics, combined with the performance of the individual robots are expected to be the main performance drivers.

The operations model uses a parametric model of the Subsea Robot with varying input parameters. The simulation is run for all valid Subsea Robot designs, after which the best Subsea Robot design can be identified for that specific scenario by looking at the overall cost of the mapping process.

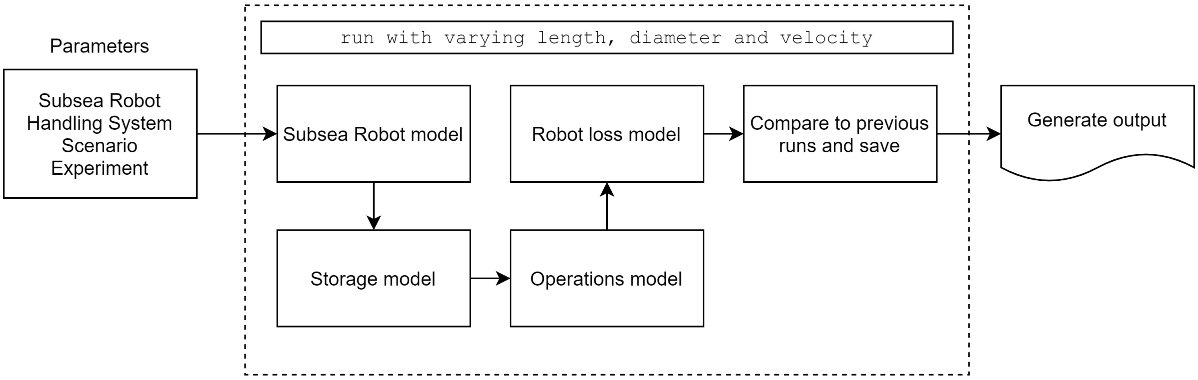


Figure 7.1: The modeling is focused on the activities on the ship. The Storage Model and Robot loss model are described in Section 7.3.

The performance of the system is evaluated for different scenarios to build an understanding of the various design considerations that might be relevant in each scenario.

7.1. Subsea Robot model

To support the design optimization of the subsea mapping system, a parametric model of the Subsea Robot is developed in this section. The main objective of this model is to provide a relation between the robot's size, velocity and range. The section starts with a description of the assumptions and modeling relations used. Then, a number of validation steps are taken to build trust in the veracity of the model.

7.1.1. Description

AUV design is a complex practice, involving many tradeoffs across different disciplines. The model developed here makes a number of assumptions to reduce design complexity. The main variable component of the design is the size of the battery compared to the other subsystems of the AUV.

The primary parameters of the model are the length, diameter and velocity. The output is the range and battery capacity for that every combination of parameters. The entire model is summarized in Figure 7.2

Appendix **??** contains a detailed description of the modeling equations.

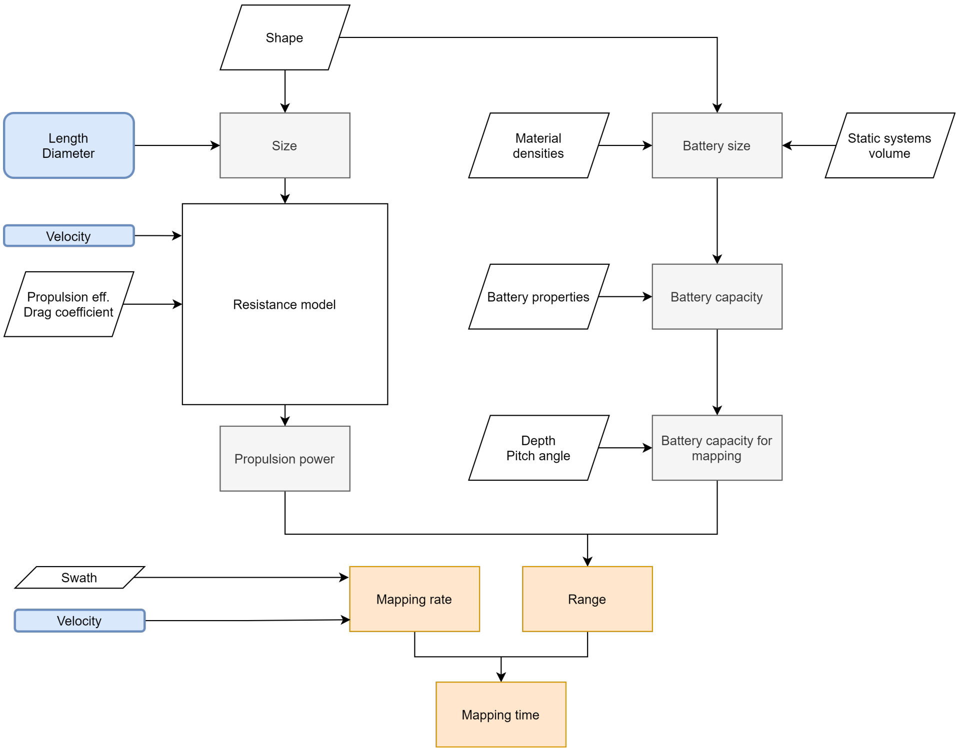


Figure 7.2: A flowchart describing the modeling done to find the range and endurance of the Subsea Robot.

7.1.2. Validation

The model of the Subsea Robot requires some extent of validation before it can be used in further work. The modeling relations employed originate mostly from basic mechanics. The Subsea Robot model is systematically validated by means of a progressive analysis; the behavior of the model under different circumstances is tested at different stages. The stages are the following;

1. Input parameters
2. Geometry calculation
3. Resistance model
4. Determination of mission characteristics

First, the input parameters are verified. After this, at the beginning of each stage, the relevant input parameters are given and one or more hypotheses are tested.

Input parameters A number of parameters used in the model require justification, listed in Table 7.1

Parameter	**Symbol**	**Value**	**Units**
Syntactic foam density	$\rho_{syn.foam}$	550	kg/m3
Battery cell density	ρ_{cells}	2200	kg/m3
Battery energy density	ρ_{energy}	660	Wh/L
Water density	ρ_{water}	1027.9	kg/m3
Net buoyancy	B	10	N

Table 7.1: Some of these design parameters are founded in the current state of technology and will likely change over time.

The syntactic foam density is based on a product of BMTI Alseamar, a French company specializing in buoyancy solutions [71]. The battery cell specifics are representative figures for the higher-end Lithium ion type battery cells, found in [41]. The water density is a global average for a depth of 4000-6000m, at 3.5% salinity and $3°C$ [11]. The net buoyancy represents the buoyancy force acting on the Subsea Robot when it is in the water, and ensures that in case of a malfunction the Subsea Robot will slowly return to the surface, where it can be recovered for troubleshooting.

Geometry calculation With the input parameters of the diameter and the length, as well as some of the specifics of the robot's subsystems, the length, surface area and volume of the robot are calculated. The following statements should be true for a robot with length of 2m and a diameter of 0.2m ;

- The lengths of the modules should decrease with an increase in diameter, except that of the battery, which should increase;
- The total surface area of the robot should be slightly larger than $\pi DL = 1.26m^2$;
- The total volume of the robot should be slightly smaller than $\frac{\pi}{4}D^2L = 0.063m^3$

The model outputs the following subsystem dimensions;

$$L_{loc} = 0.15 \tag{7.1}$$
$$L_{nav} = 0.45 \tag{7.2}$$
$$L_{pay} = 0.31 \tag{7.3}$$
$$L_{bat} = 0.61 \tag{7.4}$$

with a fore and afterbody of

$$L_{forebody} = 0.10 \tag{7.5}$$
$$L_{afterbody} = 0.37 \tag{7.6}$$

The reported volume is $0.054m^3$ and the reported surface area is 1.14, both in agreement with the hypothesis, with a difference of 14.3% and 9.5% from the estimated value respectively. Similarly, the ratios of the respective lengths of the three subsystems requiring off the shelf equipment show good agreement with the ratios of their masses.

Now when the diameter is increased by 20%, from $0.2m$ to $0.25m$, the subsystems' length changes;

$$L_{loc} = 0.12 \tag{7.7}$$
$$L_{nav} = 0.36 \tag{7.8}$$
$$L_{pay} = 0.23 \tag{7.9}$$
$$L_{bat} = 0.7 \tag{7.10}$$

All but the battery length decrease, like hypothesized.

This proves the validity of the first stage of the Subsea Robot model. With trust in this part of the model, the subsequent stage is validated; the resistance model.

Resistance model The resistance model takes the wetted area, the frontal surface area and computes a skin friction drag component as well as a form drag component which together make up the total resistance force of the robot for a certain speed. The input parameters, such as the water viscosity and density, have been verified in previous work [60]. A change from the previous work is that the form drag coefficient C_d has been increased from 0.22 to 0.3, which is similar to validated AUV form drag coefficients [35]. The former value corresponds to a very streamlined body with no appendages except for some tail-flaps for steering. The new value better reflects potentially additional appendages or different tradeoffs in the hull design benefiting the handling process.

The following statements should hold up;

1. The form drag should increase quadratically with an increase in velocity;
2. The skin friction drag should increase slightly less than quadratically with an increase in velocity;
3. The skin friction coefficient should be in the order of magnitude of 10^{-3}

Figure 7.3 shows the resistance curves for both resistance components for the same design robot but with an increasing cruise velocity. The results are in agreement with the hypotheses.

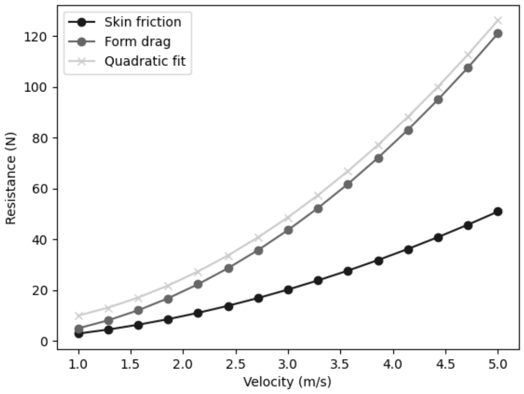


Figure 7.3: The individual components of the total resistance of the robot.

The skin friction coefficient that was calculated is approximately $4 \cdot 10^{-3}$, which is in agreement with the findings of Schoenherr in 1957 [26]. In submarine engineering, the skin friction component is reported to be the major component in the total resistance [6], which is not the case in Figure 7.3. Both the skin friction and form drag estimates are verified for this model, so this discrepancy should be explained by a difference in scale. The form drag coefficient is not dependent on scale, and the skin friction coefficient actually decreases slightly. However, the frontal and wetted area scale differently. This can be verified by examining the frontal and wetted area of a cylinder;

$$A_{frontal} = \pi r^2 \tag{7.11}$$

$$A_{wetted} = 2\pi r^2 + 2\pi r h \tag{7.12}$$

$$\tag{7.13}$$

It is likely that this difference in scaling explains that the reported ratio of skin friction to form drag for submarines does not apply at the scale of the Subsea Robots considered here.

Determination of mission characteristics Finally, the mission characteristics are calculated by the model. These are the total range and corresponding endurance, the time it takes to travel to and from the sea floor, dubbed 'commute' times, and the remainder is defined as the mission time and mission range.

The following statements should hold up;

1. The same shape and size robot should have a shorter total range when the velocity is increased;
2. When the water depth is decreased, the same robot design should have a greater mission range.

The results are evaluated for a Subsea Robot with a length of 2m and a diameter of 0.2m. At a speed of $2m/s$, the total range is $131km$, while at a speed of $4m/s$, the range decrease to $48km$, because the resistance is much greater at higher speeds. The scenario with a cruise velocity of $2m/s$ gives a mission range of $122km$ for a water depth of $4500m$ and a dive angle of $10°$. Decreasing the water depth to $2000m$ yields a mission range of approximately $4km$ more, which is in accordance with the hypothesis.

In conclusion, the Subsea Robot model has been described in detail and validated in four stages.

7.2. Operations model

Unlike the Subsea Robot model, the Operations model is a simulation of the processes executed by the Handling System. The purpose is to gain insight in the way these processes interact and affect the overall system performance. The most important input parameters are the duration of the different processes.

The model can be classified as a discrete event simulator, and is implemented using the salabim package [61]. This package was chosen over alternatives due to its familiarity to the author from previous experience in addition to the ease of animating the live processes.

The first subsection provides a description of both the overall model and its respective components. A number of steps are taken to validate the model in the second subsection.

7.2.1. Description

The purpose of the operations model is to determine the overall time it takes to map a certain area, for a given subsea robot design. Other outputs include the energy used by the system, the amount of data gathered and the number of robots used. All inputs and outputs are summarized in Table 7.2.

Inputs	Outputs
Subsea robot design • length • diameter • velocity • range • mission time • battery capacity	Time (from start to last robot recovered and charged)
Handling system design • t_storage • t_predive • t_postdive • t_charge • t_recovery • t_launch	Overall cost
General parameters • total_opex • mapping_area • mapping_data_rate	Data collected
	Energy used

Table 7.2: The inputs to the Operational Model.

The Handling System parameters are summarized in Table 7.3.

Input	Symbol	Value	Units
Storage removal duration	t_storage	120	s
Charging duration	t_charge	3600	s
Predive inspection duration	t_predive	180	s
Postdive inspection duration	t_postdive	300	s
Launch duration	t_launch	300	s
Recovery duration	t_recovery	600	s
Queue capacity	q_capacity	2	-

Table 7.3: These parameters are based on estimates of what could be achieved with the Handling System in Chapter 6

The general design parameters are summarized in Table 7.4.

Input	Symbol	Units
OPEX of ship and system	OPEX_total	$\$/d$
Area to be mapped	A_map	m^2
Rate of data acquisition per robot	R_data	GB/s

Table 7.4: Possible input values, which depend on the scenario at hand.

The handling system and environment are modeled as depicted in Figure 7.4

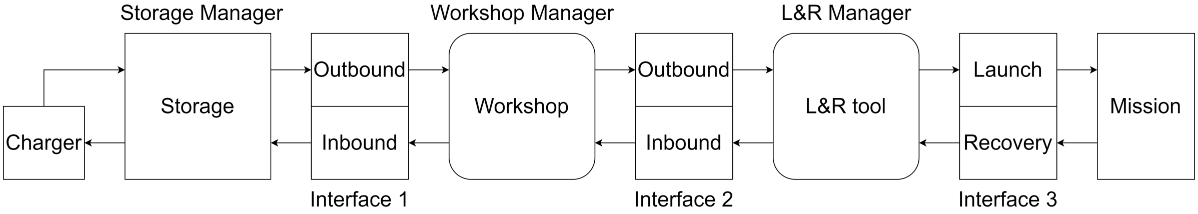


Figure 7.4: The interfaces described in the diagram have a buffer capacity of two robots.

The simulation starts with a number of robots in the Storage. The Storage Manager then starts placing robots to the Outbound Queue of interface 1. The Workshop Manager then waits for the duration of the predive inspection and transfers the robot from Interface 1 to Interface 2 Outbound Queue. The L&R Manager waits for the duration of the launch and then activates the Mission process of the robot. The robot places itself in the Mission Queue, waits for the duration of the mission, and then places itself in the Recovery Queue. The whole process is executed in reverse, by the L&R Manager and Workshop Manager respectively. Instead of transferring the robots to the Storage Queue directly, the Storage Manager first places them in the Charger Queue and creates a Charger Object. The Charger waits for the duration of the charging and then transfers the robot to the Storage Queue and deletes itself.

Appendix **??** contains a detailed description of the models underlying the components discussed.

7.2.2. Validation

The operations model is validated in two steps. First, the functioning of the individual components, like the StorageManager and the WorkshopManager, are evaluated using the 'animate' feature embedded in the salabim package. This provides enough insight to judge whether the components have been implemented correctly. The second step is to try to 'force' the system in different operational modes, defined in Chapter 3, by varying the input parameters. The resulting modes should correspond with the changes in input parameters.

The Subsea Robot parameters that are used in this subsection are

$$L_{robot} = 2m \tag{7.14}$$
$$D_{robot} = 0.2m \tag{7.15}$$
$$v_{robot} = 3m/s \tag{7.16}$$
$$d = 2000m \tag{7.17}$$
$$A_{map} = 3km^2 \tag{7.18}$$

Figure 7.5 was taken at $t \approx 9000s$. From $t = 0$, the StorageManager starts removing Subsea Robots from the Storage Queue and starts placing them in the outbound queue of Interface 1, or the Storage Queue outbound. After a short time, these are transferred by the WorkshopManager to the Launch queue. The LRManager then removes them from the launch queue, and after a delay of half the commute time the Robots enter the mission queue. This process persists until all Subsea Robots are removed from the Handling System, characterizing Mode 1.

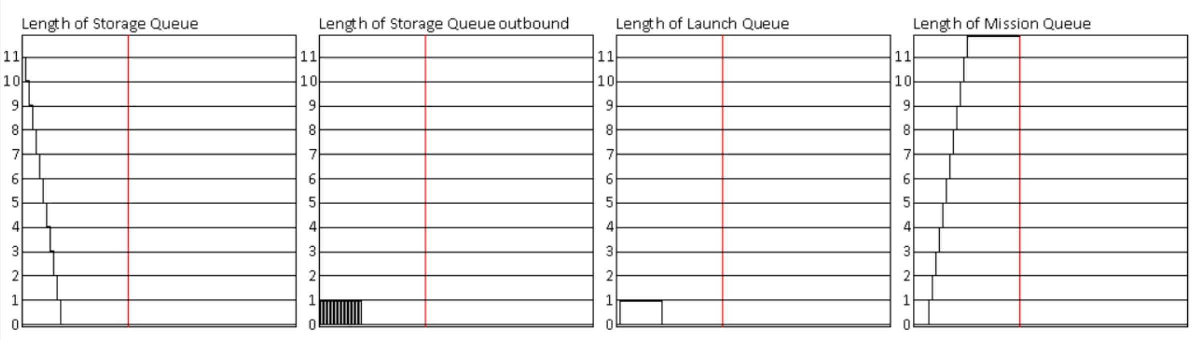


Figure 7.5: This figure was made using the in-built animation functionality of the salabim package [61].

Figure 7.6 was taken at $t \approx 38000s$. First, Robots start exiting the Mission Queue, and after half a commute duration enter the Recovery Queue. Note that this queue does not have a capacity limit, as its physical form is just the ocean surface at the back of the ship. The time between launching is shorter than the time between recoveries, and thus the Robots tend to pile up after their mission. The LRManager places the Robots in the Workshop Queue Inbound, and after a short duration they are transferred back to Storage, where they are placed in the Charger Queue. After the charging is done, they are admitted to the Storage Queue again and the simulation ends.

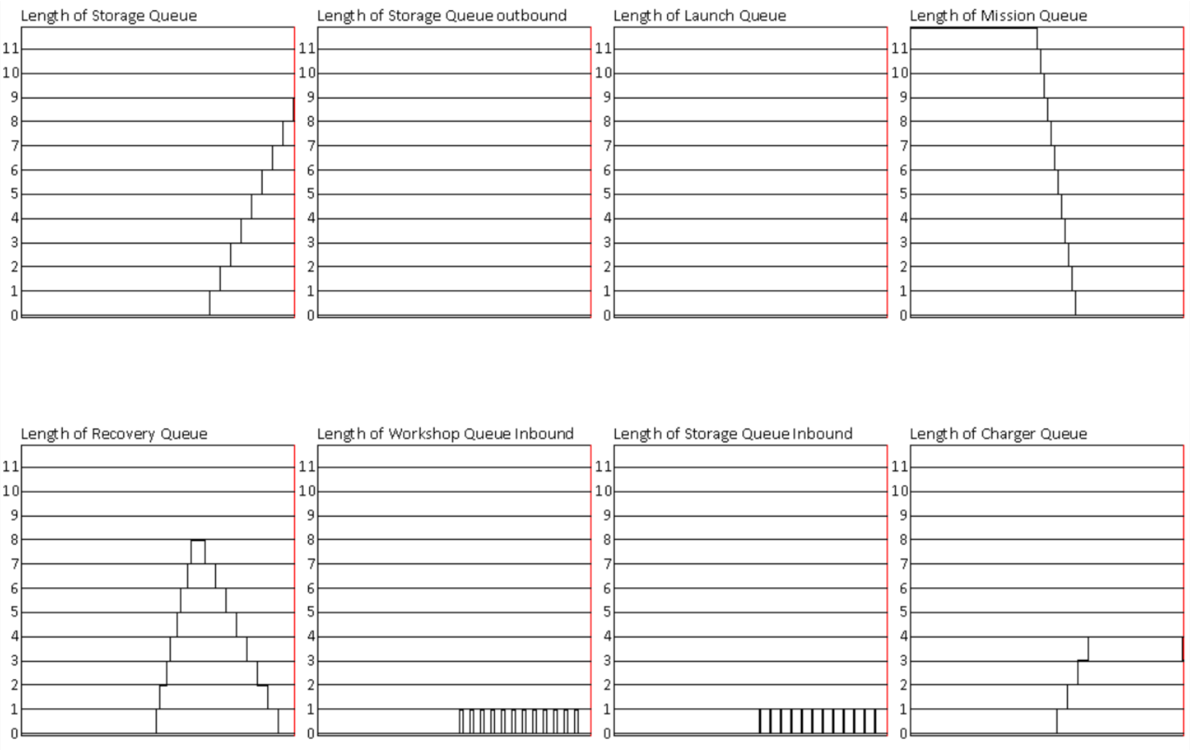
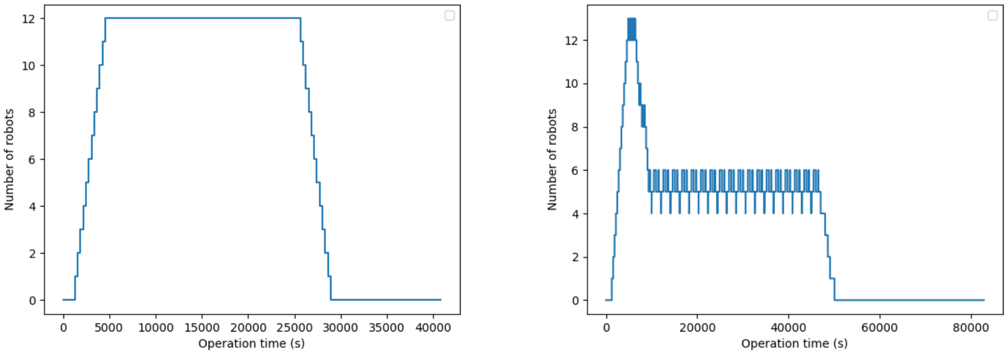


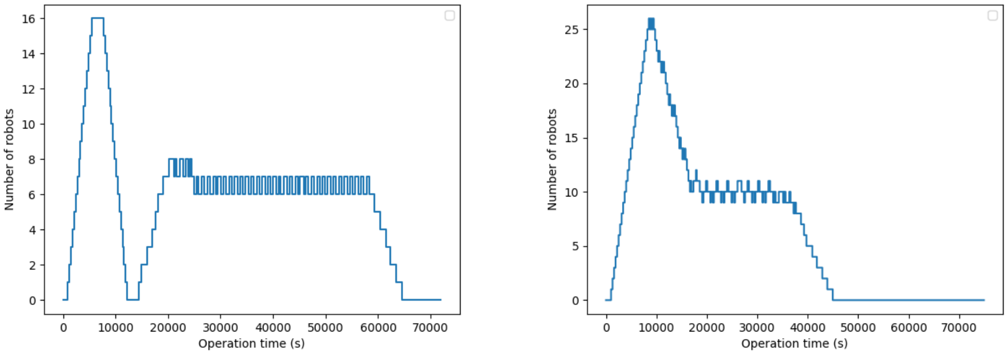
Figure 7.6: This figure was made using the in-built animation functionality of the salabim package [61].

Figure 7.7 shows four examples illustrating the different operational modes. Mode 1 is a simple ’one batch launch, one batch recovery’. Mode 2 is similar, only the recovery of the robots that were deployed first already starts before the last robots are launched, resulting in a slightly more complex behavior. Mode 3 is a scenario where the area is larger than can be covered by the total number of robots in a single deployment. The scenario starts out like in Mode 1, but the speed of the second launch phase is bottlenecked by the recovery process, and thus later deployments show behavior similar to Mode 2. In Mode 4, this simultaneous launch and recovery, that occurred in Mode 2 and the second part of Mode 3, exists already in the first round of launch.



(a) Mode 1

(b) Mode 2, by reducing length by 25%



(c) Mode 3, obtained by increasing the area and increasing the size of the robots

(d) Mode 4, obtained by increasing the area and decreasing the range of the robots

Figure 7.7: Examples of the different operational modes of the system and the parameter changes to obtain these results.

Table 7.5 lists the parameters with which these results were obtained.

	Subfigure 7.7a (Mode 1)	**Subfigure 7.7b** (Mode 2)	**Subfigure 7.7c** (Mode 3)	**Subfigure 7.7d** (Mode 4)
Velocity $[m/s]$	3	3	6	5
Length $[m]$	2	1.5	2.6	2
Diameter $[m]$	0.2	0.2	0.5	0.3
Area $[km^2]$	3	3	9	9
P1	83	14	24	27
P2	12	76	60	65
n	12	76	16	42

Table 7.5: With the input parameters, the range and speed of the robot can be controlled, leading to recognizable changes in system modes.

The values of P_1 and P_2 correspond what mode would be expected based on their definition from Chapter 3, concluding the validation of the operations model.

7.3. Integrated model

The integrated model connects the outputs of the Subsea Robot model to the Operations model, with some additional functionality in between.

Figure 7.8 shows the entire model. The process starts with a number of input parameters, including the Subsea Robot design specifics, the Handling System design specifics, the Scenario parameters and finally some additional experiment parameters. Then the processes contained in the slotted box in Figure 7.8 are executed for varying values for the length, diameter and velocity of the Subsea Robots. The start and end conditions, as well as the resolution of these parameter sets are set in the experiment parameters.

After every run, the total cost of the system with these specific parameters is evaluated and compared to previous runs. If it is lower than any of the previous runs, the results are added to a list of the best designs. The final entry of this list is the best possible design for the provided input parameters.

After the models have been run for all parameter variations, the results are prepared for further use and can be plotted.

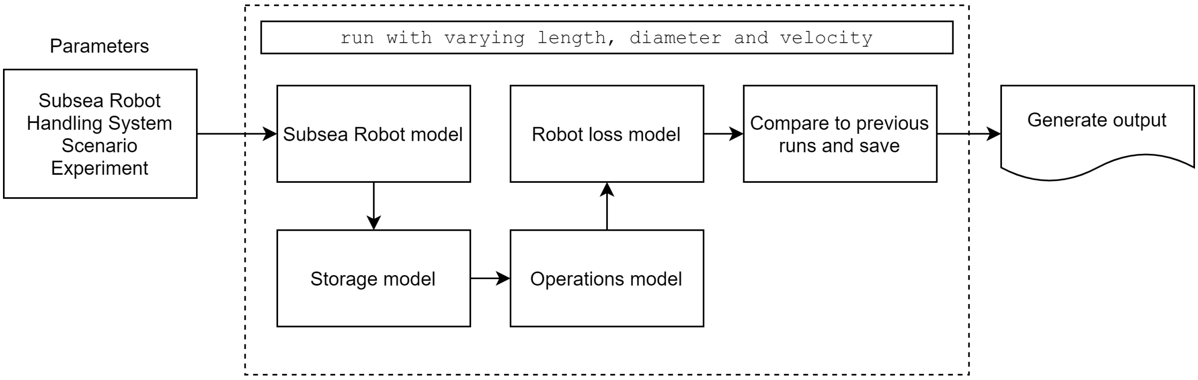


Figure 7.8: The total model overview. A large part of the processing is done in the Operations Model.

Storage model The number of robots that can be used for a scenario is limited by the available storage space in the Handling System. The Handling System design of Chapter 6 assumes that one 20’ shipping container is available for the storage of the Subsea Robots.

The Storage model first determines the storage capacity for the given diameter and length of the Subsea Robots. The Subsea Robots are stacked horizontally in rows. The number of rows is determined using the width of the container, of the walkway and the diameter of the robots.

The number of deployments that are required are determined as well, by dividing the area to be mapped in the Scenario by the area that can be mapped per Subsea Robot deployment. If the number of deployments that is required is smaller or equal to the storage capacity for Subsea Robots, that number of Subsea Robots will be assumed present in the system. If more deployments are required than there is storage capacity, the maximum storage capacity is used as the number of robots in the system.

Robot loss model To penalize bringing as many Subsea Robots as possible, a simple ’robot loss model’ is introduced. It assumes a uniform chance for a Subsea Robot to be lost every deployment. This results in additional costs depending on the number of deployments. This penalty is added to the total mapping cost of the Scenario (which was based solely on ship time costs before now).

$$p_{penalty} = \text{deployments\_required} \cdot c_{loss} \cdot C_{robot} \tag{7.19}$$

7.4. Validation

To build confidence in the validity of the results from the integrated model, a number of experiments is run and their results discussed. A range of input parameters for the Subsea Robot size is taken, indicated in Table 7.6

	Minimum	**Maximum**
Length $[m]$	1	Length of the container
Diameter $[m]$	0.1	0.5
Velocity $[m/s]$	1	7
Ship OPEX $[\$/day]$	-	22.000

Table 7.6: Some of the input values to the integrated model.

The simulations are run with 15 values for each parameter. The results of each run are provided for the set of robot design parameters which resulted in the best performance (lowest specific mapping cost).

One square kilometer

The area to be mapped is initially set at $10^6 m^2$, or one square kilometer, with a water depth of 4500m. The results are listed in Table 7.7.

Output	**Result**
Cost	$4,814\$$
Length	$3.1m$
Diameter	$0.24m$
Velocity	$7.0m/s$
Specific cost	$0.00481\$/m^2$
Mapping time	$17532.62s$
Mapping rate	$57.04m^2/s$
Number of robots	7
Simulation time	$19.98s$

Table 7.7: The results for the scenario of mapping $1km^2$.

It is expected that, given the maximum length and diameter, there should be Subsea Robot designs such that operation in Mode 1 or Mode 2 can be done. Indeed, Figure 7.9 confirms this.

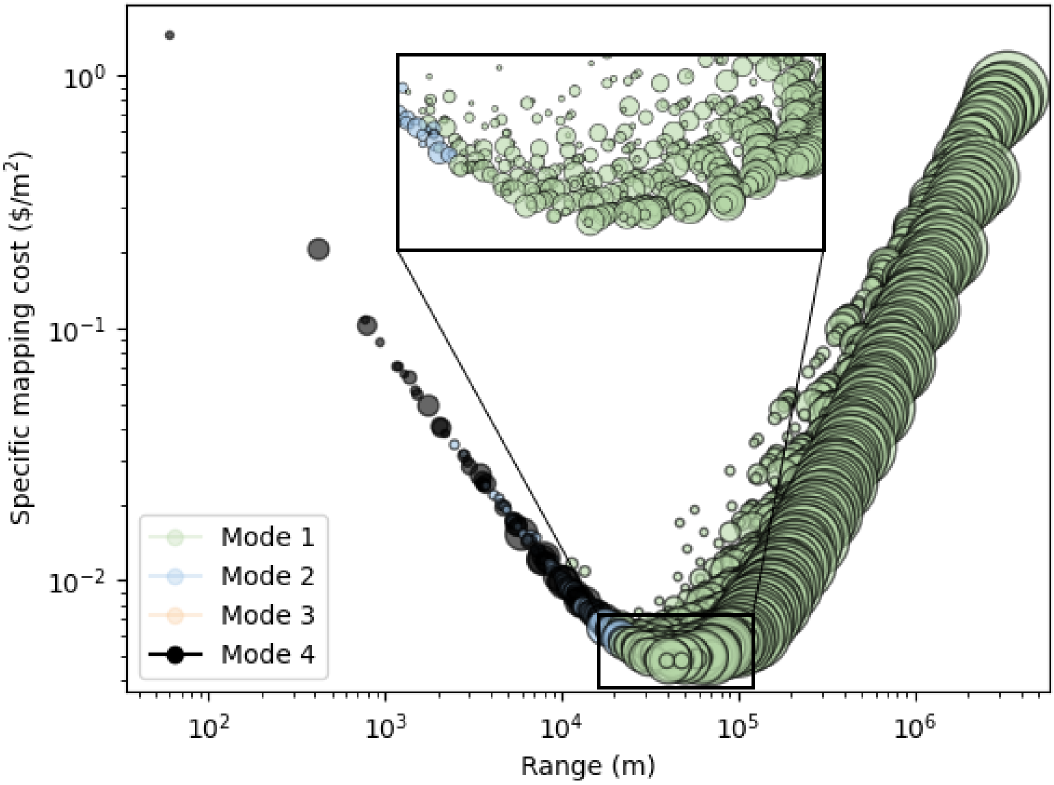


Figure 7.9: A graph showing the results of the experiment. The size of the points corresponds to the size of the robots.

The higher-range Subsea Robots have a lower velocity associated with them, or are larger such that less can be brought on the ship. For this small area they all result in Mode 1 operations. The lower-range Subsea Robots are faster or smaller and as such result in Mode 2 operations.

The best performing Subsea Robot designs vary widely in size, velocity and number, resulting in a number of designs that have similar performance but very different designs. This leaves some freedom to the designer to make tradeoffs, for example to have a mapping system with fewer Subsea Robots in it to lower the initial investment costs, or to add complimentary activities.

Ten square kilometers

Next, all parameters are kept the same but the mapping area is increased by a factor of 10, from one to ten square kilometers. The results are tabulated in Table 7.8.

Output	**Result**
Cost	$13,917\$$
Length	$4.50m$
Diameter	$0.3m$
Velocity	$5.29m/s$
Specific cost	$0.00139\$/m^2$
Mapping time	$50,533.43s$
Mapping rate	$197.83m^2/s$
Number of robots	21
Simulation time	$76.37s$

Table 7.8: The results for the scenario of mapping $10km^2$.

This time, a slightly larger Subsea Robot design with a lower speed yielded the lowest specific mapping cost, which is almost 4 times lower than the previous scenario. Interestingly, the total mapping cost almost tripled, a decline in growth compared to the last scenario. More Subsea Robots were required to achieve this result however. The performance of the generated Subsea Robot designs can be seen in Figure 7.10.

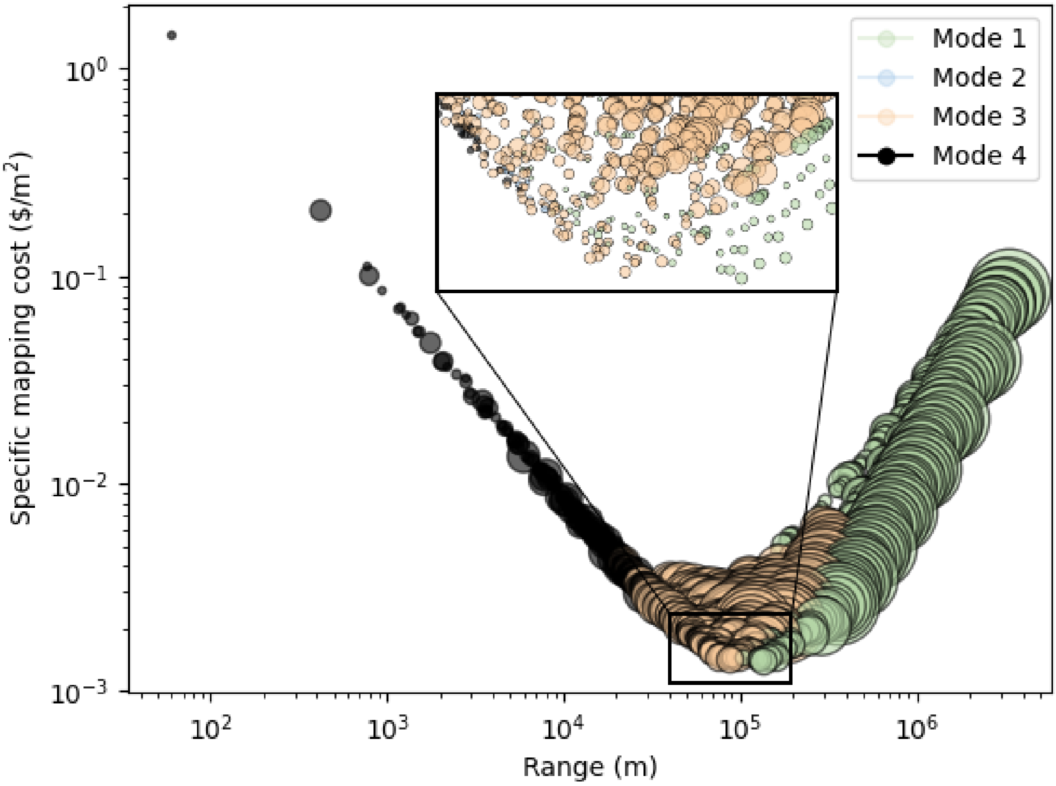


Figure 7.10: A graph showing the results of the experiment. The size of the points corresponds to the size of the robots.

This time, Mode 3 and Mode 4 also occur frequently. In this scenario, there are Subsea Robot designs with which the operation cannot be completed in one batch, either because there are not enough robots or the robots have insufficient range. It seems that the larger Subsea Robots are generally worse than the smaller ones, as can be seen in Figure 7.10 by paying close attention to the relative sizes of the symbols. Mode 3 only occurs for larger Subsea Robots. This time, the best results are achieved in Mode 1 operations, although Mode 3 competes closely for the lowest specific mapping cost.

Hundred square kilometers

Again, all parameters are kept the same and the mapping area is increased by a factor 10, from ten to hundred square kilometers. The results are tabulated in Table 7.9.

Output	**Result**
Cost	$63,518\$$
Length	$2.75m$
Diameter	$0.21m$
Velocity	$2.71m/s$
Specific cost	$0.00064\$/m^2$
Mapping time	$221,570s$
Mapping rate	$451.32m^2/s$
Number of robots	80
Simulation time	$717.47s$

Table 7.9: The results for the scenario of mapping $100km^2$.

The mapping cost has increased by a factor slightly less than 4, like the previous scenario. This time, a slightly smaller Subsea Robot at a lower speed resulted in the best specific mapping cost. The decrease in size might be explained by a corresponding greater possible number of robots in the system, and thus greater mapping speed. The specific mapping cost has again decreased by slightly less than a factor three. A large number of Subsea Robots is required to achieve the lowest mapping cost in this scenario.

It may be expected that Mode 1 or Mode 2 operation are less common now because the area has increased while the Subsea Robot size still has the same limits as before.

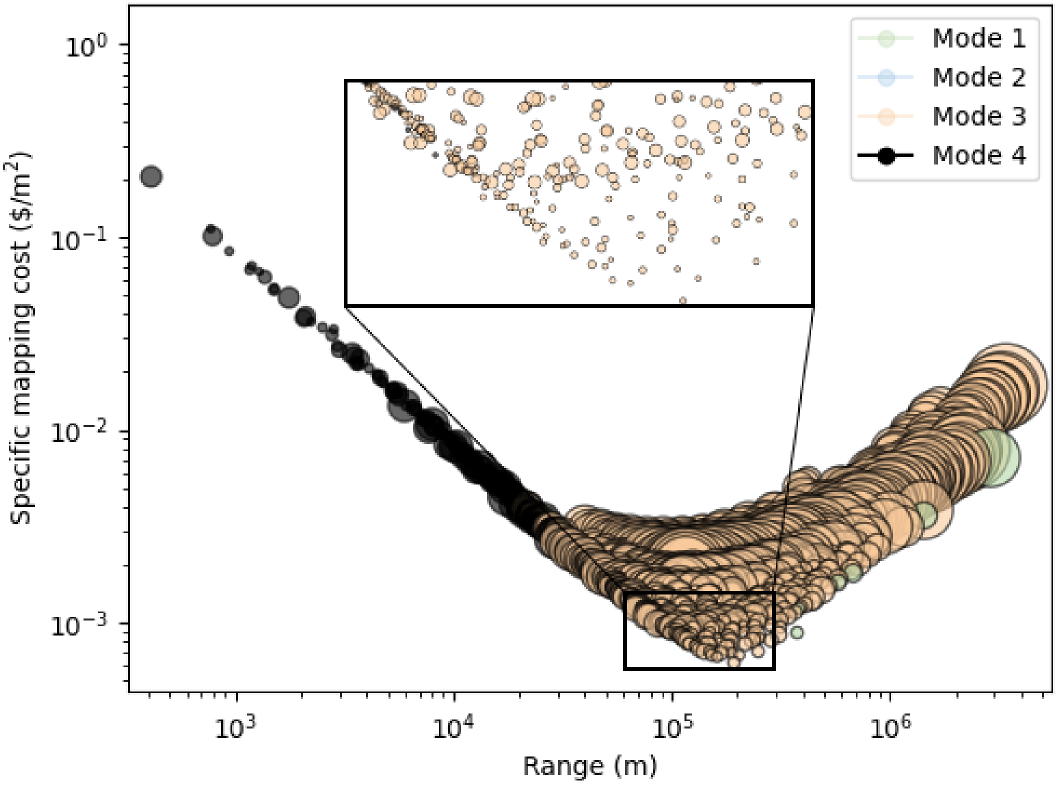


Figure 7.11: A graph showing the results of the experiment. The size of the points corresponds to the size of the robots.

Indeed, the smaller, faster Subsea Robot designs result in the lowest specific mapping cost, even though the operations cannot be done in a single deployment batch anymore. There are almost no Mode 1 designs near the bottom anymore, especially compared to the first scenario of mapping one square kilometer. The prevalence of Mode 4 has increased but it does not seem optimal compared to Mode 3.

Thousand square kilometers

Finally, a scenario with an area of thousand square kilometers or $10^9 m^2$ is explored. Like before, all other parameters were kept the same. Table

Output	**Result**
Cost	$465,261\$$
Length	$2.75m$
Diameter	$0.21m$
Velocity	$2.71m/s$
Specific cost	$0.00047\$/m^2$
Mapping time	$1,549,550s$
Mapping rate	$645.35m^2/s$
Number of robots	80
Simulation time	$63,867s$

Table 7.10: The results for the scenario of mapping $1000km^2$.

Unlike the previous two scenarios, the mapping cost increases with about a factor of 7, and the specific mapping costs decreases by less than a factor 2. The Subsea Robot design is slightly smaller, to allow for a greater number in the system. The simulation time also increased significantly.

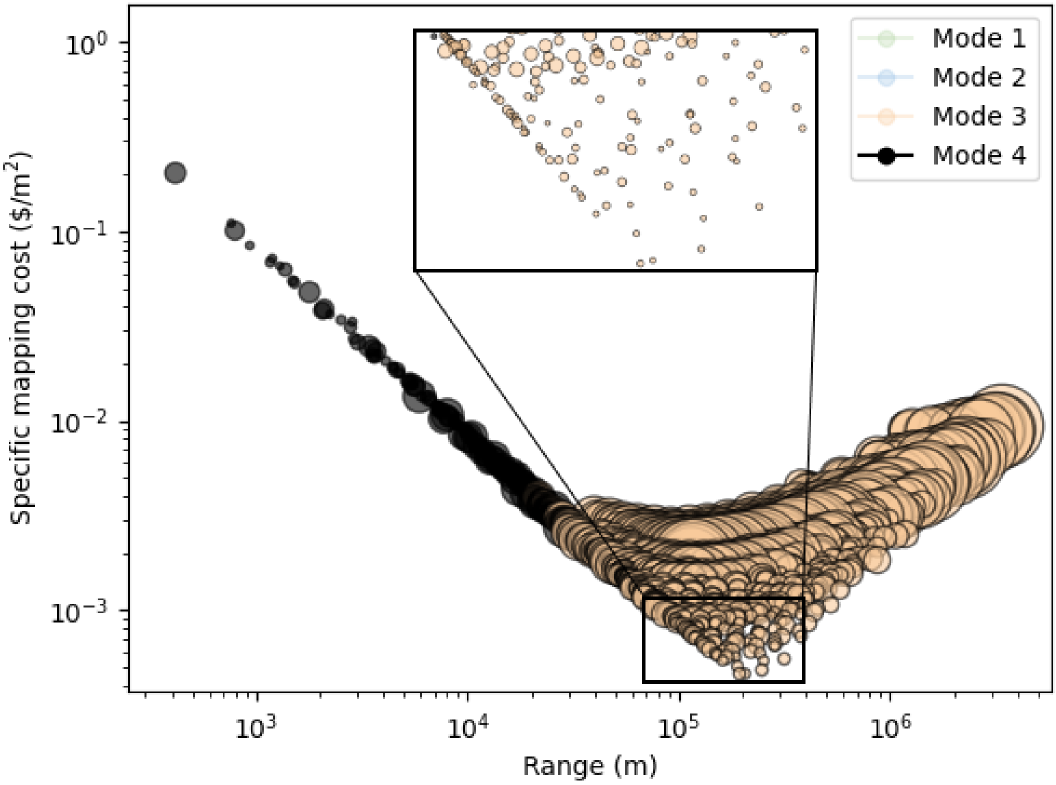


Figure 7.12: A graph showing the results of the experiment. The size of the points corresponds to the size of the robots.

Figure 7.12 shows the results of this scenario. There are no more Subsea Robot designs which result in Mode 1 or Mode 2 operation. Instead, Mode 3 results from relatively larger Subsea Robots which operate at a lower cruise velocity, resulting in a greater range. The top performing designs all operate in Mode 3, sacrificing size for numbers.

In conclusion, the integrated model has been tested for mapping areas ranging five orders of magnitude. The specific mapping costs decrease with increase in area, but at a diminishing rate. At some point, the storage capacity limit of Subsea Robots on the ship is reached. From the simulations, it appears that Mode 1 yields the lowest specific mapping cost up to around a mapping area of $10km^2$. After that, Mode 3 solutions dominate.

7.5. Conclusion

At the beginning of this chapter, the question *”How can the performance be modeled and validated at an early stage?”* is posed.

A parametric model of the Subsea Robot was developed to determine the range and endurance for a specific combination of robot length, diameter and velocity. The validity of this method is substantiated in several stages, each building on the previous stage. A discrete event simulation is developed to

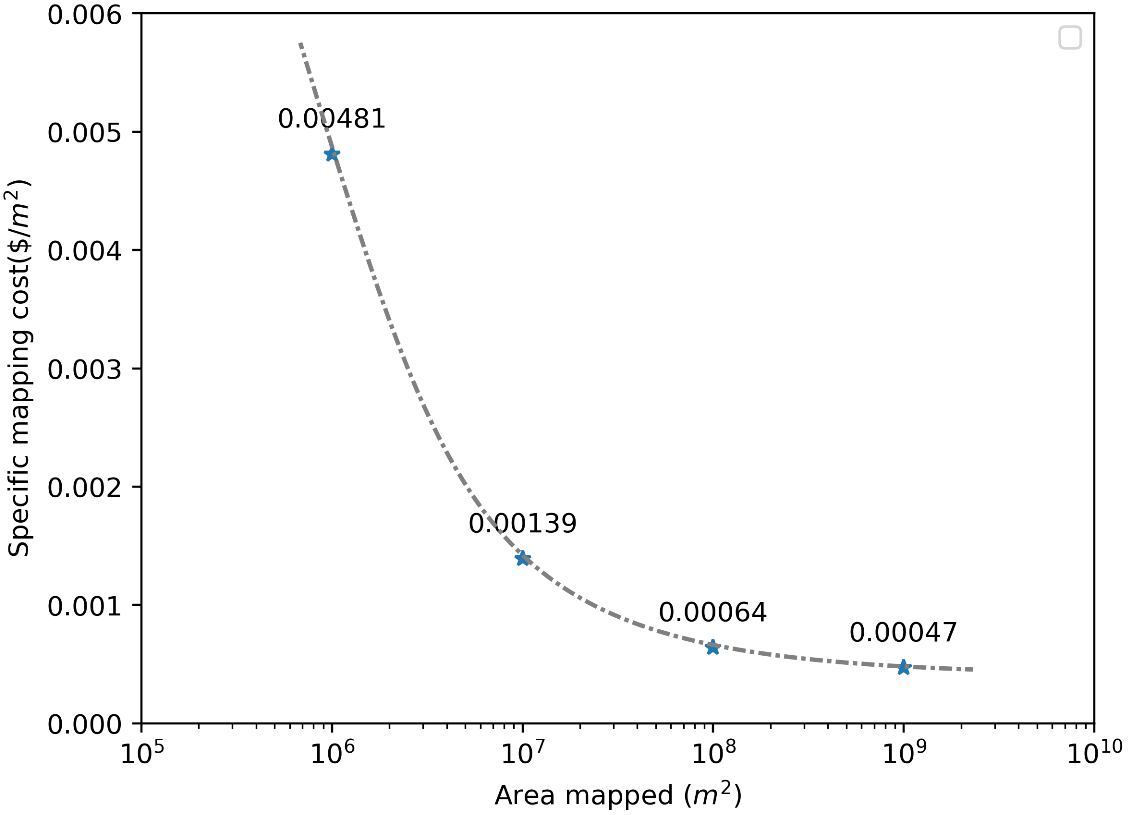


Figure 7.13: The specific mapping costs for the different orders of magnitude areas. The dotted line is an interpolation.

simulate the Handling System, in which the different components execute the outbound and inbound processes, such as launching and charging. This allows for the modeling of the behavior of the logistics of the mapping system, while leaving any Subsea Robot interaction or path planning open for later specification.

The output of the Subsea Robot model is used in the simulation of the Handling System to determine the performance of the seafloor imaging system. This is done for every variation of the length, diameter and velocity of the Subsea Robot design. The best performing design is selected and can be categorized in operational modes. Finally, scenarios with different orders of magnitude of the to be mapped area are evaluated using the integrated model. Mode 2 and Mode 4 appear suboptimal when it comes to the specific mapping cost, while designs resulting in Mode 1 operations perform best up to $10km^2$. For greater areas of seabed, Mode 3 operations result in the lowest specific mapping cost.

With the input parameters and design assumptions in this thesis so far, the lowest specific mapping cost is indicated per area order of magnitude in Figure 7.13.

The main driver in reducing the specific mapping cost shifts from faster Subsea Robots to greater storage capacity of Subsea Robots on the ship when the seabed area to be imaged is increased. For smaller areas, the (constant) turnaround time of the Handling System is significant; thus it is more efficient to have less Subsea Robots in the system that are faster individually. A faster Subsea Robot requires more power, thus a larger battery. A robot with a larger battery takes up more space in storage. So the storage capacity limit is reached but with fewer robots. For scenarios in which larger areas are to be photographed, the Handling System turnaround is less significant. Having Subsea Robots with a moderate speed, greater range and a smaller footprint in the storage system leads to the greatest mapping rate, and thus the lowest specific mapping cost.

In conclusion, the mapping system design with the lowest possible specific mapping cost depends on the area of seabed to be photographed. The size of the Subsea Robots and their optimal cruise velocity differs significantly between scenarios.

8

Case study

To fully answer the main research question, it is not sufficient to outline only the technical feasibility and the model the performance of the system. In this chapter, the performance of the system is applied to a real world application; the photographic mapping of the seafloor of a possible future deep sea mining site. The following question is posed:

> *How does the multi-robot system perform compared to a state of the art single-robot system in a real world scenario?*

8.1. Context

Somewhere between Mexico and Hawaii[1] lie abyssal plains, scattered with polymetallic nodules, at about 4500m below the ocean surface. These plains are relatively flat and made up of said nodules positioned on a very fine sediment, which, when disturbed, immediately clouds the surrounding area and can take days or even weeks to settle down completely [70].

The polymetallic nodules will likely be collected with a device comparable to a huge vacuum cleaner. Nodules and sediment are sucked into the machine at the front. Most of the sediment is discarded directly behind the vehicle, while the nodules are sent through a riser to the mining vessel for further processing [8].

The sediment plume could be a threat not only to the ecosystem in the immediate surrounding, but can be spread to a much greater area by the current. Most lifeforms at this depth are filter feeders, whose guts will be congested by the suddenly dense concentration of nutrition-less material in the water, leading to their starvation [70]. It is feared that this will lead to a massive loss of biodiversity.

With concrete data about the biodiversity and biomass per species, this concern can be validated and inform international regulations surrounding this upcoming mining industry. The area considered is called the Clarion-Clipperton Zone, after the two respective fracture zones bordering the north- and south of the territory. It spans approximately $4.5 \cdot 10^6 km^2$ or 4.5 trillion square meters, with an average depth of about 4500m [76]. For this case study, it is assumed that 1% of the seafloor of the Clarion-Clipperton Zone needs to be photographed (assumed that this is not one area, but multiple that make up 1% in total). This results in an area of $4.5 \cdot 10^4 km^2$ or $4.5 \cdot 10^{10} m^2$, approximately the area of the Netherlands.

The water clarity is mostly good, allowing for clear photographs from a distance between 5m to 10m

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[1] Refer to Figure 1.2 in the introduction of this thesis.

[70]. The ship used in this example is the RV Pelagia, the flagship of the Dutch research fleet. This ship has been used before for deep sea exploration [51]. It is approximately 66m long, has a beam of 13m and a draft of 4.2m. The operating costs are approximately $\$22.000$ per day[2]. The aft deck has space for three 20' shipping containers.

8.2. Results

Two studies are conducted; one with the multi-robot system, in which the Subsea Robot design is optimized for the lowest specific mapping cost, and one with a commercially available AUV, in this case the Hugin 6000 AUV, using only a single robot.

Multi-robot system scenario To minimize the computation time, an iterative approach was taken to the limits of the input parameters; starting from the input parameters that led to the $1000km^2$ result in Chapter 7 and a coarse step size, refining the step size and input bounds after each iteration.

State of the art system scenario The minimum values for the handling times from 2.2 are used. Furthermore, the simulation is changed such that only a single robot is used from the ship. The other parameters are listed in Table 8.1.

	Multi-robot		**Single-robot**
Input	**Min.**	**Max.**	
Length $[m]$	2.5	3.5	6.2
Diameter $[m]$	0.18	0.5	0.875
Velocity $[m/s]$	2.5	3.5	2.06
Ship OPEX $[\$/day]$	-	22000	22000
Swath $[m]$	-	7.5	7.5
Output			
Cost $[\$]$	17,720,000		1,323,144,000
Length $[m]$	2.88		”
Diameter $[m]$	0.24		”
Velocity $[m/s]$	3.25		”
Specific cost $[\$/m^2]$	0.00394		0.0294
Mapping time $[years]$	1.88		201
Mapping rate $[m^2/s]$	761		9.4
Number of robots $[-]$	54		1
Simulation time $[s]$	2622		8.38

Table 8.1: The inputs and results of the simulation for both the multi-robot and single-robot (state of the art) scenarios.

There is a significant difference in the performance between the two scenarios. With 54 robots that cruise at a higher speed, the mapping speed is about 80 times higher, leading to a similar cost benefit. The time it takes to map 1% of the CCZ in case of the state of the art scenario is over 200 years.

8.3. Discussion

The multi-robot system approach which was designed in this thesis results in a total mapping cost of $\$18mln$ and takes about 1.9 ship-years. If multiple seafloor imaging systems are developed, with

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[2] The back-of-the-envelope calculation in Chapter 1 assumed the use of a larger ship, at $\$100k$ per day. The author believes however that it could also be possible with this smaller ship, which would save a lot of costs.

each 54 robots, these ship-years can be divided between multiple ships to decrease the duration of the mapping project. Both the time-frame as well as the operational cost are feasible compared to the overall budget and duration to start off commercial deep sea mining [42]. This does not take into account the investment cost of the multi-robot system, which would be in the same order of magnitude as what is currently considered the state of the art. However, there is considerable development needed to get to an operationally validated system, which would add to both the investment cost and the lead time.

The state of the art estimate, using a single robot to map 1% of the CCZ, results in a total mapping cost of $\$1.3bln$ (10^9), which is about 32% of the total investment require to kick off deep sea mining as an industry [42]. It would take 201 ship-years to execute. In an industry that is projected to start commercial mining in 2027, this is not an acceptable result. More ships can be deployed, increasing the initial investment cost, and against the same operational costs, the duration of the mapping can be reduced, but the significant operational cost alone remains a insurmountable barrier. Even if the approach currently taken by Ocean Infinity, a company that is able to use up to 6 Hugin 6000's simultaneously from the same mothership, the initial investment cost would increase significantly and the total operational cost would only decrease by about 23%, as the mothership that Ocean Infinity uses is 5 times more expensive to operate [9].

The input parameters for the state of the art study were all retrieved from credible sources. The most significant uncertainty lies in the estimate of the range of the Hugin 6000 when only the camera system is used. In the single-robot system, the main performance indicator is the ratio between the handling time and the mission endurance of the robot; this ratio determines the period that there is actually being mapped. Any deviation in the estimate of the mission range or endurance translates with this ratio to the total mapping time; for example, if the range is actually 10% better than what was estimated, and the handling/mission ratio is 1:10, the total mapping time is approximately 1% less than predicted.

Furthermore, it is likely that the processing times and imaging capabilities of the current state of the art can be improved, considering the significance of the investment that would be done in seafloor imaging systems. However, the time and resources spent could also be dedicated to further developing and improving the multi-robot approach, which is fundamentally more scalable.

8.4. Conclusion

A case study was executed where the multi-robot system design developed in this thesis was compared to a representation of the state of the art, a single Hugin 6000 AUV deployed from the same ship, in the scenario of mapping 1% of the Clarion Clipperton Zone, the most promising region for large-scale seabed mining.

The best design with the multi-robot system approach results in a total mapping cost of $\$18mln$, taking 1.9 ship-years to complete using 54 robots. The single-robot approach results in a total mapping cost of $\$1.3bln$ (10^9) and takes 200 ship-years.

This comparison both highlights how infeasible the current state of the art is for seafloor imaging on such a large scale, and how much can be gained by using a multi-robot approach, even if the individual robots are significantly less performant.

9

Conclusions

Deep sea robots are expensive and laborious to operate, and due to the limited autonomy that these robots have in operation, only one robot can be deployed at the time. As a result, it takes a lot of time (years) to map a stretch of sea floor, and thus a lot of money. If more robots could be deployed simultaneously, seafloor mapping could be faster and thus more cost-effective. This thesis investigates the main research question;

> *To what extent can seafloor imaging be made technically feasible and cost-effective at large scale by shifting from single-robot to multi-robot operations?*

Seven research questions were defined, leading to: the identification of barriers that need to be overcome (Question 1), a suitable system architecture (Question 2), concept designs for the localization, robot and handling that overcome said barriers (Question 3, 4 and 5), a parametric model of the robot design, combined with a model of the handling logistics (Question 6), and finally a case study to indicate the performance of a multi-robot system (Question 7). Figure 9.1 summarizes this in an overview.

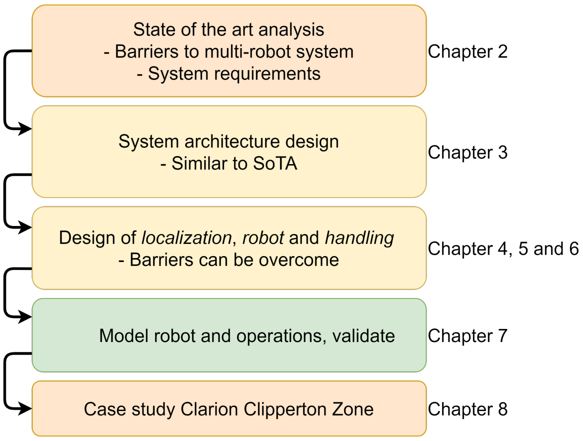

Figure 9.1: A schematic summary of the report.

The questions and their conclusions are as follows:

Chapter 2 *How is seafloor imaging currently done and what are the main barriers to using multiple robots simultaneously?*
The state of the art seafloor mapping systems use a single, high performance, untethered robot.

This 1000kg+ device typically costs over $\$5mln$. The pictures it takes are related referenced to a global coordinate system through an acoustic localization system. Three significant barriers to using multiple robots were identified:

- High cost: $\$5mln$ is a significant investment, let alone a multiple of this number
- Handling time: its size and complexity result in multi-hour launch & recovery operations
- Localization: the current technology is limited to localizing only a few robots at the time

If these three barriers can be eliminated, no significant challenges stand in the way of using a multi-robot system to increase the overall mapping speed and thus lower the cost per area mapped. Some global requirements and design objectives, which correspond to the barriers, were defined:

R1 provide footage of the sea floor of a resolution of at least 1 pixel/cm
R2 provide position of images with an accuracy of 0.5m or better
R3 operate up to a depth of 6000m
R4 deliver the data to the ship

O1 reduce capital cost of AUVs to below $C_{AUV} < \$100k$
O2 localize 100 robots simultaneously
O3 reduce handling time $HT < 11.75h$

Chapter 3 *What system architecture can support multiple robots?*
A number of design choices concerning the system architecture can already be derived by using knowledge about the offshore environment. Five subsystems were defined:

1 *Camera System* provides illumination and takes pictures of the seafloor
2 *Subsea Robot* transports the Camera System to the right location, temporarily stores images, and facilitates the geo-referencing of the captured images
3 *Handling System* launches and recovers Subsea Robots from the ship, charges their batteries and transfers images from the robots to the ship's data storage
4 *Localization System* provides an acoustic reference network to localize the robots underwater such that the images can be related to a position coordinate
5 *Governance System* manages the logistics of individual Subsea Robots and their interaction with the Handling System, provides an interface to the seafloor imaging system for the operators

This architecture does not differ significantly from the current state of the art on the surface. However, the subsystems are all more complex and so are their interactions. The designs and interactions of the Subsea Robot, Localization and Handling System are investigated in more detail in subsequent chapters.

Chapter 4 *What is a localization method that can support multiple Subsea Robots and meet the performance requirements, while impacting the system operations as little as possible?*
Underwater localization is challenging because of the unbounded position estimate error in the horizontal plane. To support multiple Subsea Robots, there are a number of design considerations:

- A conventional two-way localization scheme is not suitable due to the bandwidth limitations of the acoustic channel. This excludes most if not all of the commercially available localization options.
- A single-way (silent) scheme is suitable but requires an additional reference, such as a common time-base using synchronized clocks. The time- and frequency synchronization requirements complicate operations however.
- Another approach does not require a common time-base but instead uses relative travel times in a synthetic beacon network to come to a position estimate.

This last solution is selected because it satisfies the global system requirements (**R2** and **R3**) while keeping the subsea infrastructure limited. The estimated physical and power requirements are passed to the Subsea Robot design in Chapter 5.

The design of the localization method, including the hardware, signal processing and the position estimators requires a more in depth investigation in future work.

Chapter 5 *What is a cost-effective Subsea Robot design that enables photographic mapping of the deep sea floor?*

The Subsea Robot is a battery powered, autonomous underwater vehicle which carries the Camera System. Its design, compared to the current state of the art AUVs, is different in two ways to save cost:

- Pressure hulls and feedthroughs are avoided as much as possible, and pressure tolerant electronics are used to save weight, space and cost
- No capabilities other than those used for photographic mapping are realized in the design

The cost of individual robots is estimated to be around $\$100k$ in serial production, and as a result, the cost-barrier to a multi-robot seafloor imaging system is significantly reduced.

The Camera System could pose a velocity constraint on the cruise speed of the Subsea Robot. A brief analysis finds that this is likely not an active constraint. It is possible to include the design of the Camera System in the global optimization of the seafloor imaging system, however, only an outline of the model required is provided here.

No definite design of the Subsea Robot was realized, rather, the design relations were captured in simple equations to abstract the subsystems to size and power parameters. These relations are used in a parametric model to relate the size to the performance of the robot in Chapter 7.

Chapter 6 *How can multiple robots be deployed effectively?*

The Handling System launches and recovers the Subsea Robots, charges their batteries and transfers images from the robots to the ship's data storage. In single-robot systems this is mostly done manually, but this is not economical for a multi-robot system. A mostly automated, 'assembly line' style configuration of three stations was defined; the Storage, the Workshop and the Launch & Recovery Tool. The first two are designed to be housed in standard size shipping containers. The Subsea Robots move through this system in four process steps:

1 *Pre-launch operations* the Subsea Robot is moved from Storage to the Workshop, where system integrity and mission parameters are checked. It is then queued for the L&R Tool.
2 *Launch* the Subsea Robot is transported from the deck to the water surface, where it starts its mission and dives.
3 *Recovery* after the robot completes its mission, it is recovered by the L&R Tool and moved to the Workshop for post-mission system integrity checks.
4 *Storage* the Subsea Robot is moved back to Storage, where it is charged and the collected images and other data transferred to the ship's data storage.

These solutions result in a Handling System design that requires little crew, has a high throughput, and uses simple, commercially available technology while facilitating easy access to all systems for repairs, maintenance and upgrades. The Launch & Recovery Tool is the most complex component in this subsystem and its design and integration with the Subsea Robots requires further investigation.

Chapter 7 *How can the performance be modeled and validated at an early stage?*

The previous chapters found design solutions for the three critical subsystems in the seafloor imaging system; the Localization System, Subsea Robot and the Handling System. The result is a concept design with the promise that a much lower specific mapping cost can be achieved by deploying robots in parallel. This hypothesis is validated and specified by modeling the performance of the system with different Subsea Robot design realizations.

First, a parametric model was developed to relate the physical (design) properties of the Subsea Robot to its performance (endurance, range, etc). The resulting robot specifications are used in a simulation of the logistics of the Handling System. This integrated model determines the time it takes to map a specified area of seafloor, from which the total mapping cost and mapping cost per area is calculated. In other words, these two models combined provide a relation between the individual robot design parameters and the performance of the multi-robot system measured in time and cost per mapped area.

The Subsea Robot design parameters (size and velocity) are then varied, and the parameters which result in the lowest mapping cost for the scenario are used to determine what the optimal

Subsea Robot design is. The models are validated step by step individually. The integrated model is tested through analyzing the optimal performance of the multi-robot system in scenarios with increasing seafloor areas. The lowest specific mapping cost results from faster Subsea Robots for small areas, while for large areas, a greater number of slower Subsea Robots yields the lowest specific mapping cost. Overall, it was found that the specific mapping cost changes from $0.0048\frac{\$}{m^2}$ for $1km^2$ to ten times lower for an area of $1000km^2$, first rapidly, then slower.

Chapter 8 *How does the multi-robot system perform compared to a state of the art single-robot system in a real world scenario?*

A case study was done to investigate the costs of imaging 1% of the seafloor at the Clarion Clipperton Zone[1], drawing a comparison between the designed multi-robot system and the current state of the art.

At 70 times lower cost and 80 times faster, the multi-robot approach is much faster by using over 50 low-cost Subsea Robots, and unlike the state of the art option, economically feasible. The current state of the art is assumed here as a single, high performance Subsea Robot operated from a medium-sized ship. It would take 200 ship-years to map 1% of the CCZ with this approach. Even if the number of high performing, state of the art Subsea Robots is increased from 1 to 6, it would still take 33 ship-years. This case study shows the potential of using a multi-robot system for large-scale seafloor imaging, despite that those individual robots are significantly less performant due to their lower cost.

The answers to the seven research questions result in the final outcomes of this project;

- an overview of the different high-level tradeoffs
- a system architecture
- crucial subsystem concept designs
- an initial performance estimate for different scenarios
- a relevant case study

The concept design that is developed in this thesis promises an operating cost of two orders of magnitude less than what would be possible with the current state of the art, for a comparable investment cost, within a time frame that is relevant to the deep sea mining industry.

The performance of the design can be improved by applying more advanced techniques such as inter-robot communication and distributed localization. The approach to base the design off high TRL technologies results in a high-confidence initial concept design. Furthermore, the concept design outlined in this thesis already shows significant improvement over the state of the art.

In conclusion, there are no significant technological barriers to make large scale seafloor imaging economically feasible on a short term.

9.1. Recommendations

This research is intended as a high level design investigation to evaluate the technological and economical feasibility of a multi-robot seafloor imaging system. A number of aspects in the design were discussed only briefly and require more attention in future research:

- The Localization System has a limited range per surface-node, and every surface-node has to be launched and recovered. This affects what mapping strategies can be used in a specific scenario. It requires modeling the spatial distribution of the Subsea Robots as well as the performance & logistics of the Localization System, and is an important next step to form a more complete picture of the imaging system's performance characteristics.

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[1] An important area for deep sea mining, spanning 4.5 million square kilometers in the Pacific Ocean, between Hawaii and Mexico.

- The current model yields a large Pareto-set of robot designs. Visualizing the results along different axes or isolating parameters might help elude what Subsea Robot design might be preferred depending on desired versatility of the system or maturity of technology.
- Both the specifics of the Camera System and the Localization System require a deeper understanding of the respective fields' challenges to come to a more accurate performance estimate. The further exploration of these design spaces should be a priority when continuing this research.
- The recovery of the Subsea Robot to the ship remains a challenging topic, mainly due to the different, often unpredictable, forces affecting the motions of the ship, the surrounding water and the robots. Surface and sub-surface docking are both active topics of research, which, with the introduction of better state estimation and control algorithms, will continue to improve.
- The optimization of the design parameters of the seafloor imaging system could be expanded to not only include the basic parameters of the Subsea Robot, but also the Camera System's properties, the Handling System's process elements and the Localization System's performance. The choice of the optimization process should be reconsidered, because the brute-force option would probably result in infeasible computation times.
- The more detailed optimization will provide a more complete insight in the different optimal points in the design space for different operating scenarios. With a more detailed survey of specific usecases, either a single generally optimal system configuration might be chosen, or alternatively multiple specialized configurations which have in-built provisions to switch operations profiles.

9.2. Personal reflection

I started preparing for this thesis over three years ago. It took me a while to define where my interests were, as well as some convincing from my supervisor to start by writing down the problem, not the solution. I am glad I started early and stuck with the subject. This gives me confidence that when I want something, I will work until I have it. My desire to do some design studies on a system level involving subsea robots has persisted during these years, and the result is this thesis.

Combining studies with starting a company was not easy. Studying is something I had experience with, but starting a company was not. On the one hand, my study program and my retention of the study materials has suffered because of this. On the other hand, I am not sure if I could have graduated without the pressure and meaning that the startup provided.

I learned a lot and had fun. I hope I get to do something like this again.

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