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Microsystems Technology for Underwater Vehicle Applications

JONAS JONSSON



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Abstract

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The aim of this thesis work has been to investigate how miniaturization, such as microsystems technology, can potentially increase the scientific throughput in exploration of hard-to-reach underwater environments, such as the subglacial lakes of Antarctica, or other challenging environments, including cave systems and wrecks. A number of instruments and subsystems applicable to miniature submersibles have been developed and studied, and their potential to provide a high functionality density for size-restricted exploration platforms has been assessed.

To provide an onboard camera system with measurement capabilities, simulation and design tools for diffractive optics were developed, and microoptics realized to project reference patterns onto objects to reveal their topography. The influence of murky water on the measurement accuracy was also studied.

For longer-range mapping of the surroundings, and under conditions with even less visibility, the performance of a very small, high-frequency side-scanning sonar was investigated using extensive modeling and physical testing. In particular, the interference on the acoustic beam from tight mounting in a hull was investigated. A range in excess of 30 m and centimeter resolution were obtained.

Besides these systems, which can be used to navigate and map environments, a two-dimensional, thermal sensor for minute flows was developed. Measuring speed and direction of water flows, this sensor can aid in the general classification of the environment and also monitor the submersible's movement. As the flow of waters in subglacial lakes is estimated to be minute, the detection limit and sensitivity were investigated.

Measurements of water properties are facilitated by the chip-based conductivity, temperature, and depth sensor system developed. Macroscopically, this is an essential oceanographic instrument with which salinity is determined. Contrary to what was expected, MHz frequencies proved to be advantageous for conductivity measurements.

Finally, sampling of water using an acoustically enriching microdevice, and even enabling return of pristine samples via the use of integrated latchable, high-pressure valves, was realized and evaluated. Particularly, investigations of the device's ability to capture and hold on to microorganisms, were conducted.

Further developed and studied, these devices – as subsystems to miniature submersibles, or as stand-alone instruments – should enable exploration of previously unreachable submerged environments.

Keywords: Aquatic, Submersible, Underwater, Micro, Miniaturized, Sonar, Sidescan, Topography, Laser, Diffractive, Optics, Sampler, Particle, Microorganism, Acoustic, Enriching, Conductivity, Temperature, Depth, CTD, Flow

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“All these worlds are yours, except Europa. Attempt no landing there.
Use them together. Use them in peace.”

-2010: Odyssey Two, Arthur C. Clarke

To Kathryn

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I Jonsson, J., Edqvist, E., Kratz, H., Almqvist, M., Thornell, G. (2010) Simulation, manufacturing, and evaluation of a sonar for a miniaturized submersible explorer. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 57(2), 490-495, DOI: 10.1109/TUFFC.2010.1429.
- II Jonsson, J., Lekholm, V., Kratz, H., Almqvist, M., Thornell, G. (2012) Enclosure-induced interference effects in a miniaturized sidescan sonar. *IEEE Journal of Oceanic Engineering*, In Press, Digitally published, DOI: 10.1109/JOE.2012.2188160.
- III Jonsson, J., Berglund, M., Kratz, H., Nguyen, H., Thornell, G. (2012) A compact system to extract topography information from scenes viewed by a miniaturized submersible explorer. *Sensors & Actuators A*, In Press, Digitally published, DOI: 10.1016/j.sna.2012.02.034.
- IV Jonsson, J., Ogden, S., Johansson, L., Hjort, K., Thornell, G. (2012) Acoustically enriching, large-depth aquatic sampler. *Lab on a Chip*, In Press, Digitally published, DOI: 10.1039/C2LC00025C.
- V Ogden, S., Jonsson, J., Thornell, G., Hjort, K. (2011) A latchable high-pressure thermohydraulic valve actuator. *Sensors & Actuators A*, In Press, Digitally published, DOI: 10.1016/j.sna.2011.11.027.
- VI Palmer, K., Jonsson, J., Nguyen, H., Thornell, G. (2012) Two-dimensional thermal velocity sensor for submersible navigation and minute flow measurements. Submitted to *IEEE Sensors Journal*.
- VII Jonsson, J., Smedfors, K., Nyholm, L., Thornell, G. (2012) Towards chip-based salinity measurements for small submersibles and bio-loggers. Submitted to *Lab on a Chip*.

Author's Contribution to the Publications

Paper I	Most of planning, experimental work, evaluation and writing.
Paper II	Most of planning, experimental work, evaluation and writing.
Paper III	Major of planning and evaluation, most of experimental work and writing.
Paper IV	Part of planning, major part of experimental work and evaluation and most of writing.
Paper V	Part of planning, experimental work, evaluation and writing.
Paper VI	Part of planning and evaluation, major part of experimental work and writing.
Paper VII	Most of planning, experimental work, evaluation and writing.

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Abbreviations

AFM	Atomic Force Microscope
AUV	Autonomous Underwater Vehicle
CAD	Computer-Aided Design
CCD	Charge Coupled Device
CTD	Conductivity, Temperature, and Depth
DADU	Deeper Access, Deeper Understanding
DOE	Diffraction Optical Element
FEA	Finite Element Analysis
GPS	Global Positioning System
GUI	Graphical User Interface
IMU	Inertial Measurement Unit
JAMSTEC	Japan Marine Science and Technology Center
LED	Light Emitting Diode
LMA	Low-Melting-point Alloy
MIT	Miniaturized Integrated Transducer
MST	Microstructure/system Technology
MEMS	Microelectromechanical System
NASA	National Aeronautics and Space Administration
ORA	Optimal-Rotational-Angle algorithm
PVD	Physical Vapor Deposition
PZT	Lead Zirconate Titanate
ROV	Remotely Operated Vehicle
SEM	Scanning Electron Microscope
WHOI	Woods Hole Oceanographic Institution
ÅSTC	Ångström Space Technology Centre

Introduction

In order to explore otherwise inaccessible and constricted underwater environments, a miniaturized submersible explorer concept, named Deeper Access, Deeper Understanding (DADU), has been investigated. The applications for this submersible are vast, ranging from exploration of subglacial lakes, which can only be accessed through long and narrow boreholes, to, e.g., the survey of small cave systems, the internal inspection of pipes, extensive investigation of wrecks, and as a resource in different rescue missions.

This thesis represents the amalgamation of relevant miniaturized subsystems and instruments for underwater exploration with the DADU submersible, aimed at readers without a previous background in the related science and technology fields.

The design of the submersible is torpedo-shaped, 20 cm long and 5 cm in diameter, about the size of two soda cans stuck together end-to-end. Its small size makes it easily transportable and deployable by hand. However, to enable a high functionality despite its limited size, the use of miniaturization technologies, such as microelectromechanical systems (MEMS) technology, for its subsystems and instrumentations is crucial, and has been investigated in this thesis, **Papers I-VII**. The design goals for the submersible, and its subsystems, have been for a deployment depth up to 1000 meters, i.e. for them to be able to handle an external pressure of about 100 atmospheres, and in submerged environments from the freezing poles to warm tropical waters.

Instrumentation necessary to enable a good scientific return on missions includes imaging systems, both acoustical, **Paper I** and **II**, and visual, **Paper III**. This not only gives scientists a telepresence, but also enables mapping of the surroundings, as well as aids in navigation. The incorporation of a flow sensor, **Paper VI**, also increases navigational tools by monitoring current flow in two directions. Furthermore, to assess the environment, sensors measuring different properties of the water are important, **Paper VI** and **VII**, particularly to classify the existence and nature of life present. If life conditions are plausible, sampling of the environment and collection of microorganisms for return is of high interest, **Paper IV** and **V**.

To motivate this work, some of the relevant underwater environments where a small submersible may be of interest, along with the current state of the art in underwater exploration technologies, are presented directly after this introduction. Readers are then provided with a more general background

on miniaturization technologies and the relevant materials of interest in the subsequent sections. The DADU concept and devices developed and evaluated in this thesis follow. Lastly, a discussion and some future perspectives are provided.

Submerged environments

Oceans of life

When the Voyager 1 spacecraft turned its camera towards its home world from the edge of our solar system, it captured a picture of Earth as a small pale bluish-white dot against the dark vastness of space, 6 000 000 000 km away.

Earth is not called “the blue planet” for no reason. Oceans cover more than 70% of its surface. However, it has been estimated that only 5% of the oceans have been explored, and largely to a depth of no more than 300 meters [1]. However, the average depth of the oceans is 3 800 meters and the deepest point in the oceans, the Challenger Deep in the Mariana Trench, is 10 916 meters below the surface. Until just recently, only two persons had reached this depth [2], and it took 52 years before a third person ventured down to this depth again, compared with the over 3 000 people who have climbed Earth’s highest peak above the ocean surface, Mount Everest at 8 848 meters height, and the over 500 people who have ventured into space, reaching an altitude of 100 km or more, and the 12 people who have even set foot on the moon, some 400 000 km away.

Water environments have and will always play a vital role on this planet. It has come to the world’s attention that with the increased emission of greenhouse gases, the climate of Earth has experienced a global warming trend. The Intergovernmental Panel on Climate Change (IPCC) is coordinating the investigation on the climate change [3] and has found that there has been, and continues to be, an increase in Earth’s temperature, on land as well as in the oceans. Furthermore, there is a reduction in the land snow cover, including small glaciers as well as the vast ice sheets of Greenland and Antarctica, and also an increase in the melting of sea ice, *Figure 1*.

This melting of ice will result in a global sea rise where, for instance, the unstable West Antarctic Ice Sheet alone would contribute about 4 meters [4]. Furthermore, subglacial water systems, i.e. water underneath glaciers and thick ice sheets, may have an important impact on the ice flow and balance, as they lubricate the ice-ground interface and potentially speed up the process of glacial ice loss to the oceans. All of these factors are predicted to have a major effect on Earth’s inhabitants and its environments. Therefore, further investigations, including exploration of the oceans, are needed to be able to understand these vast and complex processes [5], [6].



Figure 1. Summer melt water flowing across the vast Greenlandic ice sheet.

When one considers life in the oceans, larger species generally come to mind, such as fish, dolphins, crabs, etc., whereas one is likely to forget that microorganisms are the dominating life form in the oceans, and have been found to inhabit all marine ecosystems investigated [7], [8]. Prokaryotic microorganisms, constituting the archaea and bacteria domains on the tree of life, are generally found in the size range of a couple micrometers, i.e. millionths of a meter, while eukaryotic cells can even be visible to the naked eye [9]. Also, it is believed that life emerged from the oceans on the early Earth, sprung forth from a primordial soup of organic and inorganic compounds, including the building blocks of life [10], [11]. Therefore, in the interests of determining the origin of life on Earth, exploration of the subsurface environments is vital.

Extreme environments

‘Extreme’ is a relative word. Something that is extreme to one organism or device may be benign with respect to another. However, extreme environments are generally defined as environments that are hostile to human beings and can be with regards to factors, such as temperature, radiation, pressure, acidity, alkalinity, oxygen level, salinity, or available energy, to mention a few. To date, however, wherever man has found liquid water to exist in nature, he has also found life [12], [13]. The organisms that can withstand one or more of these extreme conditions are called extremophiles and are classified depending on in which extreme condition they thrive.

One sub-classification of extremophiles is thermophiles, which thrive at high temperatures, such as in hot springs on land, responsible for giving some of them their characteristic variation in colors. Submerged versions thrive around the hydrothermal vents at the bottom of the oceans, forming the base of the local food chain. One example is the smallest living organism discovered, the *nanoarchaeum equitans* microorganism, which was found in

a hydrothermal vent off the coast of Iceland in 2002, and is only 0.4 μm in diameter [14]. Thermophiles have been found to have potential for growth in temperatures as high as 122°C [11], [15]. At the other end of the temperature scale are psychrophiles, which thrive in cold conditions, such as in highly saline, i.e. brine, cavities in ice, even at temperatures as low as -20°C [11]. Under conditions even more extreme, some microorganisms can lie dormant for several millions of years, waiting for return of better conditions, whereafter they come back to activity [11].

Hydrothermal vent systems

Environments of particular interest include the deep-sea hydrothermal vents. These geological features can be found on the ocean floors where two tectonic plates spread apart, such as the mid Atlantic and Pacific ridges. They were first discovered and documented in the late 1970s by using submersibles, and scientists were surprised to find life thriving around these vents on the otherwise so barren bottoms of the oceans.

At these locations, the hot magma heats up water to over 400°C in the thin and porous crust, which is kept from boiling due to the high pressures at this depth. As warm water is more buoyant than cold water, it starts to rise. On its way up through the crust, the superheated water dissolves minerals. As the water reaches and mixes with the cold ocean water through vents in the ocean bottom, the dissolved minerals precipitate. Depending on the temperature and the mineral content, transparent, white, or black plumes of the mineral rich warm water are spewed out, where the latter are more famously known as “black smokers” and belong to the hottest form of hydrothermal vent, *Figure 2*.



Figure 2. Diver behind a hydrothermal vent, which has a sampling nozzle inserted into it. The transparent 78°C hot water plume can be seen as it blurs out half of the divers head, in the 2°C ambient water.

The precipitating minerals build up chimney-like structures and life thrives around these vents where microorganisms based on chemosynthesis, living off the chemicals and minerals brought up with the hot vent water, instead of light dependent photosynthesis, form the base of the food chain.

As the tectonic plates continue to spread apart, the vents are shifted farther from the hot spot. Eventually the vents are cut off from the hot magma source and go cold and dormant. However, these areas continue to support life through ecological succession. It has been found that the microbes once living off the methane and sulfur in the hot vent fluids are replaced by microorganisms that thrive off the solid iron and sulfur of the vent structures [16].

Furthermore, the hydrothermal vents are considered a candidate for the source of life and evolution on the Earth billions of years ago [17-19]. It is also believed that hydrothermal systems could exist on other planets and moons in our solar system, providing life sustaining environments [20]. In addition to having a great impact on supporting life in otherwise hostile environments, hydrothermal vents are of economic interest, where ocean mining could harvest the rich mineral deposits on the bottom of the oceans.

Ice-covered oceans and lakes

Ice-covered lakes and oceans pose challenges to life. Generally, ice forms in the wintertime when the temperature drops below freezing. As the lakes are covered by ice, there is little or no mixing with atmospheric gases or sediments, and light penetration is greatly reduced, *Figure 3*. Then, as the season shifts and the temperature rises, the ice melts, opening up the body of water to interact with the surrounding atmosphere and landscape again.



Figure 3. Diver entering the ice-covered Baltic Sea. The subsurface environment is much darker and clearer when the ice covers the surface.

Shelf ice is the outer most floating part of one or more glaciers, flowing out into the ocean. The thickness of the shelf ice can be 100 to 1,000 meters, compared with sea ice that usually is 2 meters thick [21]. Due to the difference in densities between the ice and the water, only about a ninth of the ice is visible above the water surface.

Except for smaller parts of Canada and Greenland, shelf ice only exists in Antarctica, where it covers almost half of the coastline and the largest one is the Ross Ice Shelf, covering an area as large as France. Since an ice shelf usually covers a vast area, the world underneath is hard to access and explore. It was long thought that only simple microorganisms could exist in the extreme condition beneath the shelf ice, in the cold and the dark, far from open water. However, discoveries have been made of diverse benthic assemblages in these environments, i.e. life in the lowest regions in a body of water [5], [22].

In Antarctica there are a number of lakes that do not rid themselves of their couple of meter thick ice sheets over the seasons. These perennial ice-covered lakes were believed to be barren and lifeless when first discovered. However, life was found to flourish there by lush microbial mats systems, made by cyanobacteria, in the cold and dark polar waters [23]. Furthermore, life that inhabited these lakes was found to differ from each other, even for those lakes lying next to one another. Some were found to harbor microbialites [24], carbonate structures, which coral reefs are made from, grown in the microbial mats. These are believed to have been the only life forms for the first few billion years on Earth, before oxygen accumulated in the atmosphere, but are rare today and only exist in extreme environments. Stromatolites are the fossilized remains of these ancient formations.

These ice-covered lakes in Antarctica can teach us about Earth's earliest organisms, and how life might look like on other planets with similar environments.

Subglacial lakes

Subglacial lakes are, as the name implies, lakes covered by glaciers. Over 145 subglacial lakes have been found in Antarctica, where the largest is Lake Vostok, [25], [26], which has a surface area similar to three times that of lake Vänern, Sweden, the largest lake in the EU, and a maximum depth of 1000 meters, *Figure 4*. To be able to find these lakes, which can lie beneath ice sheets up to four kilometers thick, air and satellite borne ice-penetrating radar and laser altimeters have been used.

Some of these lakes formed when the continent was still connected to Australia, under much warmer conditions than today, and some are believed to have been isolated by the ice cover for millions of years, possibly harboring organisms [27]. These organisms would have to sustain conditions with

high pressures, low abundance of nutrients, cold water, and naturally, no sunlight.

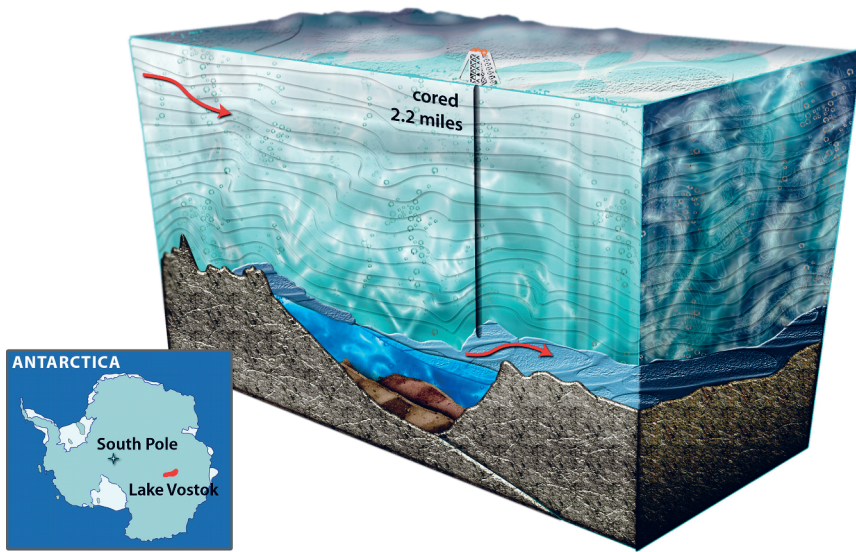


Figure 4. Lower left, the position and size of Lake Vostok and, upper right, an artist's impression of a cross-section. Courtesy US National Science Foundation.

There has been a large concern with regards to penetrating and exploring these subglacial lakes without contaminating them. However, a Russian team, stationed on the ice above the lake, where the lowest temperature on Earth of -89.2°C was recorded in 1983, has managed to penetrate through the ice in this year and reached the lake 3.8 km underneath. The lake is now open for sampling, where previously, microorganisms were discovered in a core of lake water accreted ice from a depth of 3.6 km, near the ice-water interface [28]. Next, Russian engineers have plans to explore the lake using submersibles, to collect water samples and sediments from the bottom. However, first an assessment of the plan needs to be submitted at the Antarctic Treaty's meeting in May 2012.

Lake Ellsworth is an approximately 10 km long and some tens of meter deep body of water situated underneath 3.4 km of ice in West Antarctica [29], [30]. The lake is relatively easy to access and a team of scientists from the British Antarctic Survey will drill through the ice, planning to commence in November of 2012, and then sample the lake and the bottom sediments.

Subglacial lakes also exist in the northern hemisphere. For instance, underneath the Vatnajökull ice cap in Iceland there is bodies of water that are formed from geothermal heating by the underlying volcanoes. These lakes are the source of the periodically occurring glacial outbursts, called Jökulhlaups, such as in the big melt water-flooding event of 1996 [31].

Other targeted environments

Apart from the mentioned environments, the DADU submersible could enable the exploration of various other environments on Earth, which are inaccessible or hazardous to humans due to their location or state, and not necessarily due to the environment being classified as extreme. Presented below is a selection of potential environments where the DADU would be useful.

Underwater caves

Underwater caves are natural spaces in rock that are formed by various geologic processes, either with the formation of the surrounding rock, such as lava tubes, or after, such as by water erosion, tectonic forces, chemical processes, etc. Most common of the latter category is through the dissolution of soluble rock, such as limestone.

Scientific exploration of caves and their surroundings is called speleology, while the recreational term is caving or spelunking. Caves can be found all over the world, but only few have been properly explored, for various reasons. However, one factor is that many caves exist in hard-to-reach locations, restricting the amount of equipment that can be brought in for exploration. Also within the caves, narrow troughs and openings restrict the equipment that can be brought through the cave system, *Figure 5*. As a portion of a cave goes below the water table or the local level of the groundwater, it will be flooded. This further restricts the possibilities of exploration.



Figure 5. Exploring caves can be size restricting. Here, only the bottom part of a leg is visible, belonging to a person squeezing up the Devil's Chimney, a 45 cm narrow and 3.5 meter long tunnel in the Cango Caves, South Africa. For further exploration, equipment and instrumentation needs to be brought in through such narrow access holes.

Cave diving is a type of technical diving where submerged caves are explored. It is hazardous work, since there often is no direct access to the surface and breathable air, and requires specialized techniques and equipment.

There are life forms in cave systems that exist nowhere else, so called troglobites. They often resemble surface dwelling animals, but with certain adapted features, such as no pigments or no eyes, and their other sensing organs, applicable to the extreme environment, are often enhanced. Although humans are adapted to an above-surface life, caves have been frequently used as a habitat, burial sites and shelters, throughout human history, and caves can therefore also be rich in archeological artifacts, which lay there protected from the elements [32]. The longest underwater cave that has been explored is Sistema Ox Bel Ha in Mexico, where the length explored as of February 2012 is 233.2 km.

“Blue holes”, so called due to their appearance as circular shaped blue shades in water that differ from their surroundings when viewed from up above, are subsurface cave structures. There are more than 1,000 of these geologic features in the Bahamas alone, where scientists have found bacteria, differing in type and density between different caves and in different regions within the caves themselves, adapting to their particular environment [33], [34]. It is believed that these bacteria have evolved over millions of years, some in environments where no other forms of life can survive. Less than 5% of the estimated tens of thousands of subsurface caves worldwide have been scientifically explored. It is believed that these cave structures and the microbes that live there under extreme conditions, act as analogue environments and natural laboratories of how life once formed and existed on the early Earth, and will thus provide an insight to what life was like many millions of years ago, and perhaps of what types of life could be found on distant planets and moons elsewhere in our solar system.

Mines

Similar to caves, mines are subsurface voids in rock, but unlike caves they are not natural. Humans have extracted minerals and other geologic materials from the ground for several thousands of years [35]. As humans are a wide spread species, mines can be found all over the world. As the excavations took miners deeper underground in tunnels and shafts, or as the environment around the mine site changed, the deepest parts of the mines started to fill up with water. The water could be removed to continue mining, but as soon as mining ceased, the parts of the mine beneath the ground water level became flooded. Therefore, there is a large amount of archeological artifacts that can be found in the mines. However, exploring the submerged parts is, as with cave diving, extremely dangerous work and requires much support and preparations, *Figure 6*.



Figure 6. The water table level in Queen Christina's shaft in Sala Silvermine, Sweden. The boat and the dock used for launching divers to explore the subsurface. The shaft continues some 100 meters further below the surface with a labyrinth of several branching tunnels and passages.

There are also many abandoned mines that pose environmental and health risks, not only by the caving in of the mine itself, but also by the release of toxic elements in gas or soluble form. In the USA alone, it has been estimated to be a \$10 billion cleanup job [36], justifying exploration and classification of these subsurface environments.

Pipes

Household water has been redirected and transported to settlements at least since the time the ancient Romans built their aqueducts. Nowadays, pipelines are used to transport potable or irrigational water over long distances, inhibiting pollution from the environment and the water from evaporating. Furthermore, sewage and waste pipes are used to transport water away, to sewage treatment plants, and back out to nature.

These water pipes are often under ground and therefore hard to access to check for defects and leakages. Microphones are often used to try to pinpoint the location to mitigate the need to dig up long stretches of pipes. This method is, however, time consuming and not accurate enough. A better method would be to be able access to the inside of the pipe, and to use sensors for in-situ investigation of the leakage positions.

Wrecks

Not all wrecks may contain a golden treasure, but many bear with them cultural heritage and irreplaceable historical resources. Wrecks quickly become part of their surroundings, attracting aquatic life as their habitat and hideout, and as artificial reefs in shallower waters. Whether or not on a quest for aquatic life, maritime history, or a chest of gold, entering and exploring

wrecks poses significant hazards, such as from rust-sharpened metal, splintered wood, broken glass, coral encrustations, and entanglement in objects, and therefore, special training is mandatory.

Access can be limited to tight passages and portholes. As structures and portions of a wreck deteriorate, supports give way and walls can shift as they age, and collapses can be imminent. Wrecks usually also contain a lot of silt, which if stirred up can deteriorate visibility to practically nothing for a long time before settling again, *Figure 7*.

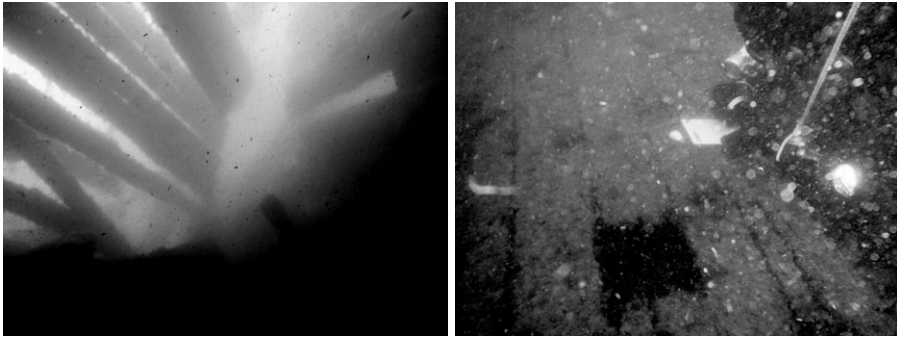


Figure 7. Left, picture taken from within the wooden hull of an up-side-down wreck in the Baltic Sea. Even though situated at a depth of no more than a few meters, stirred up sediments can render the visibility to zero and protruding objects can easily snag and entangle a diver. Right, diver exploring the hull of an 18-century wreck, however, access to the inside is limited to a hole too small for the diver.

The RMS *Titanic*, which sank in 1912 after striking an iceberg in the Atlantic Ocean, is now resting at a depth of approximately 4 km below the surface. It is one of the most famous wrecks of all time, but was not located until 1985 by imaging the bottom using a camera system [37]. Although many artifacts have been salvaged from the ship, the ship itself is deteriorating due to underwater microbes and damage from visitors, and has been predicted to collapse to the ocean floor in less than a century [38]. However, sections that have not been frequented, by their inaccessibility to submersibles, have been reported to be in good condition [38] and the deep interior has yet to be explored and documented. As the movie *Titanic* from 1997 was filmed, James Cameron used the two *Mir* submersibles to include astounding footage of the actual wreck.

The recent *Costa Concordia* catastrophe, where the cruise ship ran aground in January 2012, is an example of a wreck where the investigation of the wreck itself is not of prime interest, but the search and rescue of survivors and missing persons, an endeavor that continues as of this writing. The ship was carrying 4200 passengers and is 290 meter long, 36 meter wide, and 52 meter high, and as time is very critical, good and safe accessibility is needed. Valuable time has to be spent opening new and larger openings using explosives for access and emergency exits for the divers. Fur-

thermore, even though no sediments have accumulated in the wreck, the large amounts of debris render very low visibility and dangerous working conditions for divers. The list, i.e. tilt, of the ship also makes orientation and the use of natural references confusing.

Using easily portable and deployable submersibles can substantially increase the capability and safety of exploring wrecks.

Beyond the pale blue dot

Everywhere we look where there is liquid water on Earth, there is life. “Follow the water” has been a mantra that scientists and engineers have used in the search for extraterrestrial life. Water, along with essential elements and energy resources, are the fundamental requirements for life as we know it [39]. What is especially intriguing, is that many of the extreme environments on Earth, where life has been found, can be seen as analogue environments to what could exist elsewhere in our solar system [40], [41]. Thus, exploring the extreme environments here on Earth can teach us much about the future exploration needs in engineering technology and sciences, to enable further exploration of the worlds beyond ours. For instance, if life was to be found in the inhospitable depths of Lake Vostok, the possibility for extraterrestrial life in the outer solar system would be strengthened. A final answer to the questions, “are we alone?”, “is life as we know it a fluke event in the Universe?”, and “are there other civilizations out there?”, will have a substantial impact on us as a species and our civilization [39].

Worlds of interest

The habitable zone, also known as the “Goldilocks” zone, is the planetary orbital band around a star where temperatures allow for liquid water to exist on its surface. Whether a planet is within this zone or not is generally used as a first estimate if life is possible there, since all life as we know it requires liquid water, although other factors also play a role [42]. In our solar system this zone starts just outside Venus’ orbit and ends just before Mars’, making the Earth the only planet within it. However, it is believed that if life exists somewhere else in our solar system, one of the most likely places to find it will be in water-filled subterranean environments, where the surface shelters these environments and “stretches” the rule of the habitable zone.

Of the many intriguing places in our solar system, the Galilean moons of Jupiter are of great interest. Io, the innermost of the Galilean moons, and the most volcanically active body in the solar system [43], through the gravitational tug of war with Jupiter, is believed to be too harsh to sustain life [44]. However, the remaining Galilean moons, in particular Europa, but also Ganymede and Callisto, experience less gravitational forces, which could be

enough to maintain a melted subsurface environment and hydrothermal-like systems. From the magnetometer measurements by the Galileo spacecraft [45], Europa is believed to harbor a global saltwater ocean, containing more water than all of Earth's oceans combined underneath its frozen crust [46], [47], *Figure 8*.

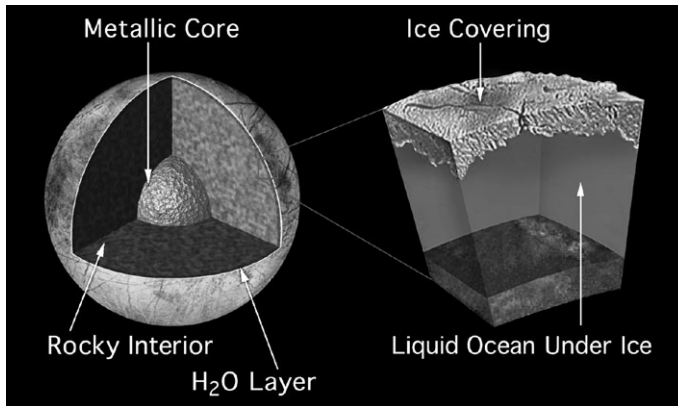


Figure 8. Artist's impression of the possibility of a liquid ocean underneath the frozen crust of the moon Europa. Courtesy NASA/JPL.

Estimations of the ice thickness range from 1 to 30 km [48]. Recent findings have also suggested that the thick ice crust can mix well enough with the underlying ocean to transport nutrients and energy to the liquid water, and the existence of giant shallow lakes within the ice crust [49] makes Europa more habitable than previously thought, and thus increases the plausibility that Europa could sustain extraterrestrial life [50], [51], *Figure 9*.



Figure 9. Surface of Europa as seen by the Galileo spacecraft. The view is approximately 70 by 30 km and iceberg-like structures and cracks in the ice can be seen. Courtesy NASA/JPL-Caltech.

To confirm or deny the presence of the subsurface liquid water, a future spacecraft lander mission to search for the possibility of habitable environments and life is needed [52-55]. This is being studied by space agencies, and the National Research Council (NRC) in the USA recently rated such a

mission as the second highest priority flagship mission in their Planetary Science Decadal Survey [56].

Recently, other bodies in the solar system have shown prospects of harboring liquid water. Orbiting around the second largest planet, Saturn, is Enceladus, whose plumes of icy particles expelled from its surface have a salt content that could indicate a subsurface ocean, which could in turn harbor life underneath its surface [57], *Figure 10*.



Figure 10. Backlit icy plumes expelled from the surface of Enceladus, as seen by the Cassini spacecraft. Courtesy NASA/JPL/Space Science Institute.

Titan, Saturn's largest moon, has long been of interest since it's the only moon with a substantial atmosphere, mostly made of nitrogen (N_2) with a surface pressure of 1.5 times that of Earth's, and a liquid on the cold surface, although not water but mainly methane (CH_4) and ethane (C_2H_6) [58]. The moon is seen as an analogue to the early Earth, and rich in complex organic chemistry that could support life on its surface [59], [60], or in an underground liquid ocean [61], [62].

Furthermore, subsurface liquid water could exist in many more icy planetary bodies in the outer solar system, sustained by the heat from radioactive decay within them, including the moons Rhea, Titania, Oberon, Triton, the dwarf planet Pluto, and the largest of the trans-neptunian objects, such as 2003 UB₃₁₃, Sedna, and 2004 DW [20], [63], [64]. This means that the habitability of the solar system could extend far beyond, to even the icy objects making up the Kuiper belt of the solar system. Further evidence of this will be available as NASA's New Horizons spacecraft cruises by Pluto in 2015, making measurements and capturing images of its frozen surface.

Exploration

Naturally, many of the previously described hard-to-reach and extreme environments have strict size restrictions on the devices that can be used to explore them. To investigate these environments, development and deployment of specialized scientific instrumentations for in-situ measurements and sampling, are often needed [30]. So little of Earth's underwater environment has been explored, which is mostly due to the fact that it is so inhospitable to us. Although human beings can sustain and briefly visit some of these extreme environments on Earth, we are not designed to survive there, which usually results in costly and technically demanding missions. However, with the advantage of lower cost and risk, current robotic technology enables both remote and autonomous in-situ exploration of such environments for long periods of time, where no human needs to boldly go anymore.

The key to most scientific explorations is to equip suitable vehicles, such as airplanes, rovers, boats, or submersibles, and stationary system platforms, with instruments to monitor specific environments, enabling novel discoveries. What these systems have in common is the need for control hardware and software, power sources, data handling protocols, short or long-range communication, and in cases of the mobile platforms, a means of controlling its movements automatically or remotely.

Off-the-shelf components are often not suitable for extreme environments, being bulky and not built to handle the size requirements of some exploration platforms, and customization and miniaturization of these are often needed. Furthermore, for sending a vehicle to explore environments beyond Earth, size and weight is a pricey issue, given the cost of around \$30,000 for each kilogram of mass lifted into Earth orbit [65]. This also drives the need for miniaturization of instruments and systems, in addition to the high interest in small devices for the exploration of hostile and hard-to-reach environments on Earth.

For underwater exploration, the hostile environment of water is added to any instrument or platform, where the pressure increases by approximately 1 atmosphere for every 10 meters of depth. Moreover, leakages pose a threat to any mission as electronics are highly incompatible with the watery environment.

Most submersibles are built to handle depths no greater than 6000 meters, however, this still allows them to reach and explore about 98% of the ocean

floors [66]. Submersibles can be divided into two main categories, manned and unmanned.

Manned deep-sea submersibles

A submersible can be described as the general workhorse of the underwater world, contrary to a submarine, which is a fully self-sustaining craft that usually has a military purpose, housing a large crew and machinery, capable of renewing its own power and breathing air. Submersibles generally require a surface vessel and crew, or some similar support, and are smaller, only supporting a few human occupants for shorter timeframes. However, submersibles are generally built to dive much deeper than submarines and to perform much more varied tasks, using mechanical manipulators, imaging systems, and different sensors.

Alvin was the first manned deep-sea submersible, commissioned in 1964. It belongs to the Woods Hole Oceanographic Institution (WHOI) in USA, and is capable of diving to a depth of 4 500 meters for up to 9 hours. Like most of the other deep-diving submersibles, it can support a crew of 3 in a 2-meter diameter pressure sphere. Alvin has, for instance, been used to find a lost hydrogen bomb from the Palomares B-52 crash in 1966, at 850 meters depth off the coast of Spain. The submersible was used in the discoveries and investigations of the deep-sea hydrothermal vents [67] and was also used to explore the wreck of Titanic by Dr. Robert Ballard in 1986 [68], *Figure 11*. A dramatic event in 1967 forced the submersible to make an emergency surfacing after being attacked by a swordfish at a depth of 600 meters. The fish, lodged in the hull, was brought up with the submersible, and subsequently cooked for dinner.

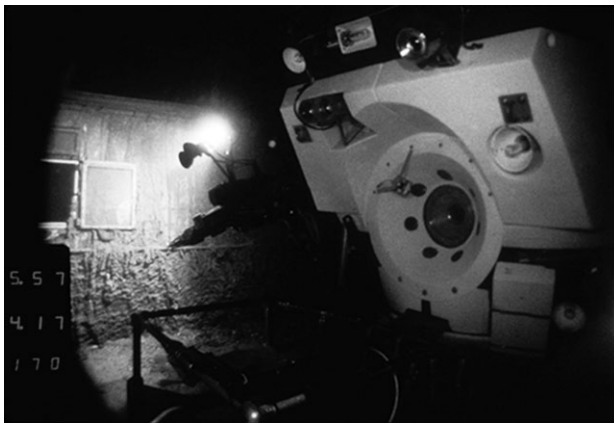


Figure 11. Alvin along the side of RMS Titanic as photographed by the ROV Jason Jr. Note the open window to the left, which requires a small vehicle to penetrate and access the inside of the wreck. Courtesy WHOI.

The Mir 1 and Mir 2 submersibles are the Russian equivalents of Alvin, capable of diving to a depth of 6000 meters for 3 days. As mentioned previously, they were, for instance, used by director James Cameron to make some fabulous footage in the film *Titanic*, and used to place the Russian flag on the ocean floor of the North Pole. Shinkai 6500 was commissioned in 1990 by the Japan Marine Science and Technology Center (JAMSTEC), and is capable of diving to 6500 meters depth. The French Nautile, owned by the Research Institute, was commissioned in 1984 and can dive to a depth of 6000 meters. It was used in the search for the Air France Flight 447 and its flight recorder, which crashed in the Atlantic. Jiaolong is the Chinese manned submersible and was launched in 2010. It has, so far, dived to just below 5000 meters.

The most recent manned deep sea diving submersible, as of this writing, is the Deepsea Challenge submersible, which was used by James Cameron to reach the bottom of the Mariana Trench in 2012. The crew compartment is only 109 cm in diameter and can only fit one person. The submersible, which reached the bottom after 2 hours, carried with it scientific instrumentation and high-definition 3-D cameras.

Unmanned submersibles

Unmanned submersible technology is maturing to readily available commercial systems where exploration of deep underwater environments can be made without getting yourself wet. By using these systems a reduced risk, savings in time, and reduction in cost can even be obtained since no human needs to go down with the submersible and less support and preparations are needed for this same reason.

There are two main sub-categories of unmanned submersibles, Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs). The main distinction between these is in the manner by which they function. The AUVs are either pre-programmed or logic-driven and usually untethered, while the ROVs are controlled directly by an operator, usually through an attached tether. A common consideration in AUV design is a streamlined, such as a torpedo, shape, to create as little drag as possible to extend the operation time as long as possible. ROVs, however, are commonly powered through a tether, and their shapes therefore do not have this restriction. Instead, ROVs are built to be stable while hovering and maneuvering around objects, and to be equipped with a multitude of sensors, to measure and investigate its surroundings, and actuators, mechanical devices for movement or control.

In this work, focus lies with the ROV submersibles, where a telepresence is provided to the operator, who can directly select and control the submersible to investigate interesting areas in real time.

There are three main categories of ROV systems: the observational class, the work class, and the special use class. The observational class, which is of interest in this thesis, is used for subsurface observations, using cameras and other sensors. The work class is to perform subsurface work, such as using multifunctional manipulators and heavy tools. The special use class contains other submersibles that have been built for a specific purpose, such as burial of telecommunication cables on the sea floor.

ROVs come in a variety of sizes, with weights measured in kilograms or tons, and they are generally a compromise between power and size. The large ROVs have more thrust, tools and sensors, but in turn need more resources and support, in men and machinery, to deploy and operate than the smaller systems. The smaller ROVs have better accessibility to and movability within size-restricted environments, but with the natural cost in functionality, as not as many tools and instruments can fit on a smaller submersible. ROVs that weigh around 15 kg can be said to belong to a mini-ROV class, while submersibles around 3 kg belong to a micro-ROV class. The smallest of these, however, are basically only propelled waterproof cameras, attached to a control station through tethers.

It has been stated that the perfect small observational ROV should have a minimal tether diameter, non-limited endurance by receiving power from the surface, be very small in size, and have an extremely high data pipeline for sensor throughput [66]. Focus in this work is on the smallest of the ROVs, but still enabling a high functionality.

A brief history of ROVs

Some credit the POODLE, built in 1953 and used for archeological research, to be the first ROV. The US Navy took interest in the potential of ROVs and development of these took up with the successes of the Cable-Controlled Underwater Research Vehicle (CURV) series, which was the submersible that recovered the lost hydrogen bomb off the coast of Spain from the Palomares B-52 crash [69] and just in time managed to retrieve the stranded PISCES III manned submersible and its crew from 480 meters depth off the coast of Ireland in 1973 [70].

The US Navy developed the first portable vehicles, the SNOOPY series, weighting about 90 kg, [71] and instruments to equip them with, which spurred the development of smaller submersibles. With miniaturization and increased reliability of subsystems, the ROVs became accepted by offshore industries, and with more affordable and portable vehicles, academic institutions and civil organizations also started to use them. Nowadays anyone, with a little bit of budget of course, can own their own hand-portable ROV for exploration of shallow waters, *Figure 12*.

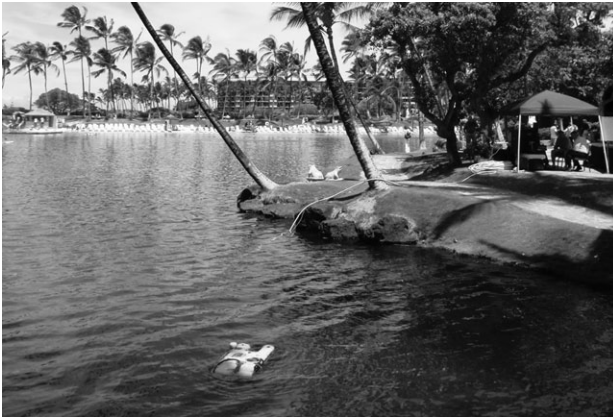


Figure 12. A small hand-portable ROV deployed in a lagoon. The ROV is controlled through the tether from the pavilion tent to the right.

Some ROVs on the market

Depending on the application, whether for public safety, military, maritime security, archaeological investigations, scientific exploration, assisting commercial divers, to mention a few, different general and specialized ROV systems are available.

SeaBotix is a type of mini-ROV made by SeaBotix Inc., San Diego, CA. They have a different range of systems, but the smallest is 53 x 24.5 x 25.4 cm in size and weighs 11 kg. It is equipped with 2 forward, 1 vertical, and 1 lateral thruster. It has a camera and lights and is depth-rated to 150 meters. The largest is 62 x 39 x 39 cm in size, weighs 18.1 kg, and has a depth rating of 950 meters. These basic units can be equipped with additional sensors, such as a multi-beam sonar, however with an added cost in size and mass to the submersible.

VideoRay is a type of micro-ROV made by VideoRay LLC. Their smallest version, Scout, is 30.5 x 22.5 x 21 cm in size and weighs 3.6 kg. It has a maximum depth rating of 76 m and is equipped with a camera and lights. Larger models exist, with a size of 37.5 x 28.9 x 22.3 cm, a weight of 6.1 kg, and a depth rating of 305 meters. Some models can be equipped with additional instruments and subsystems, such as scanning and imaging sonars, however, again with an added cost in size and mass to the submersible.

Penetrating and probing ice

Different sorts of drills are used to penetrate thick glacial ice sheets to reach and explore the subsurface. When the drill hole has been made, ice probes can be used to investigate the different layers and the composition of the ice

along the borehole, such as the ice streambed interactions, the basal ice structure, and its composition throughout its thickness.

Devices to perform these investigations include The Antarctic Ice Borehole Probe [72], [73]. This probe is 63.5 cm long and 12 cm in diameter. It is lowered down in a pre-drilled hole by a spool and reel system on the surface, providing data and power transfer. It is equipped with one down-looking and one side-looking CCD camera. From the front of the probe, half-meter long metal rods with flags on their ends, were used in deployments to visualize distances. An up-looking camera was added to the probe for an expedition on the Ross Ice Shelf in 2009. The expedition managed to drill down through the approximately 200 meter thick ice, 19 km from the open water. When the ice probe was lowered down to the ice-water interface, and to everyone's surprise, a 7 cm long *Lysianassidae* copepod appeared, dancing around the tether in front of the back-looking camera, *Figure 13*.



Figure 13. An unexpected finding 200 meters below the ice shelf surface. Courtesy NASA/JPL-Caltech.

The Cryobot [74-76] is a cylindrical probe, 1 meter long and 12 centimeters in diameter, *Figure 14*. It drills cryogenically with its heated nosecone, which melts the ice in front and then, with the aid of gravity, it pulls the probe down. Behind the probe, a tether connects it with the surface.



Figure 14. Cryobot prototype. Courtesy NASA/JPL-Caltech.

Vatnajökull is the largest glacier in Iceland, covering more than 8% of the country. As the ground below the ice is geological active, ice is melted and bodies of liquid water are created. These lakes have been reached by drilling and sampled for microbes [77]. A specially built hot-water drill was used to penetrate the 300 m thick glacier for in-situ investigations [78]. Holes from 6.6 to 14.7 cm in diameter were created at the bottom of the drill holes, depending on the speed used for drilling. When the drill hole was made, a 4 cm in diameter and 185 cm long custom built probe was built to collect 400 ml water samples at certain depths in the water column below the borehole [79]. The retrieved samples were used to characterize the water and the microbial life found in it. [79].

Liquid water environments underneath a layer of ice can be accessed by drilling and vertically investigated using probes. However, the drill hole is very unlikely to have been made straight above the most, or to include all, interesting sites of an ice-covered water body where investigations and sampling is to be performed. To reposition and penetrate the ice at several areas would be time consuming and costly, if even at all possible. To be able to extend the investigation horizontally and to reach other areas away from the vertical axis of the drill hole, small submersibles equipped with the appropriate instruments, which can fit in the narrow drill holes are needed. The submersible will also need to be designed to permit sterilization. Currently, not many submersible designs fit these requirements.

Subglacial lake explorers

After penetrating a thick ice sheet and reaching a subglacial lake environment by, for example, a cryobot, a self-propelled submersible, a.k.a. hydrobot, would be deployed to investigate and explore the liquid environment's composition and search for signs of life [74], [80], *Figure 15*.

The Environmentally Non-Disturbing Under-ice Robotic Antarctic Explorer (ENDURANCE) is an AUV that has been designed to explore the underwater environments in Antarctica, such as in the West Lake Bonney [81], [81], [82]. However, due to its size, a hole with the diameter of 2 meters is needed for its deployment.

To be able to reach and explore subglacial lakes, which can have an ice cover several kilometers thick, the submersible must be small to fit in the narrow boreholes that can penetrate these thicknesses, or even to fit inside an ice-penetrating probe. As a consequence, the various instruments the submersible will use for exploration, also need to be small and packaged tightly to fit within the submersible.

To probe the limitations on the miniaturization of instrumented autonomous submersibles, the Miniature Autonomous Submersible Explorer (MASE), concept was proposed [83]. The goal of the submersible was to be

designed extremely small to fit inside other vehicles or access areas where no other vehicles had previously managed to. Furthermore, the small size enabled simple deployments and easy shipping. The submersible was to carry MEMS-based instruments for astrobiology related applications, i.e. the study of extraterrestrial life, in extreme aqueous environments, such as the deep-ocean hydrothermal vent waterways and to be deployed through narrow boreholes of the sub-glacial lakes.



Figure 15. Artist's impression of a hydrobot, deployed by a cryobot, exploring a hydrothermal vent system in an ice-covered environment. Courtesy NASA.

A requirement was that the submersible should enter and operate with a minimal and controllable contamination of the environments. However, the submersible was also intended to be a disposable unit when deployed. The submersible was intended to operate autonomously and on battery power, however, it was connected with a tether to enable high-speed full-duplex communication. It was to be able to perform real time science data processing, providing intelligent input to the autonomy system. The instrumentation, built in a modular concept for easy interchanging of instruments specific for different tasks of the submersible, was to acquire images, comprehensive hydrographic and compositional data, including a high-resolution camera, depth & temperature sensors and an electrochemical tongue [84].

It was required that the submersible design should be smaller than 8 cm in diameter and less than 30 cm in length, which was the space available in the NASA/JPL Cryobot, and the design for the MASE concept was set to roughly 5 cm in diameter and 20 cm long. It had a single main motor in the center stern with fins placed in the stern for steering. The fiber optic tether was to be reeled out from a center axis shaft of the propeller, and hundreds of me-

ters to kilometers of fiber would be stored in its stern, as the submersible should have an operational range of 1 km.

A further development of this concept, focusing on the miniaturization and packaging of the electronics and instrumentation into multichip-modules, was the MEMS Enablement and Analysis of the Miniature Autonomous Submersible Explorer (MEMSEMASE) [85]. Further estimates of the power and range of the submersible were made. The maximum range of such a submersible was estimated to 25 km and the operation time to 5 hours. The submersible was to contribute an operational platform for data acquisition to be conducted by other systems, where a limiting factor mentioned was the availability of relevant MEMS instrumentation.

To contribute to the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) expedition, to explore Antarctica's subglacial environments, the Micro-Subglacial Lake Exploration Device (MSLED) has been designed [86]. This submersible design is 8 cm in diameter and 70 cm in length. The design has also taken into account that it needs to withstand decontamination procedures to not contaminate any environments during a mission. For its deployment, it will utilize existing infrastructure, such as the Ice Borehole Probe described above. The submersible is designed to operate down to a depth of 1.5 km and with a range of 1 km from a borehole. It will be remotely operated through its tether, which will provide with real-time bi-directional communication. The submersible is also designed mainly using off-the-shelf components to minimize development costs, and its instrumentation includes high-resolution video and a CTD instrument. The operation time is 2 hours, and at the end of the mission it will return for retrieval.

The design from the MASE and MEMSEMASE concepts evolved and were funded by MISTRA, the Foundation for Strategic Environmental Research in Sweden, to further investigate the vehicle concept and its subsystems for environmental research in small and harsh environments on Earth. The project, named *Deeper Access Deeper, Understanding* (DADU) was to design and develop such a miniaturized submersible and relevant subsystem to enable a high function density through the use of MEMS technologies.

The DADU vehicle

The *Deeper Access, Deeper Understanding* (DADU) submersible [87] is primarily designed to explore subglacial lakes, which can be found under several kilometer thick ice sheets, and can thus only be accessed through long and narrow boreholes. However, also for other areas of applications, it is very advantageous to have a small and light system, for instance enabling easy transportation and deployment. In particular, with future extraterrestrial missions in mind, a low mass and volume are of critical importance. The dimensions of DADU were set to 20 cm long and 5 cm in diameter, and the system is aimed to be neutrally buoyant in water, *Figure 16*.

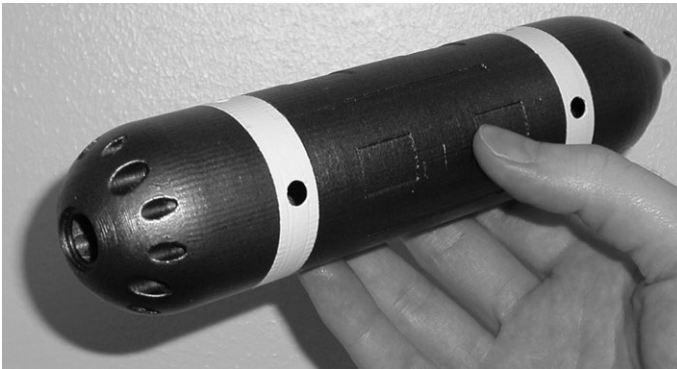


Figure 16. Model of the DADU submersible, 20 cm long and 5 cm in diameter.

The vehicle will be tele-operated through a fiber optic tether, providing the operator with real-time sensory input for direct control of the submersible. However, simpler tasks could be automated, such as evasive maneuvers and to stay at a set depth, using input from instruments. Eight small thrusters, strategically placed in its hull, maneuver the submersible with five degrees of freedom. An onboard data and control handling system supervises the peripheral units, data and command flow. Power to the submersibles subsystems is provided by rechargeable battery packs, with an added possibility of recharging these over the fiber optic tether.

A common feature for ROVs, both large and small, is that off-the-shelf components are often used to keep the costs down. This works for applications where no strict size restrictions are enforced or a high degree of functionality is not required, however, when size and weight are of essence, and

more instrumentation and functionality are required for a single system, tailor made miniaturized subsystems are required.

Further descriptions of the subsystems of the DADU vehicle follow in their respective sections.

Hull design

For submarines with a cylindrical hull, a length-to-diameter aspect ratio of 7:1 or 6:1 has been concluded to be optimum [66], [88], [89]. However, the design also depends on the application. For the DADU submersible, which is to be operated at relatively low speeds with the need to maneuver in confined spaces, a short and compact size is desired. Many ROVs have a box-shaped design, however, the design of the DADU submersible was set as a cylinder, since this would better fit through boreholes and when penetrating small holes and cave openings. The final design of the submersible was derived after a concept generation and evaluation phase, attempting to maximize the submersible's maneuverability in tight and confined waters, and to provide some maneuver redundancy in case of thruster malfunction, *Figure 17*.

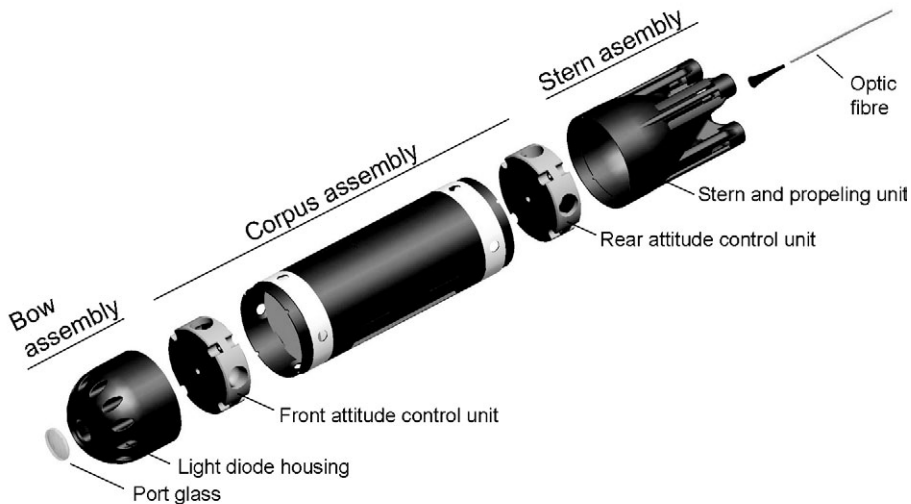


Figure 17. Exploded view of the DADU submersible, divided into three main sections: the bow, corpus, and stern assembly.

The hull is divided into three main sections, the bow, the corpus, and the stern, and each of these are sealed from each other. They each contain guiders, fixtures and supports for the subsystems inside. Interfaces between the modules and to external subsystems are kept to a minimum, as feed-

throughs in the hull make leakage elimination a great challenge at large depths.

To be neutrally buoyant at operating depths, the overall density of the submersible has to be considered. Empty or gas-filled compartments can be used to compensate for higher-density-than-water subsystems. To be able to change the buoyancy and the pitch angle of the submersible during a mission, a solution with internal water tanks, each placed close to the ends of the corpus assembly, has been investigated.

The center of mass of the submersible should also be located at an appropriate distance below the center of buoyancy, to enable a stable platform when stationary and during maneuvers.

Rapid 3-D prototyping, using fused deposition modeling of an ABS-plus plastic, has been utilized for iterative design and testing of the hull and the locomotion modules, *Figure 16*

Propulsion and attitude control

Most ROVs use their thrusters to push the ROV and to pull the tether behind it. If this force exceeds the drag force of the vehicle and its tether, the submersible will make way forward, where the pulling of the tether is usually the highest factor affecting the total drag of the system [52], [66]. To mitigate this drag on the submersible, the fiber optic tether will be stored and reeled out from the stern as it ventures forth.

Small electric engines and propellers, four for main forward and backward motion and four for lateral and vertical motion, have been custom fitted and integrated into the hull of the submersible, *Figure 17*. Four thrusters have been placed in the back of the stern in a configuration so to free up the space in the center of the stern, where the optic fiber will be attached. There is also a redundancy in this system, opposed to a single central thruster, as the loss of up to three forward-backward motion thrusters still enables the submersible to put out some thrust in those directions, provided the drag is not too large. The other four thrusters are placed, one vertical and one horizontal, at each end of the corpus assembly. By activating these in different configurations, translations in vertical and horizontal directions can be controlled, as well as changing the submersibles pitch and yaw.

Through this thruster configuration there is no need for any external rudders, which means the submersible can adjust its attitude when stationary, and is not limited to having to move forward or backward to do this. This increases the submersibles maneuverability in tight and confined spaces. Maneuvering and propulsion tests of a prototype submersible were performed in an aquarium, *Figure 18*. Due to the short distance between the operator and the submersible in the aquarium, a model airplane radio controller could be used instead of an optic fiber.

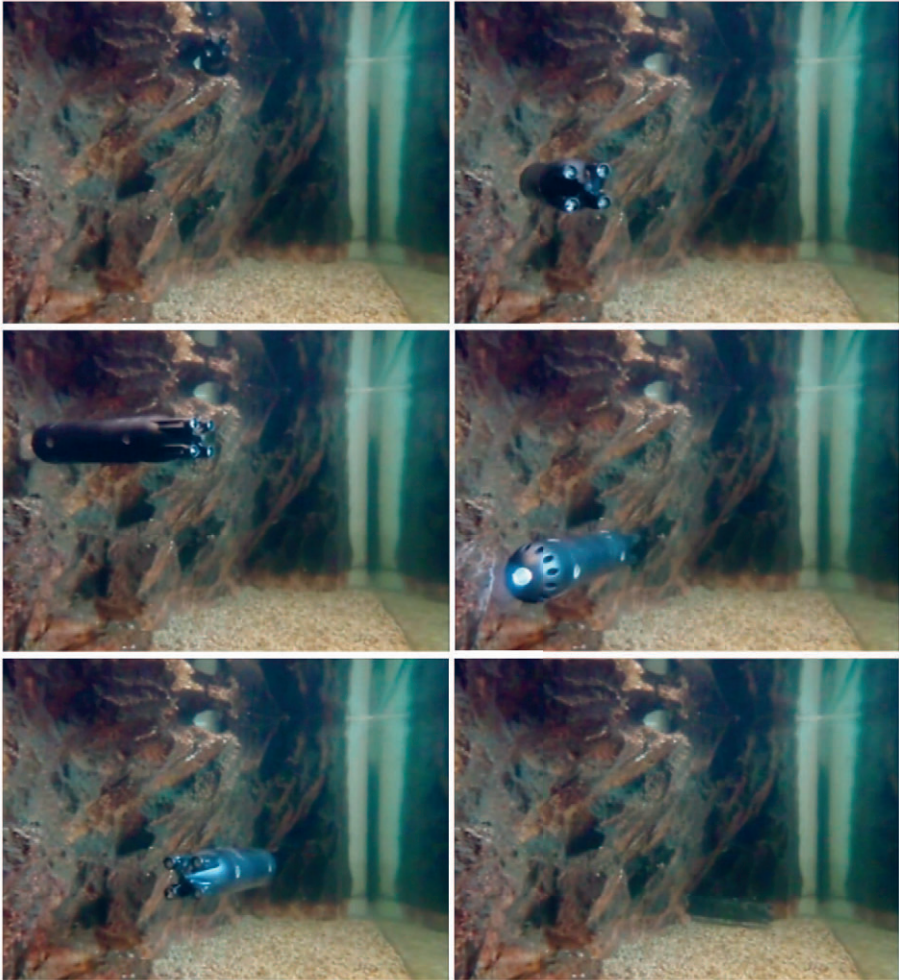


Figure 18. Sequence photographs of a maneuverability and propulsion test of a DADU prototype in an aquarium, using a radio controller. Submersible backs out from a narrow opening (top right) and turns around as it moves up and down along the wall (top right, middle left, and middle right) after which it propels itself towards the other end of the aquarium (bottom left) and enters another narrow cave opening (bottom right).

There is also less risk of getting tangled up in the tether or any other objects in the environment, since there are not any large protruding objects from the hull. There is also no need for any additional space-demanding mechanisms in the stern, which would be required to control rudders.

Communication

Communication under water is a bit different than above the surface. Wireless communication is not optimal as radio frequencies are strongly attenuated under water, lower visibility and higher attenuation also renders free space optical devices short ranged, and acoustic communication is limited to low rates and bandwidths. A hardwire tether is necessary to be able to transmit and receive large amounts of data in real-time, such as video or sonar images to perform tele-operation, when in a confined space. However, as an ROV's tether is usually the largest contributor to the drag of the submersible, this needs to be as small as possible. The optimal design of an ROV should have no more than a single-strand of unshielded optical fiber for its communication [66]. An optical fiber has the advantage of being able to transmit more data over longer distances at much higher rates than electrical wires.

The design of the submersible's communication is based on such a single-strand optic fiber, which is stored in the stern assembly of the submersible and reeled out gradually as the submersible moves, similar to the Nereus ROV concept [90]. To enable high bi-directional data rates, and the additional feature of transferring power to the submersible to charge its onboard batteries, the ability to transfer three wavelengths simultaneously is needed.

Commercial couplers exist; however, mostly for the two wavelengths of 1550 and 1310 nm. Furthermore, the couplers are too large and heavy to fit the submersible design. Investigations into manufacturing customized evanescent couplers for the DADU submersible have been made, where the three different wavelengths can be combined and separated to their respective laser and photo diodes, even though sharing the same optic fiber. Preliminary results shows that a coupling efficiency of over 90% can be reached, according to simulations of waveguide designs for wavelengths of 940 nm, 1060 nm, and 1550 nm. The waveguides and guide structures, aligning the fiber core to the waveguide core on the chip, which is only a few micrometers in cross section, are made from microstructured polymer materials, *Figure 19*.

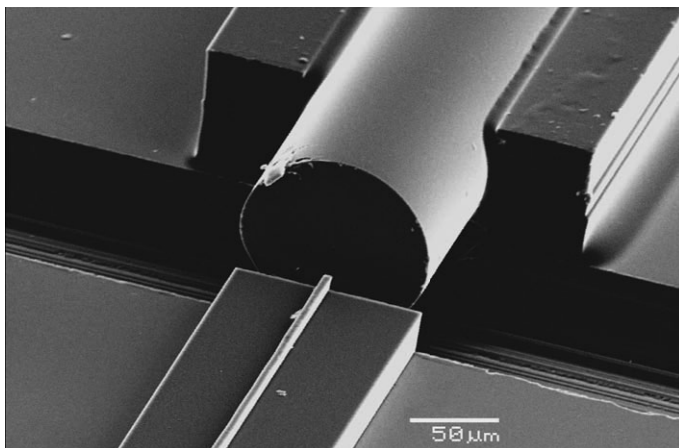


Figure 19. Scanning electron microscopeⁱ image of a fiber optic tether, 100 μm in diameter, interfacing to a polymeric waveguide, 5 x 5 μm in cross-section.

Control system

The DADU submersible is designed to be tele-operated, meaning an operator without direct line of sight, but with feedback from imaging and other sensor outputs controls the submersible through the attached optic fiber tether. The vehicle will provide an operator with a telepresence experience, as telemetry, measurement of data, videos, and control instructions, is transmitted in real time.

In the current design, a low-power, 8-bit microcontroller was chosen for the control and monitoring of the on-board data handling, *Figure 20*. This was estimated to be sufficient for the task. A more complex architecture could have been used, but with an increase in power consumption and system size.

A hard-wire tether connection enables direct control of the submersible in a remote control mode, where the operator has a direct line of sight of the vehicle, or in a tele-operated mode, where the operator is using the onboard sensors as input. Closed-loop feedback control systems could also be made available to increase the level of automation for different subsystems, where, for instance, the vertical thrusters could be set to keep the submersible at a certain depth, using the input from a depth sensor, or for a certain altitude, through input from a sonar ranging sensor. With more computational power and more advanced software to control the submersible, it could be made to go into a semi-autonomous, or even a fully autonomous mode of operation, to, for instance, perform a sonar mapping of an area of the bottom.

ⁱ Scanning electron microscopy (SEM) scans a beam of electrons over a surface, enabling images with a resolution superior to light microscopy.

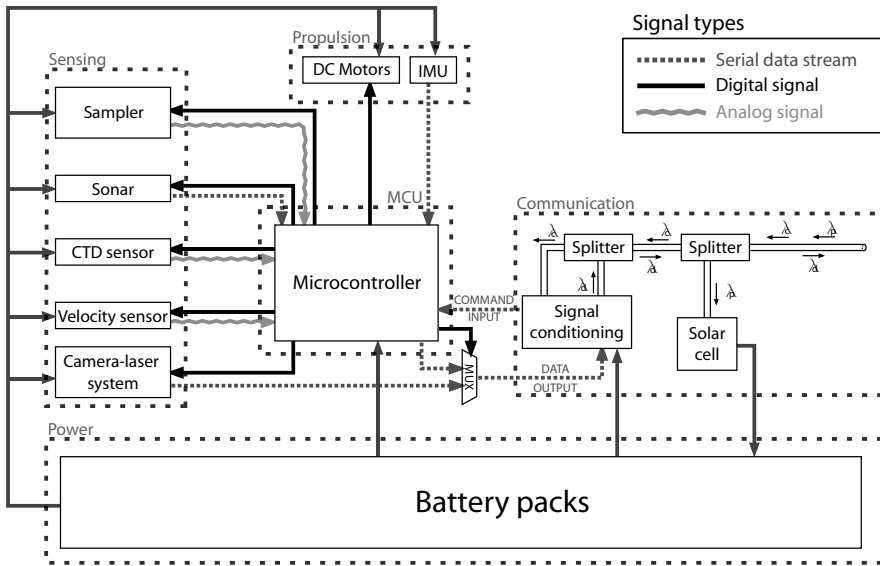


Figure 20. System architecture of the DADU submersible.

Navigation and attitude sensing

Keeping track of a submersible's position in a closed environment is challenging. Since the operation environment is subsurface, commonly used above surface satellite navigation systems, such as GPS, are not available. Furthermore, triangulation by acoustic devices is troublesome, if deployed under a kilometer thick ice sheet.

To mitigate this, a six-axis inertial measurement unit (IMU) has been included in the design. Due to the commercial availability of small and suitable off-the-shelf accelerometers and gyros, this subsystem does not need customization and can easily be acquired. With it, it will be possible to monitor the translational and rotational movements of the submersible, although an IMU is not useful for long-range navigation, due to the accumulation of offsets and errors over time. However, it will be able to reveal the submersible's current orientation, and can be used to track movements for shorter periods of time.

Visual or acoustical tracking of the surroundings can also aid in keeping track of the position of the submersible, using the camera and laser topography subsystem and the side-scanning sonar.

Power handling

Low power consumption is important for a miniaturized system designed to be operational in hard-to-reach environments over extended periods of time. The power system on the DADU vehicle is designed to be a hybrid between vehicle and surface power. There will be batteries on the vehicle as a main power source, with a surface-supplied charging feature through the tether to recharge the batteries.

Lithium-ion polymer batteries were chosen as the main power system because of their high energy density. Due to their flexibility in shape, these batteries could be custom made to fit in oddly shaped spaces between other components and subsystems within the submersible, to enable a more compact mounting.

Power will be transferred through the fiber optic cable in the form of light, simultaneously with the data and commands. In the submersible, a photodiode operating like a solar cell will collect this light and convert it into electrical power. An estimated 0.1 W of power could be transferred through the fiber. This ability to recharge the submersible’s batteries during extended missions when nestled into a cramped underwater environment, such as a cave system, can be mission critical.

Power consumption estimations for each subsystem have been made, Table 1. Not surprisingly, the 8 motors account for most of the power consumption of the system. However, it should be noted that only a few of them will be activated at the same time. Instruments, such as described in subsequent chapters, are only activated when needed.

Table 1. Estimated power consumption of subsystems, including instruments described in subsequent chapters.

<u>Subsystem</u>	<u>Estimated power consumption [mW]</u>
Microcontroller	50
Motor	1000/each
Communication	100
Sampler	10
Sonar element	10
IMU	250
Flow and speed log	100
Laser and Camera	500
LEDs	600
CTD	10

Microsystems Technology

Microelectromechanical systems (MEMS) technology, also known as microsystems technology (MST), is a field where small devices, with features and even components measured by the micrometer, are developed, manufactured, and studied [91]. This multidisciplinary technical field includes areas such as electronics, mechanics, optics, and fluidics. This technology is not only about making devices small for less volume, but can also reduce costs through batch processing, introduce new functionality, and increase performance, compared to conventional techniques.

The MEMS processing technology is inherited from the semiconductor industry, where electronic components are usually fabricated using thin polished silicon wafers and processing techniques employing photolithography, thin-film depositions and etching processes to create structures, which are described further in their respective subsection.

In addition to being a good semiconductor material, i.e. being able to both conduct and isolate electric current, silicon has favorable mechanical properties. From this, the processes developed to create the electronic components were adopted to enable 2.5-D (more than 2-D, but not quite able to make fully 3-D structures) mechanical systems and devices, for the field of MEMS.

Most microsystems are seldom larger than a few centimeters in size, enabling, amongst other features, higher functionality density. As the surface-to-volume ratio is large for MEMS devices, classical physics is not always applicable. For instance, surface effects, such as wetting, dominate over volume effects, such as inertia. These scaling effects can be used to manufacture devices with not only a smaller size than their macroscopic equivalents, but with, for instance, higher sensitivity, and improved response times. In addition, through batch processing, the components' cost can be very competitive. With features being comparable in size with dust, the processing is performed in cleanroom facilities under a controlled environment.

Some examples of MEMS devices are digital micromirror devices, ink-jet heads in printers, pressure sensors, and various sensors in automobiles.

Processing

Lithography

In order to transfer a design pattern to a substrate material, such as a silicon wafer, photolithography is commonly used in MEMS processing. Similar to the old negative 35 mm still photography films, used before the advent of digital cameras, darkroom-like conditions and an assortment of chemicals are needed to transfer the design pattern onto the silicon wafer like captured negative film is transferred into printed pictures.

The design patterns, made using computer aided design (CAD) software, are often first transferred to a chromium-covered glass mask, using a mask writer. On this mask, the pattern will be created with structures in chromium, which blocks out light, and clear glass, which transmits light enabling selective exposure of the substrate on the other side of the mask, *Figure 21*.



Figure 21. Cleanroom images: Inspecting the chromium mask with the design pattern in front of the mask aligner (left). Microscopes are crucial when inspecting the results between different processing steps (right).

A layer of UV-light sensitive polymer, called photoresist, is applied to the surface of the substrate onto which the design pattern is to be transferred. Due to the UV-sensitive nature of the photoresist, processing of this has to be performed under UV-light suppressed conditions, such as yellow light, *Figure 21*. The photoresist layer usually needs to be uniform and thin, in the range of a few micrometers, in order to enable correct reproduction of the design pattern during the subsequent exposure phase. Using this, resolutions of structures in sub-micrometers are achievable for resist thicknesses of one micrometer, while photoresist thicknesses of up to millimeters can be obtained if needed. The resist is usually applied on the surface using a spinning

system, where the different thicknesses can be obtained by using resists of different viscosities and by applying the resist with different spin speeds, i.e. revolutions per minute. The resist is often baked to drive out some of the solvents in it and harden it a bit, before the wafer and the mask are aligned against each other. UV light is then used to expose the parts of the photoresist that are not covered by the chromium structures in the mask.

By subsequently developing the exposed wafer in a developer, where the weakest parts of the photoresist are dissolved, a copy of the mask pattern will be created. After a hard baking step, hardening the photoresist layer on the wafer, the wafer is ready for subsequent processing, whether it is material deposition or etching through the developed openings. A solvent, such as acetone, or a physical process, such as through a plasma treatment, can remove the hard baked photoresist structure when it has fulfilled its purpose.

Using a set of masks and repeating this process, rather intricate structures can be created.

Thin film deposition

For thin film depositions, thin layers of various materials, such as different metals, oxides, and nitrides, are deposited onto a substrate surface. For the example wafer described in the photoresist section, this deposition can be performed either before or after the lithography process, in order to structure the deposited layer.

Physical vapor deposition (PVD) has been utilized to deposit materials for some of the devices presented in the following chapter. There are two main types of PVD deposition; evaporation and sputtering, both of which have been used. Common to these two techniques is the use of a vacuum chamber, since a low pressure is desired to produce a pure and continuous thin film on the substrate.

In the evaporation process, the target material, i.e. the source material that is to be deposited, can be heated resistively, inductively, or through radiation by electrons or ions. As the target material reaches its evaporation temperature, atoms of the material start to spread out in the chamber and become adsorbed as they hit the colder substrate. The target material is usually placed at the bottom of the chamber and the substrate material above at a certain distance. In the sputtering process, ions of a noble gas, commonly argon, are generated using, for example, plasma. These ions are accelerated towards, and made to collide with, the target material. This will eject atoms from the target, like that of a billiard ball hitting the other balls on a pool table. Along their way through the chamber, the ejected atoms are more prone to collide and change their directions before reaching the substrate and being adsorbed on the surface, than in the evaporation process. This difference between the two deposition methods can be taken advantage of, as discussed further below.

If the thin film layer is deposited before the lithography step, the structured photoresist can be used as a masking layer to transfer that pattern to the thin film layer by removing, i.e. etching, the exposed part of the thin film. When the exposed part of the thin film has been structured, the photoresist can be stripped off the wafer, leaving the thin film pattern underneath. In the case of a thin film deposition after the lithography step, the thin film will be deposited on the exposed parts of the substrates as well as on the photoresist structures. The photoresist can then be stripped off, taking with it the thin film deposited on it, i.e. lift-off, and leaving behind only the film deposited on the substrate. Through both these methods, the design pattern from the photoresist is transferred to the thin film layer.

There are pros and cons with both techniques. Depending on the processes and the materials involved, one or the other can be more advantageous to use. The deposition rate is higher for evaporation and the deposited layer is generally more pure, since the chamber has a higher vacuum during evaporation than during sputtering. However, the sputtered layer generally has a better adhesion to the substrate, since the sputtered atoms have a higher kinetic energy than the evaporated ones. There is also a wider choice of materials for sputtering than evaporation, where, for instance, the different constituents of alloys may have very different evaporation temperatures. Since the evaporated atoms have a more linear path of flight from the target than the sputtered ones, due to fewer collisions, the evaporation results in less step coverage, i.e. the covering of vertical features in a structure. This is advantageous in lift-off processes, where solvents can access and dissolve the photoresist structures, removing the deposited material on top while leaving what was deposited in the exposed parts. Sputtering, on the contrary, gives good step coverage, which is advantageous in applications where a layer needs to connect over a topographic surface.

Etching

For etch processes, various materials are removed, being it different deposited metals, oxides, or the substrate material itself. There are two major techniques to do this; dry etching, where gas is used, and wet etching, where liquid is used. Depending on which materials and processes that are used in the manufacturing, one or the other might be more beneficial.

In dry etching, either physical bombardment with ions, chemical reactions, or a combination of these effects are used to etch a material in a vacuum chamber, *Figure 22*. Often a plasma is used, to increase the etch rates of a material. In wet etching, the substrate is immersed in a liquid, usually an acid, which will dissolve the material. Both dry and wet etching can be performed isotropically, with the same etch rate in all directions, or anisotropically, with a higher etch rate in a particular direction.



Figure 22. Dry etching is performed using machines with vacuum chambers, such as the one to the right, which are operated using computers and control panels.

Selectivity is an important factor to take into consideration when etching. It is the ratio of the etch rates between different materials. For the photoresist patterned wafer described above, one wants a high selectivity to etch the substrate, i.e. a high etch rate for the substrate material and a low etch rate for the photoresist. Uniformity is also critical, as a wafer will most likely contain several structures across its surface.

Some relevant materials

Silicon

Silicon, Si, is the most common material in MEMS processing, due to the inherent availability of several well tested processing techniques used in the integrated circuits (IC) industry. Si is strong and relatively cheap, and is a very abundant element on Earth. Its natural oxide, SiO_2 , is often used as a masking material in different processes, such as etching. It can be deposited on a surface, but is often created from the Si substrate itself through thermal growth, i.e. oxidation, in a furnace. Si has a crystal structure that can be taken advantage of for anisotropic wet etching. Si comes in the form of wafers, usually 4 or 6-inch in diameter and 500 or 250 μm thick. Si was used as a substrate material in **Paper VII**, and for the fiber optic interfaces, *Figure 19*.

Pyrex

Pyrex is a brand of a borosilicate glass. It is clear and has a low thermal expansion, similar to that of Si, and the two materials can thus be joined together without inflicting too much thermal stress on each other. Glass is often used in optical and biochemical applications. Glass can be etched using both dry and wet processes. Pyrex was used in **Papers III, IV, VI and VII**.

PZT

PZT, short for lead zirconate titanate ($\text{Pb}(\text{Zr}_n\text{Ti}_{1-x})\text{O}_3$), is a ceramic piezoelectric material. Piezoelectricity, meaning pressure-induced electricity, is the effect of a build up of charges in a material due to applied mechanical stress. That is, if the material becomes deformed, a charge will be built up over the material. There is also a reverse of this effect, the converse piezoelectric effect, where a mechanical strain, i.e. a shape change, is obtained from an applied electrical charge.

It is the crystal structure of PZT that makes it piezoelectric, where the positive and negative charges within it have no center of symmetry. When fabricated, the material has no net polarization, the direction of the individual crystal charges points in different directions. However, by applying an external electric field over the material, these dipole crystals can be made to align along the electric field lines, and the material at large will have a net polarization.

The obtained shape change is small, in the order of 0.1% of its dimensions. Even so, there is a large field of applications, such as speakers and microphones, accelerometers, electronic frequency generators, and as the spark-emitting element in push button cigarette and gas-grill lighters.

PZT was used for the sonar element in **Paper I** and **II**, and for the acoustic transducers in **Paper IV**.

Paraffin

Paraffin, mostly known as the waxy solid substance that makes up the fuel in candles, is a hydrocarbon with the general formula $\text{C}_n\text{H}_{2n+2}$. Paraffin does not react or mix well with most common chemical reagents, such as water, something that is reflected in its name, meaning ‘lacking affinity’.

The melting point of paraffin is related to the chain length of its molecules and can be as high as about 150 °C [92]. By mixing different types of paraffin in different ratios, the melting point and the temperature span of melting can be tailored.

Paraffin wax is a very good electrical insulator and has a high specific heat capacity, meaning it stores heat well. Therefore, the latent heat stored in the paraffin is returned when the paraffin is solidified again. This, along with the large expansion of paraffin during phase transitions from solid to melted form of up to 22% [93], and its compressibility in its liquid phase of less than 1% per 10MPa [93], makes paraffin a good actuator material. However, paraffin does not have the same force and time-response as the PZT material described above. Nevertheless, paraffin can still produce large forces and has large volume expansions. Furthermore, it is a low cost material and has a simple and low voltage activation principle by resistive heating.

Paraffin was used to control valves in **Paper IV** and **V**.

DADU Subsystems

Topography measurement system

As visual sight is one of, if not the most, important sensory system of humans, it is imperative for submersibles to carry with them a visual aid system, such as a camera. Even though visibility can be very poor at times underwater, not providing an adequate visual overview, generally it is good enough for close-up inspections, within a few meters, *Figure 23*.

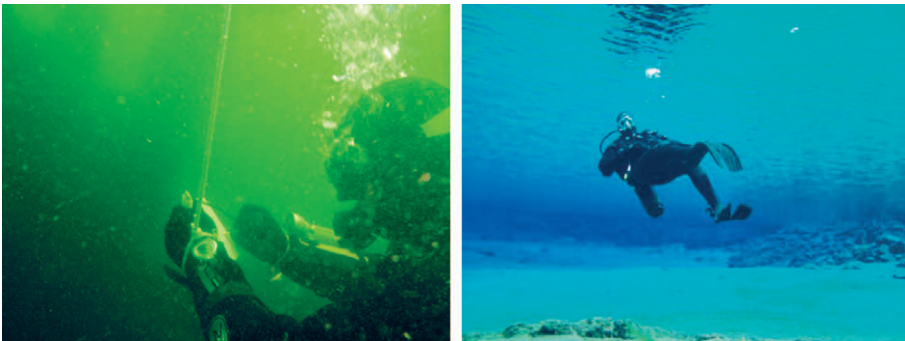


Figure 23. Examples of different underwater visibilities: Left: Investigating a wreck, barely discernable in the background, in the Baltic Sea, where particles reduce the visibility to just a few meters. Right: In the waters of the Mid-Atlantic Ridge rift valley Þingvellir, Iceland, where the water has been filtered through the porous volcanic rock and enables extreme visibilities of over 100 meters. Both pictures are taken just a few meters below the surface.

However, a common problem with images taken underwater is that they tend to make a very flat impression, lacking the usual references with respect to light and shapes that help us to determine distances and sizes of objects on land. Also, as most divers know, due to the refraction of light when passing between water and air, objects underwater appear about 25% larger and closer than they really are [94].

The ability to extract geometrical information from images is vital to many scientists and engineers, whether it is to know the size and shape of animals for marine biologists [95], of artifacts for marine archaeologists [96], geological features for a geologist [97], or underwater constructions for an engineer [98].

To enable better distance, shape, and size estimates from images underwater, and to increase the images scientific return, a means of measuring is needed. Photogrammetry is the science of making such measurements from images. If some geometry in an image is known, simple distance measurements can be made directly in the image. Stereophotogrammetry combines several images taken from different positions and uses algorithms to deduce the 3-D coordinates of points in the images. This, however, necessitates pictures taken at known positions or the use of multiple cameras set in a known geometry, and stereovision is computationally complex [99].

A simpler, and more common, solution for single cameras is to introduce a scale of some sort in the field of view. This can be a ruler or an object with a known size. However, to plant a physical object in the view requires preparation, is time consuming, and is, for several applications, not practical as it tampers with and disturbs the scene. To avoid a physical measuring scale, there is a solution to fit scaling lasers on the submersible, like projecting two parallel laser beams into the field of view. By knowing the distance between these two parallel beams, their projections in the image are known as well. However, to introduce more data points in the image, more lasers are needed, but since space is limited in many small submersibles, only a few closely placed light sources would fit, limiting the pattern's shape and coverage.

To keep the number of lasers to a minimum, scanning systems can be used [100], [101]. This, however, requires moving parts, increasing the complexity of the system and potentially decreases the reliability, making it less applicable to small submersibles. A system to provide with these measurements should be compact to fit in tight spaces and not substantially add to the power budget of the whole system.

The DADU submersible will have a small forward-looking camera with illuminating lighting in its nose cone. It will capture high-resolution images and videos, which will be transmitted over the fiber optic tether for real-time viewing, enabling tele-operation at the control center. A system to complement the camera, and enable topographical measurements, was developed, **Paper III**, using a single low-power laser diode and a diffractive optical element (DOE) to project a complex pattern onto a scene, *Figure 24*.



Figure 24. A bow assembly test setup, to the right in the figure, in which the camera, lights, and a laser with a DOE in front, are mounted. Liquid nitrogen was used to create a fog in which the emitted laser rays would be visible, to the left in the figure.

Diffractive optics

The phenomenon of diffraction refers generally to a wave breaking up into different directions [102], such as in the Young's Experiment, where two closely spaced vertical slits, illuminated by a monochromatic beam of light create an interference pattern consisting of a number of bright and dark bands along a horizontal line on a screen behind. For the slit example, one of the dimensions, usually in the vertical direction, extends longer than the wavelength of the light beam. However, if a small hole is used instead, the pattern on the screen will have an extension in both the horizontal and the vertical direction. This diffraction effect is a result of amplitude modulation of the transmitted light beam.

A DOE is a single lens that shifts the amplitude and/or the phase of coherent light shining through it, and forms a desired projection pattern on the other side. A DOE, where phase modulation is used, is called a kinoform [103] and can be obtained through the delaying of the incident light through different optical path lengths in a media, usually a structured glass lens with a refractive index different from that of the surrounding media.

Realizing the lens

A DOE kinoform solution was used for the topography measurement system, to complement the camera in the DADU submersible's nosecone. It involves vertical sub-wavelength structuring of a glass member with pixels a few micrometers wide.

The design of the lens structures, in order to obtain a certain projection pattern is not straightforward, *Figure 25*, in contrary to the case where the comic book superhero Batman is summoned to the chief of police by turning on a spotlight with a bat symbol on it, projecting the same bat symbol on the cloud cover over Gotham City. Instead, the design pattern of the lens to project a particular pattern has to be calculated using various algorithms, such as the optimal-rotational-angle (ORA) algorithm [104].

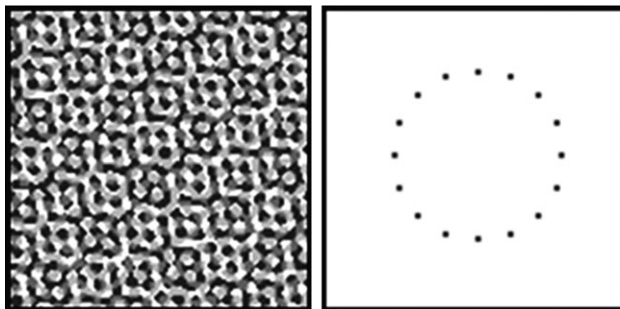


Figure 25. The design pattern of the lens, left, to create a certain projection pattern, right, is not straightforward. Algorithms are used to calculate the DOE structure design from a desired projection pattern.

To implement the ORA algorithm, the numerical computing software MATLAB was used, in which a script was created, henceforth called DOECAD. A black and white image of the desired projected pattern is used as an input to the script, from which the lithography mask design patterns for the required lens structure design, is created as an output, *Figure 25*.

This mask design pattern was used in the MEMS processing, where it was photolithographically transferred into a thin SiO₂ layer deposited on a Pyrex wafer using dry etching, *Figure 26*, after which individual DOEs were diced out. These DOEs could then be mounted in front of a laser, such as in the bow assembly of the submersible, to project the desired pattern in the camera's field of view, *Figure 24*.

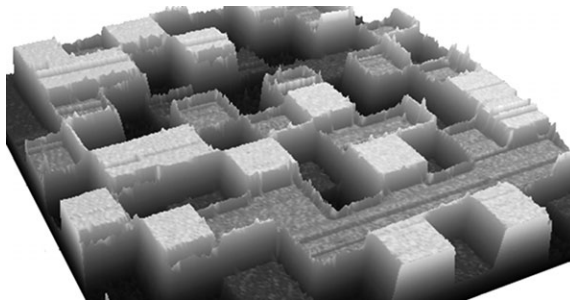


Figure 26. Atomic force microscopeⁱⁱ image of a part of a lens surface, having a structure pixel size of 10 x 10 μm , and being a couple of hundred nanometers high.

Measuring principle using projected patterns

The topography measurement principle is that as the DOE created pattern is projected onto an object, the object will deform the pattern, which can be detected by the camera. The way the projection pattern has changed can then be used to deduce the distance, shape, and size of the object.

To measure the deformation of the projected pattern and to present the measurements as topographical data, a MATLAB script was developed, henceforth called Laser Camera Measurement (LCM) script. The script picks out the projected laser dots in the image by the color and intensity. Here a red wavelength laser has been preferred, as red is the color that gets mostly attenuated in water, meaning that any ambient light will have less of this color component. Each laser spot in the image gets assigned a coordinate relative to the position of the camera. These spots are compared with a calibration image of the projection pattern on a flat perpendicular screen at a known distance in front of the camera. By knowing the geometrical setups, the script can calculate how the spots have changed their positions due to the object, and thus their position in 3-D space.

ⁱⁱ Atomic force microscopy (AFM) scans a small physical probe over a surface, enabling quantitative topographical resolutions in the nanometer range.

Measurements

Measurements were made in a water-filled aquarium, where different objects were introduced in front of the camera, *Figure 27*.

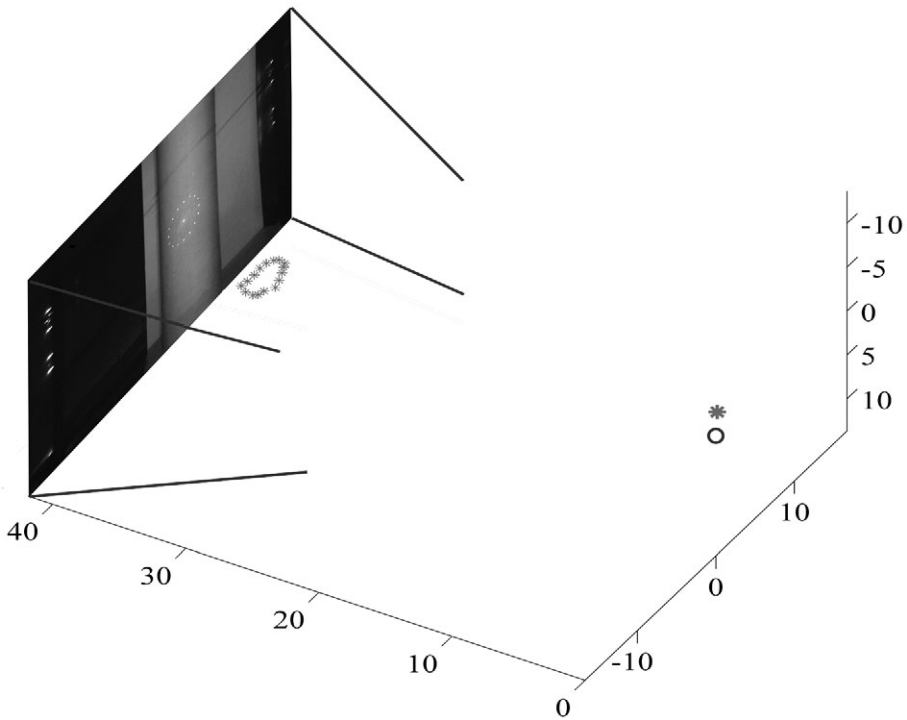


Figure 27. View from the measurement script. The camera and laser are the ring and the dot to the right, at origin. On the opposite end, is the image captured by the camera, of a white cylindrical object with the circular pattern projected on it. The lines radiating from each corner mark the camera's field of view. The scale is in cm. At about 35 cm, the measured positions of the projected pattern are visible, showing the curvature of the object.

The circular pattern was used in **Paper III** to characterize the ability of the system to measure distances and angles, and thus be able to deduce the shapes of objects. Distances were measured with an error of no more than 0.5 cm on a flat screen as it was moved towards the bow assembly, from 45 to 30 cm. The same screen was turned in front of the camera, where the angles were measured within 4 degrees error to the set values.

Furthermore, to investigate the system's ability to operate under turbid conditions, as this can be a significant limitation when using visual based systems, coffee and freeze dried crustaceans were gradually added to the water in separate tests, to see how they affected the measurements. Throughout these tests, which were performed at concentrations past where the target

screen was no longer discernable by the naked eye, the system could determine the distances to within an error of 0.5 cm at a distance of 45 cm.

The particles used in the tests were dead matter, randomly floating by in the water, obstructing the view of the camera at times. However, in real applications, especially in dark environments, light, such as that from the LEDs of the submersible that illuminate the view of the camera, can inadvertently attract zooplankton, small critters on their hunt for food. To mimic these, *Artemia*, small crustaceans commonly used to feed aquarium fish, were acquired and bred. It was found that these were attracted to the light emitted from the LEDs in the bow assembly within minutes in a small water tank, as is expected to happen during a deployment under similar conditions, *Figure 28*. Even though the above tests show reliable measurements, even under dense concentrations of particle-like objects in the water, a large enough active accumulation of these in front of the camera, can render the visibility zero. This can be mitigated by operating the lights and measurements in bursts, as it is expected the zooplanktons would disperse again when the lights are turned off, as was the case with the *Artemia*.



Figure 28. In dark submerged environments, creatures, such as these zooplanktons, are attracted to light and will accumulate in a light beam. This can pose problems for the camera, obscuring the view.

Side-scanning sonar

The rules of sight and sound are reversed in the water environment, compared to on land. In air, light can travel much further than sound, however, light can only penetrate a short distance in water, leaving most of the subsurface environment in the dark. Sound is made from vibrations that push molecules of a medium against each others, creating waves of high and low pressures that radiate out from the source. In water these waves can travel much longer than in air, up to thousands of kilometers, and about five times faster, due to the higher density. There is therefore no wonder that whales and other

sea creatures use sound for navigation and communication. In marine technology, the properties of sound in water are also taken advantage of, where, for instance, acoustic imaging systems are commonly used over visual based ones, especially when long distances are of interest and the water quality is low.

Sonar, derived from the words sound, navigation and ranging, is a device that uses sound propagation to navigate and to detect objects under water. A sonar imager is used on many ROVs for navigation and mapping purposes, and was one of the proposed instruments on a future Hydrobot mission to Europa [80]. It's been with the help of this sonar imaging technology that the discovery of many famous wrecks in the deep sea, such as the Air France 447, which crashed in the Atlantic Ocean in 2009 [105] and the discovery in 2011 of the largest man-of-war of its time, Mars, which sank in the Baltic Sea in 1564, have been possible.

The capability to image the surroundings of the submersible is of great value when exploring and sonar imaging systems complement camera systems in murky environments, as small particles in the water do not interfere with the longer wavelengths of sounds as they do with the shorter visible ones. Furthermore, objects around the submersible can be recognized and tracked as the submersible ventures forth, in order to deduce the course and speed of the vehicle over the bottom of an unknown environment.

Therefore, a miniaturized side-scanning sonar, that can fit within the DADU design, has been developed and characterized, **Paper I** and **Paper II**.

Principle of acoustic imaging

There are two main types of sonar; active and passive. The active form sends out pulses of sound and listens for the echoes, such as a depth finder or imaging sonar, whereas the passive form only listens, such as a hydrophone.

In order to create the vibrations that transmit the acoustic pulse for active sonar, PZT is commonly used. During World War I, sonar was the first application of devices using the piezoelectric effect, and was developed to detect the German submarines. As has been described previously, this material can be made to vibrate as an AC electrical signal is applied over it, creating an acoustic pulse source.

Imaging sonar uses vertical fan-shaped acoustic beams, not entirely unlike the shape of a hand fan. The shape of the acoustic pulse is determined by the geometry of the sonar element, in this case rectangular, and the frequency it is operated at, **Paper I**. The beam is made to scan an area, either by rotation or by moving in a straight line, such as when mounted on the hull of a ship or dragged behind on a tow vehicle, *Figure 29*.

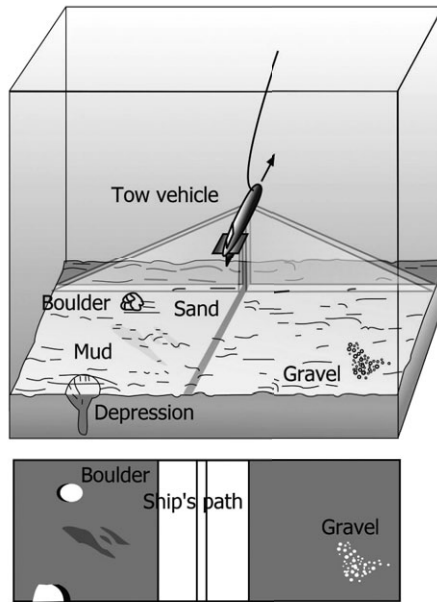


Figure 29. Principle of side-scanning sonar. A tow vehicle, with a sonar on each side, is towed over the bottom at a certain height (top part). Different objects result in different signal responses, as seen in the corresponding image (bottom part). Courtesy of the U.S. Geological Survey.

As the transmitted acoustic pulse spreads in the water, objects will cause reflections of varying strength at different times after the sonar pulse is transmitted, depending of the property of the objects and how far the objects are from the sonar. As these acoustic reflections, or echoes, return to the sonar element, the reverse piezoelectric effect in the PZT material creates electrical signals, varying in intensity with the strength of the reflected pulse. Objects with large difference in acoustic impedance to water will create stronger reflections of the acoustic pulse, such as a rock or an air pocket, while those more similar to water, such as mud or a fish, will be weaker. These different intensities of the signal enable discrimination of different objects in the returned signal. For the side-scan sonar, as it is moved along the track of movement, each received signal pulse adds line after line to build up an acoustic image, *Figure 29* bottom part.

The resolution of the image is set by the width of these scan-lines, which are related to the width of the acoustic beam along the direction of travel. The pulse length sets the resolution in the direction perpendicular to the direction of travel, i.e. the ability of the system to distinguish between two different objects. A shorter pulse will resolve two closely spaced objects better, however, the signal will be weaker as well.

The optimal frequency to operate a sonar at depends on the application and is a trade-off between image resolution, object penetration, and range, Table 2. The reason for this is that the attenuation of an acoustic pulse in

water increases with frequency, as does the resolution, because the smallest object feature that can possibly be resolved is the size of the wavelength used. Furthermore, the higher the frequency, the less is the penetration into an object by the acoustic pulse, resulting in a more detailed target shape.

Table 2. Example frequencies, wavelengths and ranges of underwater acoustics [66].

Frequency	Wavelength	Range	Area of application
< 100 Hz	> 15 m	> 1000 km	Seismic and sub-bottom profiling
10 kHz	15 cm	10 km	Acoustic positioning
100 kHz	1.5 cm	600 m	Imaging sonar
500 kHz	3 mm	150 m	
1 MHz	1.5 mm	50 m	Medical ultrasound

The miniaturized side-scanning sonar

The sonar element was designed and its performance simulated using finite element analysis (FEA) software, **Paper I**. Due to the small size of the submersible, the sonar element had to be made small to fit in its hull. The size of the PZT material making up the sonar element, was set to 50 mm long and just 2-3 millimeters in the other two dimensions, i.e. about the size of a common matchstick. However, due to its overall small size, a higher than normal frequency in the order of 600 kHz, was used to enable good quality images. For the application of the submersible, the range requirement was only a couple of meters, and since a good resolution was desired to resolve small objects, a high frequency was preferred.

The simulated design resulted in a narrow beam width along the direction of travel and a large beam width in the perpendicular direction, which enabled small and long scan lines for the acoustic image.

Test devices were manufactured, where plates of PZT were acquired and diced to the appropriate sizes. The sonar elements were mounted in brass frames using a cork-epoxy mixture, *Figure 30*. The purpose of this, so called backing layer, was to increase the directivity of the emitted acoustic pulse, by decreasing the acoustic pulses in the unwanted directions. Due to the big difference in the acoustic impedance between water and the PZT material, a matching layer was applied to the side facing the water, to increase the transmission of the acoustic pulse between the two materials.



Figure 30. The PZT sonar element mounted in a brass frame by a surrounding cork-epoxy mixture.

To characterize the sonars in **Paper I**, they were swept in front of a hydrophone in a water tank, using a robotic arm. The signal strength pattern was characterized in 2-D, and thus the beam pattern in the vertical and horizontal directions could be measured. These were compared with the simulation results, which agreed well, and hence it was concluded that the performance of the sonar could be predicted using the computer models.

Field test images were acquired using one of the sonar elements in a local river, *Figure 31* and *Figure 32*. Sonar images can be similar to an optical image of an object, however, can also differ substantially, making interpretation of what is seen less straight forward. One should keep in mind the physical differences between how an acoustic image is built up compared to that of an optical image. A smooth surface can reflect very strongly if imaged straight on, while at an angle it could be possible that there would be no indication of the object. This is similar to the techniques used when making objects, such as the stealth fighter airplanes, invisible to radar. Objects can look very different when viewed from different positions. Ranges in an image are slant ranges, i.e. distance between the sonar and the object, and say very little of the elevation. However, shadows cast by an object in an image can be used to calculate their heights, if the position of the sonar above a flat bottom is know.

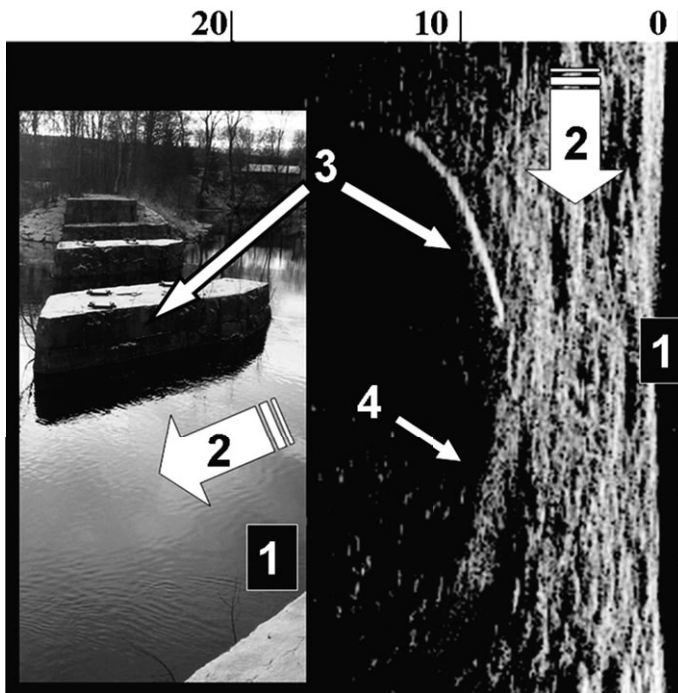


Figure 31. The sonar device used as a rotational scanner. 1) Point of scanning. 2) Flow direction of river. 3) Bridge pillar. 4) Debris ridge revealed in the sonar image downstream from the bridge pillar. The scale is in meters.



Figure 32. Side-scanning field tests were performed from a boat in a lake and a river. Objects identified include, mud flats, rocks of varying sizes, cables, a boat loading fill on the bottom, a tree trunk, and possibly also a school of fish.

Due to the short wavelengths used, and the geometries of the sonar and its tight mounting in the submersible's hull being of the same dimensions, interference effects were also investigated, **Paper II**. Computer simulation models revealed deformations in the fan-shaped beam pattern, especially in the vertical direction, which could potentially create loss of information on an acquired acoustic image. A sonar, with movable brass frame sidewalls, was

manufactured to confirm these disruptions in the pattern. In addition to hydrophone measurements, schlieren imaging, *Figure 33*, and comparative measurements in the field, *Figure 34*, were used. It was shown in **Paper II** that the sonar is sensitive to interference effects, due to enclosure structures, and thus the mounting of the sonar in the hull has to be carefully performed.

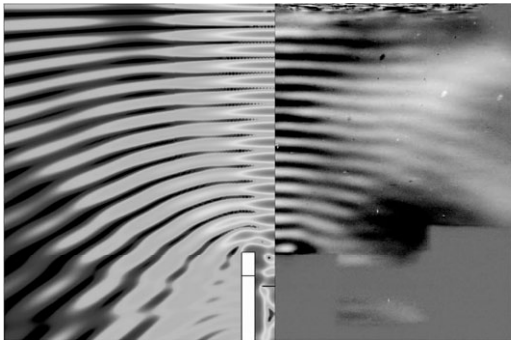


Figure 33. FEA simulation of acoustic standing waves reflected off a metallic sheet at the top of the image (left) and a schlieren image of the same setup (right). A weakness in the pattern can be seen at about 30 degrees from the normal.

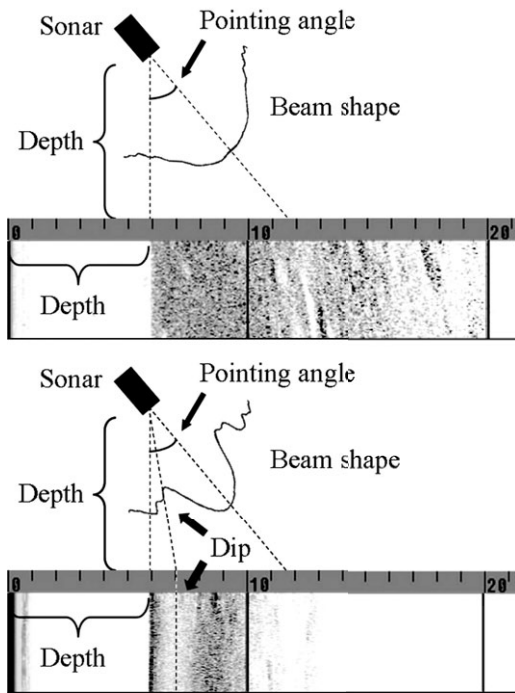


Figure 34. Comparative study using the sonar with the movable brass frame imaging over the same stretch of a river with the frame level with the sonar (top half) and when raised 3 mm above the sonar (bottom half). Sketches of the test setup and the hydrophone measured beam of the sonar have been included for each respective case.

Sampling particles

The oceans are filled with microorganisms that most people are not aware of since they are too small to be seen with the naked eye, of a size where a hundred of them fit side-by-side across the width of a hair. There can be millions of these organisms in a drop of seawater and they inhabit every marine ecosystem investigated and play critical roles in the environment. Phytoplankton, for instance, are plantlike microorganisms and some of the most abundant life on the planet. Nearly all life on Earth is dependent on these organisms for survival since the microorganisms are an essential food source for sea creatures and are also responsible for removing carbon dioxide from the atmosphere. In fact, they produce more oxygen for the Earth's atmosphere than the surface plants combined. It is believed that it was ocean organisms like these that were responsible for the massive creation of oxygen in the Earth's atmosphere hundreds of millions of years ago, enabling the evolution of more advanced and complex life forms that exists today, such as us. However, these organisms can also be harmful for life, as with their substantial increase in the spring times, so called algae blooms, which can discolor the water, create toxins, and deprive the water of its oxygen as the dead organisms decay.

It is imperative to learn more about and to keep track of microorganisms in the water because of their many important roles in the environment. However, due to their small size they are hard to study. Samples are commonly acquired from different environments and brought back to laboratories to be analyzed and studied. Usually, large samples of water are collected using Nansen and Niskin bottles in marine applications. The sampling is often combined with characterization of the sampled water, measuring parameters such as conductivity, temperature, and depth (CTD).

However, all environments of interest are not accessible for sampling using these devices, due to their large size and required support vessels. Submersibles, both AUVs and ROVs can advantageously be fitted with sampling devices to, for instance, increase the range and sampling frequency using the former, and enable sampling of specific and hard-to-reach areas using the latter, such as far underneath ice shelves, in subglacial lakes, and in cave systems.

A simple sampling device is basically an empty bottle that, at the point of sampling, is opened up and flooded, and then sealed back up again, to keep the sample from being contaminated until analyzed. A large enough sample is needed to ensure enough analysis material, especially in oligotrophic environments, where the population is expected to be sparse, such as the subglacial lakes. However, due to the size restrictions of the DADU vehicle collection of large water samples is not feasible. Therefore, a small sample system with a particle enriching feature is desirable. A mechanical filter system could be used to increase the concentration of small particles, such as mi-

crobes, in a sample volume, although a fine grid filter system require pumps to force a flow through the system. These sampling devices, especially those aimed for the smaller classes of submersibles, must fit and also not strain the power budget of the submersible.

To enable collection of particles by the DADU submersible in hard-to-reach environments, compact sample enrichment system, using microfluidics and acoustic traps, was investigated, **Paper IV**.

Microfluidics

To enable investigation of the micro-sized organisms, micro-sized analysis tools can be used, such as the field of microfluidics, where fluidics devices are used with dimensions on the microscale. Similar to electronic circuits, microfluidics involves fluidic circuits where different fluids are transported through channels and chambers using different valves [106] and pumps [107] to perform biological and chemical experiments.

Some of the advantages in the field of microfluidics are that only small amounts of samples and reagents are required, in some cases only nanoliters, and from a given sample more measurements can be performed, increasing the accuracy. Scaling in microfluidic systems is beneficial since diffusion lengths are decreased. There is also a good control of the amounts of fluids that are dispensed, much more precise than with conventional techniques.

One of the most promising developments in microfluidics is a device that goes under the designation Lab-on-a-Chip (LOC) and Micro Total Analysis System (uTAS) [108], [109]. These are essentially biological and chemical laboratories on a microscale. This can enable patients themselves to introduce samples, which might have to be pre-treated [110], in the form of blood, saliva, urine, etc., in the chip. Ultimately, a single chip and a single drop of sample could be used to perform a multitude of assays and produce the results right away. The advent of this technology has led to simpler at-home diagnostics used today, such as pregnancy tests and blood glucose monitors, eliminating wait times associated with laboratory testing. This technology could be especially helpful in developing countries [111].

Manipulation of particles by acoustic forces

As has previously been discussed, PZT can be used to create acoustic waves in water. If these waves are reflected against a wall they can create standing waves, such as was seen in **Paper II**, and *Figure 33* of this work. Similar to the sonar device, a miniaturized integrated transducer (MIT) can be used to create standing waves in a microfluidic channel. This acoustic radiation field generates forces that have an effect on particles flowing with the water in the channel. The fast oscillations of the acoustic wave, with frequencies on the order of MHz, can give rise to a non-oscillating force where a particle, such

as a microorganism, will be pushed into a pressure node of the standing wave, *Figure 35*. As water with the particles is flushed through the microfluidic channel, the acoustic forces can trap the particles in the nodes, increasing their abundance in the sample volume. These acoustic forces are generally considered to be gentle and not to affect the particle itself in such cases where it is a living microorganism.

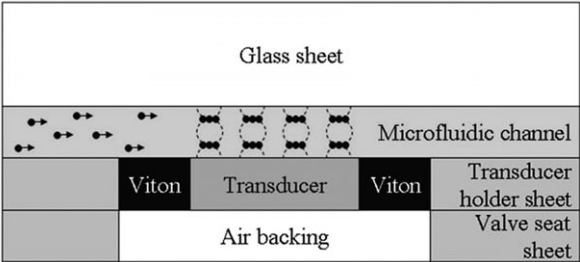


Figure 35. Cross-sectional schematic of the acoustic trap. As particles in the flow in the microfluidic channel enter the area above the MITs (transducer), which are glued (Viton) in the channel floor, these get trapped in the acoustic standing waves' pressure nodes.

Valves

An important aspect when collecting samples from specific areas is to be able to keep them pristine. Valves are commonly used to seal off the sampling areas to prohibit contamination. These valves need to create a good seal, especially in marine applications, where high pressures are involved. Valves come in two basic forms; active and passive. The active version needs a power consuming actuation to operate, while the passive version does not. Passive valves manage this by having a structure which makes flow in one direction more difficult than in the other. However, the active valves are preferred in marine applications, as these will provide a better seal, minimizing the risk of contamination of the samples.

To minimize the energy requirement of active valves, a latchable operation can be used, where the valve only requires energy when switching its states, i.e. there is no power consumption to keep the valve closed or open. This is especially important in the applications of the particle trap, where the operations of the valve are anticipated to be over very long time frames with low duty cycles.

Such a latching was investigated using three paraffin filled cavities, which could be activated, i.e. melted, individually in different sequences, **Paper IV**. Also, a combination of paraffin and low-melting-point alloy (LMA), *Figure 36*, was investigated, **Paper V**, due to the viscoelastic nature of paraffin, making it yield over time. Although an increased durability was seen for the LMA-paraffin valve, combining the actuation power of paraffin with

the structural stability of LMA, there were issues with manufacturing, where the LMA material did not wet as well as paraffin in the cavities during manufacturing, introducing air cavities that decrease the actuation of the valve. Furthermore, as the valve was activated several times, a decrease in performance was seen, due to the intermixing of LMA and paraffin. Further investigations are needed to resolve these issues.

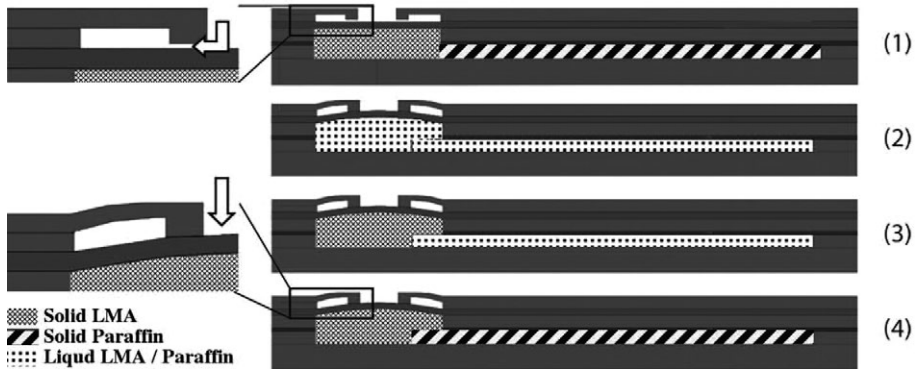


Figure 36. The actuation principle of the LMA-Paraffin valve. In (1) the valve is opened, as indicated by the arrow in the inset. In (2) both materials have been melted, where paraffin pushes the LMA to seal the gap between the membrane and the valve seat. In (3) the LMA is solidifying while the paraffin keeps pressure on the LMA. Lastly, in (4) the paraffin is allowed to cool, contracting, but since the LMA is already solidified, the valve remains closed.

Collecting the samples

Before the sampler is to be used, it should be thoroughly cleaned and sterilized, to ensure that no contaminants will compromise the collected samples. The microfluidic channel should be loaded with a non-compressible and sample-compatible sterile liquid. This is to further mitigate the risk of compromising the seal of the channel when the device is put under high pressures at depth. The microfluidic channel should then be closed by the valves and not reopened until the sample is to be acquired. As the sampling area of interest in the environment is reached, the valves should be opened and the surrounding liquid should be forced through the sampler by the movement of the submersible, where the acoustic traps will start enriching the collected sample. When some time has passed and enough liquid is deemed sampled, the valves will close and seal off the microfluidic channel. This seal should hold until opened again in a controlled laboratory environment, where the collected samples will be analyzed.

Building the sampling device

To enable a robust and small sampler device, a design with multiple stacked stainless steel, polyimide, and glass sheets were used, *Figure 37.*, forming the structures of the microfluidic channel and the high-pressure valves featured in **Paper IV**.



Figure 37. Exploded CAD view of the stack of stainless steel, polyimide, and glass sheets that make up the sampling device.

The device is 30 mm long, 15 mm wide, and a couple of millimeters high. One of the steel sheets in the stack accommodates the MITs, which forms the bottom of the microfluidic channel, while the glass sheet provides the acoustically reflective channel ceiling, as well as a viewing window, where any captured particles can be studied using a microscope. At each end of the sampling area of the microfluidic channel are the high-pressure valves, *Figure 38*.

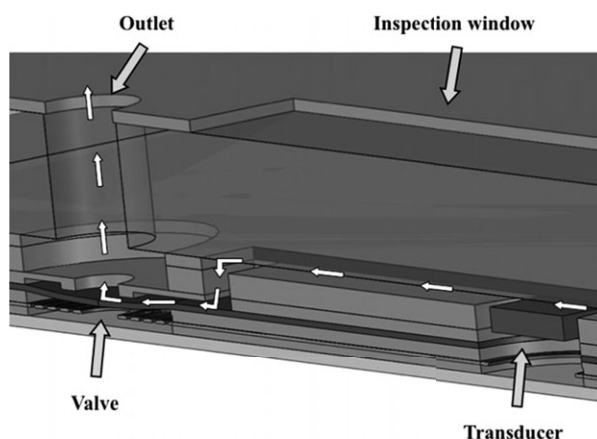


Figure 38. Cross-sectional schematic of the device, showing a valve at the left side and an MIT at the right side.

These are built by the principle where a polyimide membrane is made to seal against valve seat structures in the stainless steel through the actuation of paraffin-filled cavities. The paraffin is sequentially actuated by heater elements incorporated in the cavities, enabling a latchable function that only requires powering of the valves when they are to change their state between open and closed. On top, an inlet funnel directs a flow into the microfluidic channel by the external flow of water around the device. The stack of sheets is bonded and glued together, and contact pads are used to interface with its actuators externally.

Testing the trap

To investigate the performance of the sampling device, the acoustic trapping capability and the sealing of the high-pressure valves were characterized, **Paper IV**. It was of particular interest to investigate the acoustic trap's ability to capture and hold on to microorganisms during flow through the microfluidic channel. Tubes were connected to the device, carrying water with diluted micro-sized particles at different flow rates through the microfluidic channel. The acoustic traps were actuated and the sample volume above the MITs inspected using a microscope. It was found that the acoustic traps were able to capture particles and hold them in place, as the water was flushed through the system, *Figure 39*. It was found that the particles were trapped at flow rates of at least 15 $\mu\text{l}/\text{min}$, corresponding to an external flow of the sampling device of roughly 0.2 m/s, as investigated using computer simulations and experimental tests for a correlation between the external flow of the device and the internal flow created through the funnel. Furthermore, live microorganisms, in this case yeast cells, were also successfully captured in the acoustic trap.

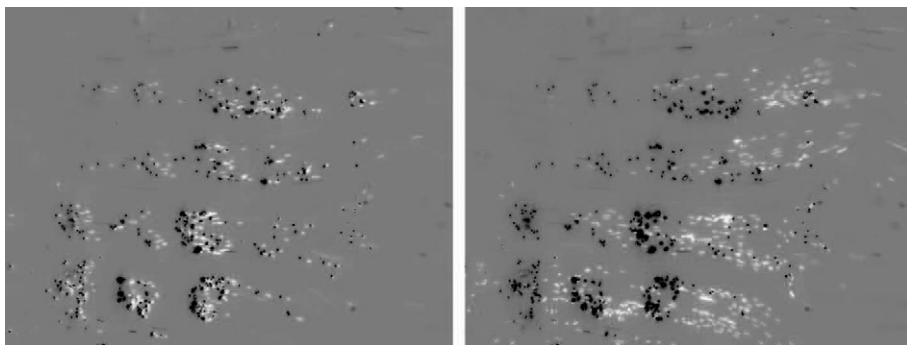


Figure 39. Micro-sized particles, white dots, held by the acoustic trap just as they are released to the flow (left) and a few seconds later (right). The black dots mark the initial places where the particles were being held.

For the valves, their ability to seal against a high pressure was tested by increasing the pressure on a valve while monitoring the pressure and the flow in the system. It was found that the valves were able to withhold a pressure difference, corresponding to over 200 meters depth, for 19 hours and to 1250 meters for a short time, without leakage. However, this was only for one actuation of the valve. By reactivating the valve, it was found that the seal could be reconditioned, increasing the time of sealing.

Conductivity, Temperature, and Depth measurements

To characterize water and its properties there are three parameters that are essential to measure: the conductivity, temperature, and depth (CTD). A CTD sensor is therefore an important instrument in oceanography, and as mentioned above, sampling of seawater is often combined with a CTD sensor. Measuring these three parameters, several other characteristics of the water can be calculated, such as density, freezing point, sound speed, but, most notably, the salinity. For instance, the salinity, along with temperature and acidity, are the main parameters affecting the functioning of cellular biology [11]. Besides directly affecting life, salinity has a great environmental and climatic impact, as it is one of the driving forces behind the world's ocean circulation. The salinity content of water also determines what water is usable for drinking and for agriculture in the world. It is therefore imperative to be able to measure and monitor the salinity of water.

Salinity is defined as the amount of salt that is present in one kilogram of water, and is commonly measured in parts per thousands (ppt) or per mil (‰). To measure the amount of salts dissolved in a sample, one would think that it is as simple as evaporating all the water. This, however, is not true, as the salinity of water stems from many different salts, and in different proportions as well. Therefore, as of 1978, salinity is defined according to the Practical Salinity Scale, where the conductivity of a sample is compared to that

of a specific potassium chloride (KCl) solution. The conductivity measurement has to be performed at precise temperature and pressure, as these two parameters affect the conductivity reading.

Freshwater is said to have a salinity of 0.5 ppt and the seawater around 35 ppt, and brine over 50 ppt. Over 90% of the ocean waters are below 5 °C [11], however the environmental conditions, under which the CTD in this work is aimed to operate, are salinities covering fresh to brine water in a temperature range of -5 to 40 °C at depths between 0 to 1000 m.

Ship based CTD measurements, although accurate and sensitive, are commonly performed with large sensors, deployed using cranes, where the sampling frequency and extent is limited to areas accessible by the ship. However, with some cost in accuracy and sensitivity, small measurement devices are feasible, able to fit on smaller vessels and even animals, to be used as measurement platforms. In **Paper VII**, a chip-based CTD sensor has been developed using MEMS technology, such as depositing and structuring processes of thin-film sensor elements.

The sensor chip

A chip, 7.5 by 3.5 mm in size, was designed to contain a conductivity, temperature, and depth sensing part, *Figure 40*. However, for a complete CTD measurement system, additional components are needed, such as the measuring electronics and batteries, which are estimated to take up a volume of no more than that of a common matchstick box.

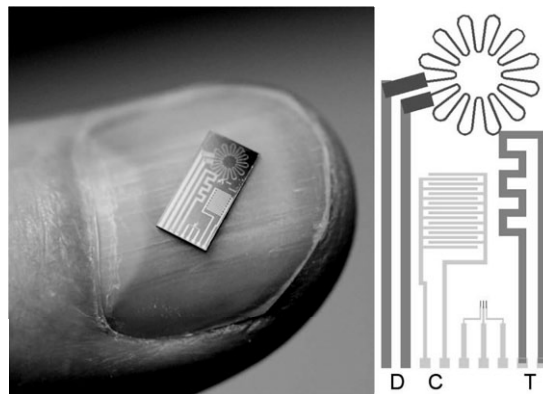


Figure 40. The 7.5 by 3.5 mm chip, left, containing a conductivity (C), temperature (T), and depth (D) sensor element, right.

Conductivity

The conductivity sensor is designed as two finger electrodes, *Figure 40*, made by a 200 nm thin layer of gold, with a 15 nm chromium layer under-

neath for increased adhesion. The structuring of the electrodes was performed by lithography and wet etching of the metallic layers.

When submerged in a saline solution, an electrical potential applied over these electrodes gives rise to a current, proportional to the ion concentration, between the electrodes. Through this, the conductance can be measured in the liquid.

Approximately 30 g of NaCl, the main constituent of the salts in ocean water, was mixed in 500 ml of water. This solution was subsequently diluted to create solutions of decreasing concentrations. As an AC potential was applied to the electrodes over a frequency span, the impedance through the liquid was measured. It was found that the sensor was able to detect the different salinities, and contrary to what was expected, operation frequencies in the MHz range were proven advantageous, **Paper VII**

Temperature

The temperature sensor is a thermal resistive device, made from a 150 nm thin layer of platinum, which is a material with a good linear resistance-to-temperature relationship. To this material, a 15 nm thick adhesive film of titanium was applied and both metallic films were structured through a lift-off process.

Due to the nature of the platinum structure, as the temperature changes, so will the resistance in the lead, and thus, by measuring the resistance, the temperature can be deduced. It was found that the temperature could be measured in the span of -5 to 40 °C with a high precision and a good linear response, **Paper VII**.

Depth

The depth sensor measures pressure, since the pressure in water increases by approximately one atmosphere for every ten meters of depth. A membrane and cavity structure was used, which was etched from the backside of the Si chip. The design of the membrane was investigated using FEA software. On the topside of the membrane, a 300 nm thin meander film, structured through the lift-off process of nichrome, an alloy of nickel and chromium, was made. Nichrome has a resistance-to-strain relationship, and as the pressure deforms the membranes, this can then be measured by a change in resistance.

As the pressure in an air container was changed between 1 and 7 atmospheres in **Paper VII**, the pressure sensor detected and recorded this change. The sensor shows potential, however, due to the test setup, higher pressures were not available and further investigations are needed to fully characterize this sensor.

Flow sensor

One of the larger problems small submersibles face in the water are currents. Since the vehicle is small, its thruster power is limited and it must overcome the overall drag on the system to be able to control its own locomotion. It is therefore crucial to monitor the water movement around the hull of the submersible, to detect increases in the flow before it is too late.

Furthermore, navigation underwater is a bit more troublesome than on land. Due to the physical properties of water, navigational aids on the surface, such as the GPS system, are not applicable. Navigation under water also includes all three dimensions, instead of the two we are accustomed to on land. As stated previously, there can be very limited visibility in water, *Figure 23* p. 49, decreasing the number of visual references available for controlled point-to-point navigation procedures. Without visual references, the surrounding body of water, if no large currents are present, could be used as a reference for navigation using a flow sensor.

In addition to the practical aspect of measuring the flow around the submersible, there is also scientific interest in the movement of water in an environment, even at very small flow rates. For instance, it has been estimated that the movement of water in Lake Vostok is a fraction of a millimeter per second.

A flow sensor can also provide valuable input in the operation of the aquatic sampler, **Paper IV**, where the flow direction and speed can be used to estimate the amount of water that has been sampled. In **Paper VI**, a thermal flow sensor that can fit on small submersibles has been investigated.

Measurement principle

The measurement principle of a thermal flow sensor is that a central heating element heats up the volume of water above it, while temperature sensors surrounding the heater register the temperature. If no lateral motion of the water is present, all sensors will read the same temperature. However, as a flow is initiated across the surface of the sensor, the heated water will be transported downstream, where an increase in temperature will be registered, compared with the sensor opposite of the heater element. By increasing the flow, a larger amount of heated water will be transported to the sensor downstream. The difference in signal output between the temperature sensors can thus be used to calculate the direction and speed of the water flow. However, as the flow rate increases further, there is a maximum sensing speed at which the water is transported too fast across the surface to heat the temperature sensor, at which point the temperature will decrease again.

As a current carries the warmed water downstream from the heating element, it will experience a cooling effect. This will result in a lower signal and measurement range. Therefore, it is beneficial to operate the heater ele-

ment in a constant temperature mode, where a feedback loop regulates the power to the heater, to keep the temperature constant.

If the sensor is hanging freely in a body of water, the measured speed will be the speed of the water. However, if mounted on a surface, the friction against the surface that is felt by the water will reduce its speed, meaning that the sensor will measure a speed which is actually slower than the speed of the free flowing water. Furthermore, depending on the structure on which the sensor is attached, water could have different speeds on different sides compared with the free flowing water, just like the difference in air speed above and underneath an airplane wing.

The flow chip

The sensors were designed on a chip measuring 9.5 x 9.5 mm, and 0.5 mm thick. The substrate used was Pyrex, because it has a lower thermal conductivity than Si, meaning there will be less heat losses through the substrate material. In the center of this substrate is a meander-shaped heater structure, and surrounding this are four meander-shaped temperature sensors, placed 90° apart. Nickel was used as the sensor material, as it has good temperature sensitivity. It was deposited as a 100 nm thick film using evaporation and patterned through a lift-off process. To protect the surfaces and to strengthen the contact bonds to the sensors, a 10 µm thick layer of Parylene was deposited on top of the sensors.

Predicting the performance

To design the heater and the temperature sensor elements, and to help predict the sensor's performance, a FEA model was created and used to simulate different flow speeds and directions, *Figure 41*. These simulations were then compared with the measurements performed.

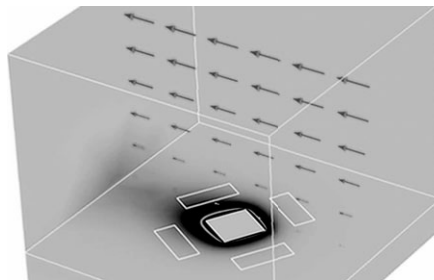


Figure 41. FEA simulation model with the heater element at the bottom center, surrounded by four rectangular temperature sensors. Water flows across the surface of the sensor, as indicated by the arrows, and carries heat downstream.

Measuring

To perform measurements, a holder with a flat surface and a submersible hull mockup were manufactured, *Figure 42*. Onto these, the measurement chip was mounted and then each set-up was fastened on a robotic arm, which was moved in different directions and at different speeds in a water tank.

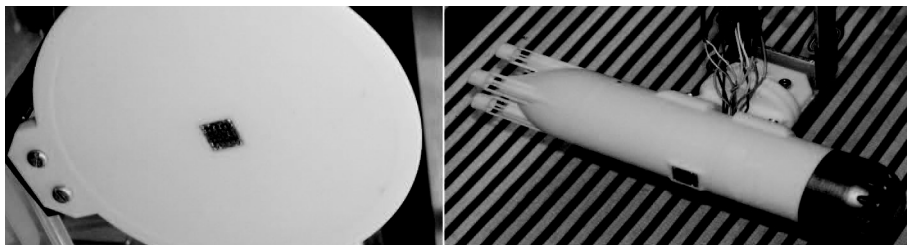


Figure 42. Flat surface structure, left, and hull mockup, right, that were used to mount the sensor chip. The quadratic flow measurement chip can be seen in the center of the left structure and on the side of the hull in the right one. The test structures were moved in a water tank with a robotic arm.

Measurement results for the different speeds and directions were plotted. The detection limit and sensitivity was of interest as the flow of water in subglacial lakes is estimated to be minute. Flow rates of under 0.5 mm/s were measured. For the direction measurements, at constant speeds, *Figure 43*, sine/cosine behaviors were obtained. As the speed in one direction is at a maximum, the speed in the perpendicular direction is close to zero, and vice versa, which was expected.

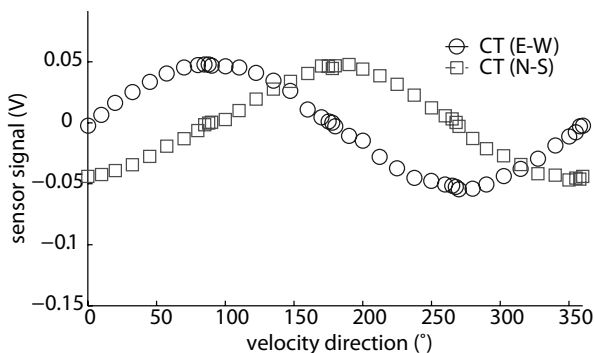


Figure 43. Fixed temperature measurement plot when travelling at a constant speed of 10 cm/s, for the pair of sensors in the east-west directions, CT(E-W) and the CT(N-S) direction.

The main finding of this work was that the flow sensors could measure the speed and direction of travel, even when operating at a constant temperature of only 2.5°C, at less than 15 mW of power, and measure speeds between 0 and 40 mm/s, where the upper speed limit was set by the robotic arm.

Discussion and Conclusions

The aim of the work presented in this thesis has been to investigate the miniaturization of some of the desirable instrumentation that could enable high functionality and good scientific return when using a miniaturized submersible for exploration of hard-to-reach submerged environments. It has been a challenge, but at the same time an inspiring experience to work with such a diverse set of instruments for such exciting applications, something that has been a great source of motivation.

Imaging systems have been developed, both acoustical and visual. The side-scanning sonar will aid in underwater navigation by long range mapping of the surroundings. The sonar has been tested in lakes and rivers, where the bottoms were successfully mapped. Despite its small size, it showed a good resolution and range. Further developments of the sonar could be to increase the frequency into the GHz range, enabling even better resolutions, however, at an expense in range.

The complementary laser topography measurement system for cameras has shown good performance in laboratory tests under simulated realistic conditions, demonstrating precise and close-range measurements and object shape reconstructions. If the size restrictions of the carrier submersible were not as strict as for the DADU submersible, a larger distance between the camera and sensor could enable measurements at larger ranges and higher accuracies, however, with a cost in close-range operations.

To further assist with the submersible's navigation and scientific measurements of the surrounding environment, the flow sensor can keep track of the surrounding water's flow direction and speed over the hull in two-dimensions. This sensor can also be mounted on a stationary object to, i.e. measure the movement at several positions in a body of water over time.

For measuring the important parameters of conductivity, temperature, and depth during a deployment, a sensor chip has been developed and tested, showing promise for measuring these properties of water. Such a small sensor chip could not only be used with small submersibles, but also on small marine animals, functioning as measurement platforms.

To sample hard-to-reach environments for small particles, such as microbes, and bring these back for studies in laboratory environments, the particle trap developed and tested, shows good potential, even at greater depths. This lab on a chip technology also has great potential applications in other

areas, such as healthcare and water environmental investigation and monitoring, which could advantageously be combined with the CTD sensor.

Overall, the systems developed, on their own or combined with each other, will enable the investigation of underwater environments only reachable by small submersibles, such as depicted on the cover of this thesis and in *Figure 44*. The systems would also be useful in concurrent applications with conventional systems, where their small size will add insignificant strain to the systems operations compared to their added scientific value. Additionally, with their small size, a larger number of devices can be accommodated compared with larger equivalent devices, increasing the redundancy and number of collected data points and samples.

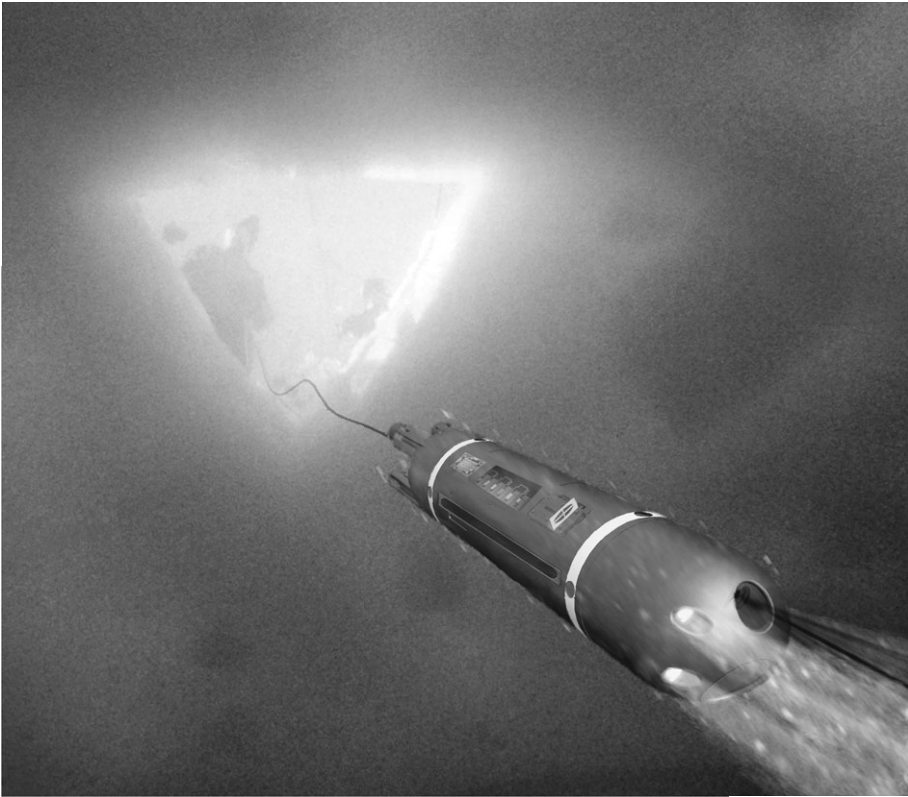


Figure 44. Artist's impression of a deployment of a small submersible, equipped with the instruments presented in this thesis, through a hole in the ice.

Outlook

Many exciting things have happened in underwater technology and exploration recently, and I believe that we will continue to see a great increase in the exploration and use of our underwater world in the future, requiring continuous technological developments to explore and use this resource in the best interests of man and the planet Earth. It would be very rewarding to see the technology and devices developed in this thesis work come to use in these endeavors.

The thick ice sheet above Lake Vostok has finally been penetrated, enabling the exploration of one of the last unvisited environments on our planet. Probing and performing in-situ investigation of this unknown but scientifically very exciting environment is now the next step, and will require technologies and miniaturized instruments such as those investigated in this thesis.

There is also strong evidence for such subsurface liquid water bodies elsewhere in our solar system, especially on the moon Europa, substantially increasing the potential for life to exist outside of Earth. A mission to explore Europa and its subsurface environment has been ranked as the second highest priority flagship space mission, and sending a submarine into this alien water world has recently been named “the holy grail of planetary exploration” by Steve Squyres, lead scientist for NASA's Spirit and Opportunity Mars rovers. A requirement for such a mission in the future is small and compact platforms and subsystems, something I hope the research that has come out of the DADU project can contribute to.

The National Geographic explorer and filmmaker James Cameron has, as I'm writing this, just returned from his trip to the deepest part of the oceans, the Mariana Trench's Challenger Deep, in a custom built one-man submersible where he collected scientific data and specimens, but most importantly, brought with him the dreams and future visions of a world that is so close, yet so far away.

To make this underwater world even closer for us as a species, and building on the visions of a future under the sea, The Atlantica Expeditions have the determination to launch and man the first permanent human colony beneath the sea, for humans to settle this last frontier on our planet. But for this to become a reality, further scientific and technologic development and research are needed.

Summary in Swedish

Jorden kallas ofta för den blå planeten, vilket inte är så konstigt då mer än 70% av dess yta täcks av hav. Haven har ett medeldjup på ca 3,8 kilometer, med ett största djup på omkring 11 km. Mount Everest, jordens högsta berg, är inte ens 9 km högt. Till följd av den globala uppvärmningen har man sett hur glaciärer och stora ismassor har börjat smälta och försvinna, vilket kan få ödesdigra konsekvenser för livet både på och under ytan.

Vatten spelar en viktig roll för livet. Var man än tittat, där det finns flytande vatten, har man också hittat liv. Man tror att livet på jorden en gång i tiden uppstod i vatten. Detta är några av anledningarna till att man i utforskningen av rymden letar efter just vatten i och utanför vårt solsystem.

Utforskningen av vissa vattenmiljöer kan dock vara väldigt svår, till exempel i de permanent istäckta och subglaciära sjöarna på Antarktis. Dessa sjöar antas likna de miljöer som kan finnas på andra platser i vårt solsystem, till exempel Jupiters måne Europa. För att undersöka sjöarna gäller det att kunna ta sig ner till dem, som i fallet med de subglaciära sjöarna kan röra sig om ett upp emot 4 km tjockt istäcke. Det enda sättet att ta sig dit är genom trånga borrhål, och då är det viktigt att farkosten, med vilken man ska utforska sjön, är liten och kompakt. Exempel på andra miljöer där storleken har betydelse för tillgängligheten och utforskningen är grottsystem, vattenledningar och vrak.

Dagens undervattensfarkoster är ofta för stora för att kunna ta sig fram till och in i dessa miljöer. Gör man dem tillräckligt små, får man istället ofta problem med att få plats med all den utrustning som krävs för att utforska dessa miljöer med. Vad som behövs för framtida expeditioner är alltså en liten, men ändå välutrustad undervattensfarkost.

Målet med denna avhandling har varit att undersöka möjligheterna till att miniatyrisera några av de instrument och subsystem som krävs för att utforska svårtillgängliga miljöer med. För att kunna åstadkomma detta har miniatyriseringsteknik, såsom mikrosystemteknik, utnyttjats, där man i väldigt rena och kontrollerade miljöer, så kallade renrum, tillverkar komponenter och system som kan ha dimensioner under en mikrometer, det vill säga mindre än en hundradel av bredden på ett hårstrå.

Undervattensfarkostskonceptet som använts i detta arbete är en torpedlik farkost, 20 cm lång och 5 cm i diameter, stor som en halvliters PET-flaska. Målet för farkosten och dess instrumentering har varit att den ska kunna operera ner till ett djup av en kilometer, där det omgivande trycket uppgår

till 100 atmosfärer. I och på undervattensfarkostens skrov ska alla medhavda system och instrument kunna få plats.

Styrning och framdrivning av undervattensfarkosten sköts genom åtta små motorer som kontrolleras via en upp till en kilometer lång fiberoptisk kabel som löper från en kontrollstation ned till undervattensfarkosten. Farkostens kraftkälla består av batterier, som ska kunna laddas upp genom den optiska fibern när undervattensfarkosten har nästlat sig in i tex en lång grotta. En liten dator ombord sköter all data- och kommandohantering.

Ett viktigt instrument i de flesta tillämpningar är en kamera, som tillhandahåller en visuell vy av farkostens omgivning, för den som opererar undervattensfarkosten och för de vetenskapsmän som vill studera något. Det kan dock vara svårt att tolka bilder som man får med en vanlig kamera, speciellt under vattnet, där miljön gör det svårt att uppskatta avstånd, storlekar, och former. För att underlätta detta har ett komplimenterande topografimätssystem utvecklats, **Papper III**. Detta består av en laser och en diffraktiv lins, som bryter ljuset som passerar genom den på ett sätt att ett visst mönster skapas på andra sidan. Genom att projicera ett specifikt mönster på ett objekt och sedan avbilda det med kameran, kan man genom att studera hur mönstret deformeras, räkna ut på vilket avstånd det belysta objektet befinner sig, och vilken form och storlek det har.

I miljöer där sikten är väldigt dålig kan man istället för ljus använda sig av akustiska vågor för att se med, eftersom akustiska vågor är mindre känsliga för små partiklar i vattnet. En mycket liten sidskanningssonar, som kan få plats på undervattensfarkosten, har utvecklats, **Papper I och II**. Sonaren skickar ut en solfjäderformad akustisk puls i vattnet, parallellt med farkostens färdriktning, och registrerar sedan reflektionerna från objekt i dess omgivning. Genom att successivt scanna, linje för linje, allt eftersom undervattensfarkosten färdas framåt, kan man bygga upp en akustiks bild över området.

De två ovan nämnda instrumenten kan underlätta kartläggning och navigation i en okänd miljö. Eftersom det är svårt att veta var undervattensfarkosten egentligen befinner sig, då vanliga tekniska lösningar på land, såsom GPS-system, inte fungerar under vattnet, kan man behöva räkna sig fram till hur undervattensfarkosten har rört sig. Detta kan till viss del göras med hjälp av gyron och accelerometrar, men som ett komplement till dessa har en flödessensor utvecklats, **Papper VI**. Flödessensorn består av ett chip över vars yta vattnets strömningshastighet och riktning kan mätas. Med denna sensor kan farkostskrovet rörelse i förhållande till det omgivande vattnet mätas, vilket, förutom som understöd till navigationen, också är intressant för utforskningen av miljöerna farkosten befinner sig i.

För att karakterisera undervattensmiljöer har också ett chip med konduktivitet-, temperatur-, och trycksensorer utvecklats, **Papper VII**. En sådan uppsättning med sensorer brukar kallas CTD efter dess engelska benämning. CTD är ett viktigt instrument inom oceanografi och från dessa tre vattenpa-

rametrar kan man exempelvis räkna ut densiteten och saliniteten. Salinitet, eller salthalt, är en parameter som har en stor betydelse, från hur de globala strömmarna i haven beter sig, till vilka sorters mikroorganismer som kan leva i en viss miljö.

Har man tagit sig in i en miljö som väldigt sällan, eller till och med aldrig tidigare har utforskats kan det vara väldigt intressant att därifrån kunna ta med sig några prover. För att möjliggöra detta har en liten partikelinsamlare utvecklats, **Papper IV och V**. Denna består av en liten kanal i vilket små akustiska element sitter monterade. När vatten strömmar genom kanalen kan dessa, likt sonaren beskriven här ovan, skicka ut akustiska vågor, vilka genom reflektion mot en glasvägg på andra sidan kanalen, skapar en stående akustisk våg. Partiklar, som exempelvis mikroorganismer, som flödar förbi genom kanalen kan fångas in av dessa akustiska vågor och, som om de vore fångade i ett filter, stannar kvar medan vattnet fortsätter ut genom kanalen. På detta sätt kan man berika ett annars volymmässigt litet prov. När insamlingen är klar, stänger högtrycksventiler i vardera änden av kanalen och håller provet isolerat tills det kan analyseras i ett laboratorium.

Den forskning som presenteras i denna avhandling kommer förhoppningsvis att kunna bidra till utforskningen av hittills svåra, eller helt oåtkomliga, undervattensmiljöer på jorden, och kanske till och med på andra himlakroppar. Jag tror att jordens undervattensmiljöer kommer att få en allt mer betydande roll, och att människan måste lära sig mer om att hantera och utnyttja denna resurs på ett hållbart sätt.

Lake Vostok som är den största av de omkring 140 kända subglaciära sjöarna, har en yta ungefär tre gånger så stor som Vänern och har detta år nåtts med ett 4 km långt borrhål. Sjön har troligen varit isolerad av ett konstant istäcke i flera miljoner år och forskarna har liten vetskap om vad som kan dölja sig där i djupet. För att få reda på detta kan man förslagsvis skicka ned en tillräckligt liten farkost och utforska denna med en uppsjö av olika instrument enligt det koncept som presenterats och studerats i detta avhandlingsarbete.

Vid katastrofer likt den då färjan Costa Concordia gick på grund med 4200 passagerare, är det viktigt att snabbt, men också säkert, kunna ta sig in genom små och trånga utrymmen för att söka efter överlevande. Här skulle en liten och portabelt undervattensfarkost kunna komma till god användning för att snabbt kunna söka igenom ett förlist fartyg.

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References

- [1] E. Seedhouse, *Ocean Outpost*. Chichester, UK: Springer–Praxis Publishing, 2011.
- [2] M. Nakanishi and J. Hashimoto, “A precise bathymetric map of the world’s deepest seafloor, Challenger Deep in the Mariana Trench,” *Mar Geophys Res*, vol. 32, no. 4, pp. 455–463, 2011.
- [3] P. Delecluse, “The origin of climate changes.,” *Rev Sci Tech*, vol. 27, no. 2, pp. 309–317, 2008.
- [4] J. Bamber, R. Riva, and B. Vermeersen, “Reassessment of the potential contribution to sea level from a collapse of the West Antarctic Ice Sheet,” *IOP Conference Series: Earth and Environ Sci*, vol. 6, p. 012004, 2009.
- [5] M. J. Riddle, M. Craven, P. M. Goldsworthy, and F. Carsey, “A diverse benthic assemblage 100 km from open water under the Amery Ice Shelf, Antarctica,” *Paleoceanography*, vol. 22, no. 1, p. PA1204, 2007.
- [6] D. G. Vaughan and R. Arthern, “Climate change. Why is it hard to predict the future of ice sheets?,” *Science*, vol. 315, no. 5818, pp. 1503–1504, 2007.
- [7] W. B. Whitman, D. C. Coleman, and W. J. Wiebe, “Prokaryotes: the unseen majority.,” *Proc. Natl. Acad. Sci. U.S.A.*, vol. 95, no. 12, pp. 6578–6583, 1998.
- [8] D. M. Karl, “Microbial oceanography: paradigms, processes and promise,” *Nature Reviews Microbiology*, vol. 5, no. 10, pp. 759–769, 2007.
- [9] J. I. Lunine, *Astrobiology: A multidisciplinary approach*. Benjamin-Cummings Pub Co, 2005.
- [10] T. Garrison, *International Student Edition-Essentials of Oceanography*. Thomson, 2005.
- [11] L. Dartnell, *Life in the universe: a beginner's guide*. Oneworld Publications Ltd, 2007.
- [12] R. Cavicchioli, R. Amils, D. Wagner, and T. McGenity, “Life and applications of extremophiles.,” *Environ. Microbiol.*, vol. 13, no. 8, pp. 1903–1907, 2011.
- [13] L. RothschildMancinelli, “Life in extreme environments,” *Nature*, vol. 409, pp. 1092–1101, 2002.
- [14] H. Huber, M. J. Hohn, R. Rachel, T. Fuchs, V. C. Wimmer, and K. O. Stetter, “A new phylum of Archaea represented by a nanosized hyperthermophilic symbiont.,” *Nature*, vol. 417, no. 6884, pp. 63–67, 2002.
- [15] K. Takai, K. Nakamura, T. Toki, U. Tsunogai, M. Miyazaki, J. Miyazaki, H. Hirayama, S. Nakagawa, T. Nunoura, and K. Horikoshi, “Cell proliferation at 122 degrees C and isotopically heavy CH4 production by

- a hyperthermophilic methanogen under high-pressure cultivation,” *PNAS*, vol. 105, no. 31, pp. 10949–10954, 2008.
- [16] J. B. Sylvan, B. M. Toner, and K. J. Edwards, “Life and death of deep-sea vents: bacterial diversity and ecosystem succession on inactive hydrothermal sulfides,” *MBio*, vol. 3, no. 1, pp. 1–10, 2012.
 - [17] J. Baross and S. Hoffman, “Submarine hydrothermal vents and associated gradient environments as sites for the origin and evolution of life,” *Origins of Life and Evolution of Biospheres*, vol. 15, pp. 327–345, 1985.
 - [18] S. L. Miller and J. L. Bada, “Submarine hot springs and the origin of life,” *Nature*, vol. 334, no. 6183, pp. 609–611, 1988.
 - [19] W. Martin, J. Baross, D. Kelley, and M. J. Russell, “Hydrothermal vents and the origin of life,” *Nature Reviews Microbiology*, vol. 6, no. 11, pp. 805–814, 2008.
 - [20] S. Vance, J. Harnmeijer, J. Kimura, H. Hussmann, B. deMartin, and J. M. Brown, “Hydrothermal Systems in Small Ocean Planets,” *Astrobiology*, vol. 7, no. 6, pp. 987–1005, 2007.
 - [21] P. R. Pinet, *Invitation to oceanography*. London, UK: Jones & Bartlett Publishers Intl, 1998.
 - [22] E. Domack, S. Ishman, A. Leventer, and S. Sylva, “A chemotrophic ecosystem found beneath Antarctic ice shelf,” *Eos*, vol. 86, no. 29, pp. 269–276, 2005.
 - [23] P. T. Doran, R. A. Wharton, and W. B. Lyons, “Paleolimnology of the McMurdo Dry Valleys, Antarctica,” *J Paleolimnol*, vol. 10, pp. 85–114, 1994.
 - [24] D. Y. Sumner, I. Hawes, and D. Andersen, “Microbialite Response to Environmental Change in Lake Joyce, Antarctica,” *LPI Contributions*, vol. 1538, p. 5048, 2010.
 - [25] M. Siegert, S. Carter, and I. Tabacco, “A revised inventory of Antarctic subglacial lakes,” *Antarctic Science*, vol. 17, pp. 453–460, 2005.
 - [26] M. J. Siegert, “Antarctic subglacial lakes,” *Earth-Science Reviews*, vol. 50, no. 1, pp. 29–50, 2000.
 - [27] J. C. Priscu, E. E. Adams, W. B. Lyons, M. A. Voytek, D. W. Mogk, R. L. Brown, C. P. McKay, C. D. Takacs, K. A. Welch, C. F. Wolf, J. D. Kirshtein, and R. Avci, “Geomicrobiology of subglacial ice above Lake Vostok, Antarctica,” *Science*, vol. 286, no. 5447, pp. 2141–2144, 1999.
 - [28] B. C. Christner, E. Mosley-Thompson, L. G. Thompson, and J. N. Reeve, “Isolation of bacteria and 16S rDNAs from Lake Vostok accretion ice,” *Environ. Microbiol.*, vol. 3, no. 9, pp. 570–577, 2001.
 - [29] M. Siegert, R. Hindmarsh, H. Corr, A. Smith, J. Woodward, E. King, A. Payne, and I. Joughin, “Subglacial Lake Ellsworth: a candidate for in situ exploration in West Antarctica,” *Geophys. Res. Lett.*, vol. 31, p. L23403, 2004.
 - [30] M. J. Siegert, A. Behar, M. Bentley, D. Blake, S. Bowden, P. Christoffersen, C. Cockell, H. Corr, D. C. Cullen, H. Edwards, A. Ellery, C. Ellis-Evans, G. Griffiths, R. Hindmarsh, D. A. Hodgson, E. King, H. Lamb, L. Lane, K. Makinson, M. Mowlem, J. Parnell, D. A. Pearce, J. Priscu, A. Rivera, M. A. Sephton, M. R. Sims, A. M. Smith, M. Tranter, J. L. Wadham, G. Wilson, and J. Woodward, “Exploration of Ellsworth Subglacial Lake: a concept paper on the development, organisation and

- execution of an experiment to explore, measure and sample the environment of a West Antarctic subglacial lake,” *Rev Environ Sci Biotechnol*, vol. 6, no. 1, pp. 161–179, 2006.
- [31] H. Kristmannsdóttir, A. Björnsson, S. Pálsson, and Á. E. Sveinbjörnsdóttir, “The impact of the 1996 subglacial volcanic eruption in Vatnajökull on the river Jökulsá á Fjöllum, North Iceland,” *J Vol Geoth Res*, vol. 92, no. 3, pp. 359–372, 1999.
- [32] J. Benjamin, C. Bonsall, A. Fisher, and C. Pickard, *Submerged Prehistory*. Oxbow Books Ltd, 2011.
- [33] T. M. Iliffe, R. Kvitek, S. Blasco, K. Blasco, and R. Covill, “Search for Bermuda’s deep water caves,” *Hydrobiologia*, vol. 677, no. 1, pp. 157–168, 2011.
- [34] B. C. Gonzalez, T. M. Iliffe, J. L. Macalady, I. Schaperdoth, and B. Kakuk, “Microbial hotspots in anchialine blue holes: initial discoveries from the Bahamas,” *Hydrobiologia*, vol. 677, no. 1, pp. 149–156, 2011.
- [35] M. Russell, J. Gardiner, Bournemouth University. School of Conservation Sciences, *Rough quarries, rocks and hills*. Oxbow Books Ltd, 2001.
- [36] S. Fields, “The Earth’s Open Wounds: Abandoned and Orphaned Mines,” *Environ Health Perspect*, vol. 111, no. 3, pp. a154–a161, 2003.
- [37] R. D. Ballard and J.-L. Michel, “How we found titanic,” *National Geographic*, vol. 168, no. 6, pp. 696–719, 1985.
- [38] D. Rounce, “How human intervention is harming the wreck of RMS Titanic, and how the site is protected by law,” *The Post Hole*, no. 5, 2011.
- [39] C. P. McKay, “The search for life in our Solar System and the implications for science and society,” *Philos Trans Roy Soc A*, vol. 369, no. 1936, pp. 594–606, 2011.
- [40] R. D. Lorenz, D. Gleeson, O. Prieto-Ballesteros, F. Gomez, K. Hand, and S. Bulat, “Analog environments for a Europa lander mission,” *Advances in Space Research*, vol. 48, no. 4, pp. 689–696, 2011.
- [41] O. Prieto-Ballesteros, N. Rodríguez, J. S. Kargel, C. G. Kessler, R. Amils, and D. F. Remolar, “Tírez Lake as a Terrestrial Analog of Europa,” *Astrobiology*, vol. 3, no. 4, pp. 863–877, 2003.
- [42] H. Lammer, J. H. Bredehöft, A. Coustenis, M. L. Khodachenko, L. Kaltenegger, O. Grasset, D. Prieur, F. Raulin, P. Ehrenfreund, M. Yamachi, J. E. Wahlund, J. M. Grießmeier, G. Stangl, C. S. Cockell, Y. N. Kulikov, J. L. Grenfell, and H. Rauer, “What makes a planet habitable?,” *Astron Astrophys Rev*, vol. 17, no. 2, pp. 181–249, 2009.
- [43] R. Lopes, “Beyond Earth: How extra-terrestrial volcanism stretches our definition of a volcano,” *AGU Spring Meeting Abstracts*, vol. 1, p. 03, May 2007.
- [44] D. Schulze-Makuch, “Io: Is Life Possible Between Fire and Ice?,” *Journal of Cosmology*, vol. 5, pp. 912–919, 2010.
- [45] M. G. Kivelson, K. K. Khurana, C. T. Russell, M. Volwerk, R. J. Walker, and C. Zimmer, “Galileo magnetometer measurements: a stronger case for a subsurface ocean at Europa,” *Science*, vol. 289, no. 5483, pp. 1340–1343, 2000.
- [46] R. T. Pappalardo, M. J. S. Belton, H. H. Breneman, M. H. Carr, C. R. Chapman, G. C. Collins, T. Denk, S. Fagents, P. E. Geissler, B. Giese,

- R. Greeley, R. Greenberg, J. W. Head, P. Helfenstein, G. Hoppa, S. D. Kadel, K. P. Klaasen, J. E. Klemaszewski, K. Magee, A. S. McEwen, J. M. Moore, W. B. Moore, G. Neukum, C. B. Phillips, L. M. Prockter, G. Schubert, D. A. Senske, R. J. Sullivan, B. R. Tufts, E. P. Turtle, R. Wagner, and K. K. Williams, "Does Europa have a subsurface ocean? Evaluation of the geological evidence," *J Geophys Res*, vol. 104, no. 10, pp. 24015–24055, 1999.
- [47] C. Chyba and C. Phillips, "Europa as an abode of life," *Origins of Life and Evolution of Biospheres*, vol. 32, pp. 47–68, 2002.
- [48] S. E. Billings and S. A. Kattenhorn, "The great thickness debate: Ice shell thickness models for Europa and comparisons with estimates based on flexure at ridges," *Icarus*, vol. 177, no. 2, pp. 397–412, 2005.
- [49] B. E. Schmidt, D. D. Blankenship, G. W. Patterson, and P. M. Schenk, "Active formation of 'chaos terrain' over shallow subsurface water on Europa," *Nature*, vol. 479, no. 7374, pp. 502–505, 2011.
- [50] C. Chyba and C. Phillips, "Possible Ecosystems and the Search for Life on Europa," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 98, no. 3, pp. 801–804, 2001.
- [51] K. P. Hand, R. W. Carlson, and C. F. Chyba, "Energy, Chemical Disequilibrium, and Geological Constraints on Europa," *Astrobiology*, vol. 7, no. 6, pp. 1006–1022, 2007.
- [52] O. Korablev, M. Gerasimov, J. Brad Dalton, K. Hand, J.-P. Lebreton, and C. Webster, "Methods and measurements to assess physical and geochemical conditions at the surface of Europa," *Advances in Space Research*, vol. 48, no. 4, pp. 702–717, 2011.
- [53] L. Zelenyi, O. Korablev, M. Martynov, G. A. Popov, M. Blanc, J. P. Lebreton, R. Pappalardo, K. Clark, A. Fedorova, E. L. Akim, A. A. Simonov, I. V. Lomakin, A. Sukhanov, and N. Eismont, "Europa Lander mission and the context of international cooperation," *Advances in Space Research*, vol. 48, no. 4, pp. 615–628, 2011.
- [54] R. Gowen, A. Smith, A. Fortes, S. Barber, P. Brown, P. Church, G. Collinson, A. Coates, G. Collins, and I. A. Crawford, "Penetrators for in situ subsurface investigations of Europa," *Advances in Space Research*, vol. 48, pp. 725–742, 2011.
- [55] A. Rager, T. Hanley, C. Calvin, and T. Balint, "Endurance: The rewards and challenges of landing a spacecraft on europa," *AGU Fall Meeting Abstracts*, p. B113, 2005.
- [56] National Academy of SciencesNational Research Council, *Vision And Voyages For Planetary Science In The Decade 2013-2022*. Washington: National Academies Press, 2011.
- [57] C. P. McKay, C. C. Porco, T. Altheide, W. L. Davis, and T. A. Kral, "The Possible Origin and Persistence of Life on Enceladus and Detection of Biomarkers in the Plume," *Astrobiology*, vol. 8, no. 5, pp. 909–919, 2008.
- [58] E. R. Stofan, C. Elachi, J. I. Lunine, R. D. Lorenz, B. Stiles, K. L. Mitchell, S. Ostro, L. Soderblom, C. Wood, H. Zebker, S. Wall, M. Janssen, R. Kirk, R. Lopes, F. Paganelli, J. Radebaugh, L. Wye, Y. Anderson, M. Allison, R. Boehmer, P. Callahan, P. Encrenaz, E. Flamini, G. Francescetti, Y. Gim, G. Hamilton, S. Hensley, W. T. K. Johnson, K.

- Kelleher, D. Muhleman, P. Paillou, G. Picardi, F. Posa, L. Roth, R. Seu, S. Shaffer, S. Vetrella, and R. West, "The lakes of Titan," *Nature*, vol. 445, no. 7123, pp. 61–64, 2007.
- [59] C. McKay and H. Smith, "Possibilities for methanogenic life in liquid methane on the surface of Titan," *Icarus*, vol. 178, pp. 274–276, 2005.
- [60] D. Schulze-Makuch and D. H. Grinspoon, "Biologically enhanced energy and carbon cycling on Titan?," *Astrobiology*, vol. 5, no. 4, pp. 560–567, 2005.
- [61] O. Grasset, C. Sotin, and F. Deschamps, "On the internal structure and dynamics of Titan," *Planetary and Space Science*, vol. 48, pp. 617–636, 2000.
- [62] A. Fortes, "Exobiological implications of a possible ammonia-water ocean inside Titan," *Icarus*, vol. 146, pp. 444–452, 2000.
- [63] H. Hussmann, F. SOHL, and T. SPOHN, "Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects," *Icarus*, vol. 185, no. 1, pp. 258–273, 2006.
- [64] G. Robuchon and F. Nimmo, "Thermal evolution of Pluto and implications for surface tectonics and a subsurface ocean," *Icarus*, vol. 216, pp. 426–439, 2011.
- [65] H. Heidt, J. Puig-Suari, A. Moore, S. Nakasuka, and R. Twiggs, "CubeSat: A new generation of picosatellite for education and industry low-cost space experimentation," in *Proceedings of the ...*, 2000, vol. 0, pp. 1–19.
- [66] R. D. Christ and R. L. Wernli, *The ROV manual: a user guide to observation-class remotely operated vehicles*. Oxford: Butterworth-Heinemann, Elsevier Ltd., 2007.
- [67] F. N. Spiess, K. C. Macdonald, T. Atwater, R. Ballard, A. Carranza, D. Cordoba, C. Cox, V. M. D. Garcia, J. Francheteau, J. Guerrero, J. Hawkins, R. Haymon, R. Hessler, T. Juteau, M. Kastner, R. Larson, B. Luyendyk, J. D. Macdougall, S. Miller, W. Normark, J. Orcutt, and C. Rangin, "East Pacific Rise: Hot Springs and Geophysical Experiments," *Science*, vol. 207, no. 4438, pp. 1421–1433, 1980.
- [68] K. Hardy, "Return to the Titanic: The Third Manned Mission," *Sea Technology*, vol. December, pp. 1–5, 1991.
- [69] J. T. Tanacredi and J. Loret, *Ocean pulse: a critical diagnosis*. New York: Plenum Press, 1998.
- [70] R. Geline, *Trapped in the Deep*. Raintree Publishers, 1980, p. 47.
- [71] R. A. Geyer, *Submersibles and their use in oceanography and ocean engineering*. Amsterdam: Elsevier Science, 1977.
- [72] A. Behar, F. Carsey, A. Lane, and H. Engelhardt, "The Antarctic Ice Borehole Probe," *IEEE Aerospace Conference Proceedings*, vol. 1, pp. 325–330, 2001.
- [73] F. Carsey, A. Behar, A. L. Lane, V. Realmuto, and H. Engelhardt, "A borehole camera system for imaging the deep interior of ice sheets," *Journal of Glaciology*, vol. 48, no. 163, pp. 622–628, 2002.
- [74] L. French, F. Anderson, F. Carsey, A. Lane, P. Shakkottai, and W. Zimmerman, "Cryobots: An answer to subsurface mobility in planetary icy environments," *Proc ISAIRAS*, pp. 1–8, 2001.
- [75] W. Zimmerman, R. Bonitz, and J. Feldman, "Cryobot: an ice penetrating

- robotic vehicle for Mars and Europa,” *IEEE Aerospace Conference Proceedings*, vol. 1, pp. 1/311–1/323, 2001.
- [76] W. Zimmerman, F. S. Anderson, M. Hecht, 7, “The Mars '07 North Polar Cap deep penetration cryo-scout mission,” *CORD Conference Proceedings*, vol. 1, pp. 1/305–1/315, 2002.
- [77] E. Gaidos, V. Marteinsson, T. Thorsteinsson, T. Jóhannesson, A. R. Rúnarsson, A. Stefansson, B. Glazer, B. Lanoil, M. Skidmore, S. Han, M. Miller, A. Rusch, and W. Foo, “An oligarchic microbial assemblage in the anoxic bottom waters of a volcanic subglacial lake,” *ISME J*, vol. 3, no. 4, pp. 486–497, 2009.
- [78] T. Thorsteinsson, S. Elefsen, E. Gaidos, B. Lanoil, T. Johannesson, V. Kjartansson, V. Marteinsson, and A. Steffansson, “A hot water drill with built-in sterilization: Design, testing and performance,” *Jökull*, vol. 57, pp. 71–82, 2007.
- [79] E. Gaidos, B. Glazer, D. Harris, Z. Heshiki, N. Jeppsson, M. Miller, T. Thorsteinsson, B. Einarsson, V. Kjartansson, A. Stefansson, L. Gabriel, Q. de Camargo, T. Jóhannesson, M. Roberts, M. Skidmore, and B. Lanoil, “A simple sampler for subglacial water bodies,” *Journal of Glaciology*, vol. 53, no. 180, pp. 157–158, 2007.
- [80] J. Horvath, F. Carsey, J. Cutts, and J. Jones, “Searching for ice and ocean biogenic activity on Europa and Earth,” *JPL Technical Report Server*, 1997.
- [81] P. T. Doran, W. Stone, J. Priscu, C. McKay, A. Johnson, and B. Chen, “Environmentally Non-Disturbing Under-ice Robotic ANtarctic Explorer (ENDURANCE),” *AGU Fall Meeting Abstracts*, vol. 1, p. 05, 2007.
- [82] S. Gulati, K. Richmond, C. Flesher, B. P. Hogan, A. Murarka, G. Kuhlmann, M. Sridharan, W. C. Stone, and P. T. Doran, “2010 IEEE International Conference on Robotics and Automation,” *IEEE International Conference on Robotics and Automation*, pp. 308–315, 2010.
- [83] A. Behar and F. Bruhn, “Exploring miniaturization limits for an instrumented autonomous submersible explorer for extreme environments,” *13th International Symposium on Unmanned Untethered Submersible Technology*, 2003.
- [84] F. Winquist, P. Wide, and I. Lundström, “An electronic tongue based on voltammetry,” *Analytica Chimica Acta*, vol. 357, no. 1, pp. 21–31, 1997.
- [85] Institute of Marine Engineers, *The journal of offshore technology*. California: Marine Management Holdings, 2005.
- [86] A. E. Behar, “Development of a Micro Subglacial Lake Exploration Device,” *AGU Fall Meeting Abstracts*, vol. 1, p. 0522, 2010.
- [87] J. Jonsson, J. Sundqvist, H. Nguyen, H. Kratz, M. Berglund, S. Ogden, K. Palmer, K. Smedfors, S. Wagner, and G. Thornell, “Miniaturized submersible for exploration of small aqueous environments,” in *OCEANS 2011*, 2011, pp. 1–8.
- [88] J. E. Moore and R. Compton-Hall, *Submarine warfare*. Bethesda: Adler & Adler Publishers, 1987.
- [89] R. Burcher and L. Rydill, *Concepts in submarine design*. Cambridge: Cambridge Univ Press, 1995.
- [90] A. Bowen, D. Yoerger, S. Hulme, 22, “Field trials of the Nereus hybrid

- underwater robotic vehicle in the challenger deep of the Mariana Trench,” *CORD Conference Proceedings*, pp. 1–10, 2009.
- [91] M. J. Madou, *Fundamentals of microfabrication: the science of miniaturization*. Bosa Roca: CRC Press Inc, 2002.
 - [92] M. Freund and G. Mózes, *Paraffin products: properties, technologies, applications*. Oxford: Elsevier Science Ltd, 1982.
 - [93] P. Zoller and D. J. Walsh, *Standard pressure-volume-temperature data for polymers*. Bosa Roca: CRC Press Ltd, 1995.
 - [94] D. Richardson, Al Hornsby, C. K. Stewart, and P. A. O. D. Instructors, *PADI open water diver manual*. Santa Ana: International PADI, Inc, 1988.
 - [95] C. Rohner, A. Richardson, A. Marshall, S. Weeks, and S. Pierce, “How large is the world's largest fish? Measuring whale sharks *Rhincodon typus* with laser photogrammetry,” *Journal of Fish Biology*, vol. 78, pp. 378–385, 2011.
 - [96] P. Drap, J. Seinturier, D. Scaradozzi, P. Gambogi, L. Long, and F. Gauch, “Photogrammetry for virtual exploration of underwater archaeological sites,” *XXI International CIPA Symposium*, 2007.
 - [97] H. Singh, F. Weyer, J. Howland, A. Duester, D. Yoerger, and A. Bradley, “Quantitative Stereo Imaging from the Autonomous Benthic Explorer (ABE),” *OCEANS '99 MTS/IEEE*, vol. 1, pp. 52–57, 1999.
 - [98] C. C. Chang, C. Y. Chang, and Y. T. Cheng, “Distance measurement technology development at remotely teleoperated robotic manipulator system for underwater constructions,” *CORD Conference Proceedings*, pp. 333–338, 2004.
 - [99] M. Z. Brown, D. Burschka, and G. D. Hager, “Advances in computational stereo,” *IEEE Trans. Pattern Anal. Machine Intell*, vol. 25, no. 8, pp. 993–1008, 2003.
 - [100] C.-C. Wang and M.-S. Cheng, “Nonmetric Camera Calibration for Underwater Laser Scanning System,” *J Ocean Eng*, vol. 32, no. 2, pp. 383–399, 2007.
 - [101] D. M. Kocak, F. M. Caimi, P. S. Das, and J. A. Karson, “A 3-D Laser Line Scanner for Outcrop Scale Studies of Seafloor Features,” *OCEANS '99 MTS/IEEE*, vol. 3, pp. 1105–1114, 1999.
 - [102] S. Pedrotti, *Introduction to Optics*. New Jersey: Prentice-Hall, 1993.
 - [103] L. B. Lesem, P. M. Hirsch, and J. A. Jordan, “The Kinoform: A New Wavefront Reconstruction Device,” *IBM J. Res. & Dev.*, vol. 13, no. 2, pp. 150–155, 1969.
 - [104] J. J. Bengtsson, “Kinoform design with an optimal-rotation-angle method,” *Appl Opt*, vol. 33, no. 29, pp. 6879–6884, 1994.
 - [105] M. Purcell, D. Gallo, A. Sherrell, M. Rothenbeck, and S. Pascaud, “Use of REMUS 6000 AUVs in the search for the Air France Flight 447,” *CORD Conference Proceedings*, pp. 1–7, 2011.
 - [106] K. Oh and C. Ahn, “A review of microvalves,” *J Micromech Microeng*, vol. 16, pp. R13–R39, 2006.
 - [107] D. Laser and J. Santiago, “A review of micropumps,” *J Micromech Microeng*, vol. 14, pp. R35–R64, 2004.
 - [108] D. R. Reyes, D. Iossifidis, P.-A. Auroux, and A. Manz, “Micro total analysis systems. 1. Introduction, theory, and technology,” *Anal. Chem.*,

- vol. 74, no. 12, pp. 2623–2636, 2002.
- [109] P.-A. Auroux, D. Iossifidis, D. R. Reyes, and A. Manz, “Micro total analysis systems. 2. Analytical standard operations and applications.,” *Anal. Chem.*, vol. 74, no. 12, pp. 2637–2652, 2002.
- [110] A. J. de Mello and N. Beard, “Dealing with real samples: sample pre-treatment in microfluidic systems.,” *Lab Chip*, vol. 3, no. 1, pp. 11N–19N, 2003.
- [111] C. D. Chin, V. Linder, and S. K. Sia, “Lab-on-a-chip devices for global health: past studies and future opportunities.,” *Lab Chip*, vol. 7, no. 1, pp. 41–57, 2007.

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