Masteroppgave

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Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for marin teknikk

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DINA module integration on underwater vehicles for improved under ice capabilities and autonomy

Systematic Approach to the design of an underwater docking station

Masteroppgave i Cold Climate Engineering: Sea Track
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Cold Climate Engineering

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Aalto University
School of Engineering

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Supervisors:

Martin Ludvigsen

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July 2022

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Master`s Agreement / Main Thesis Agreement

Faculty	**Faculty of Engineering**
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The Master`s thesis

Starting Date	**01.02.2022**
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Thesis Working Title	**DINA module integration on underwater vehicles for improved under ice capabilities and autonomy**
Problem Description	**Currently, Underwater unmanned vehicles (UUVs) face several challenges when operating unde ice. The main one being the communications and transfer of data due to the fact that acoustic communications offer very low bandwidths that lead to very slow transfer of information to and from the vehicle. The MARtera UNDINA project has proposed a new multimodal communications modem that; in addition to acoustic communications, will also allow for communication with optical and inductive methods that can offer higher rates of data transfer while underwater. This thesis will physically integrate the DINA module proposed in the MARtera UNDINA project into a docking station for a Blueye X3 ROV that may allow the vehicle for battery recharging and data tranfer while underwater as well as to determine how the designed station could help the Blueye and other vehicles have better autonomy in ice-covered waters**

This Master`s agreement must be signed when the guidelines have been reviewed.

Signatures

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21.02.2022
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Abstract

Unmanned Underwater Vehicles (UUVs) currently depend on surface vessels for their launch and recovery. While operating they still need either to be tethered to the surface vessel or resurfacing maneuvers to reliably operate in the sea. This in turn leads to logistical challenges and limitation to their overall autonomy given that in environments like heavy sea states or ice-covered waters, UUVs cannot rely on the surface without being exposed to the risk of damage or total loss.

This thesis proposes a station that will allow UUVs to operate fully autonomously without depending upon the surface as it integrates the multi communications module developed in the MarTERA UNDINA project to give UUVs the possibility of conducting their navigation and communications while underwater. It will also give UUVs the possibility of not having to be retrieved and taken back to base to have their batteries recharged as the UUVs would have the possibility of recharging them between deployments by docking unto the proposed station.

The proposed mechanical design for the station is demonstrated to be fit for its planned installation in Tronheimsfjord by aligning with DNV recommended practices and standards that ensure a sustainable building of the structure as well as for its safe installation with deck crane.

Finally, an alternative designed is proposed for the station that will make it suitable for its possible installation in other sites besides Trondheimsfjorden like Kongsfjord in Svalbard where the station would also be of help to deploy UUVs with more reliability.

The next steps in this line of work would be to build the proposed station for it to be installed in its planned deployment location and the development of the inductive module which is still in its concept state.

Sammendrag

Ubemannet Undervanns Farkoster; UUVer for forkortelsen på engelsk, med den tilgjengelige teknologien, er avhengige av overflatefartøyer for å være utplassert og berget. Når de gjennomfører et oppdrag, har de behov enten av å ha tilkobling til overflatefartøyet eller fra tid til annen stige til overflaten til å operere pålitelig ut i havet. Dette fører til logistiske utfordringer og begrensning til UUVene sin autonomi på grunn av at UUVer ikke kan være avhengig av overflaten uten å utsette seg for fare av å bli skadet eller mistet når de opererer når værforholdene er ekstreme eller områder hvor havoverflaten fryses.

Denne oppgaven foreslår en stasjon som vil tillate UUVer å operere med hel autonomi uten avhengigheten av overflaten for stasjonen integrerer den multikommunikasjonsmodulen utviklet i MarTERA UNDINA prosjektet som har formålet av å gi UUVene muligheten til å utføre sin kommunikasjon og navigasjon når de er undervanns. Den modulen vil også gi UUVene muligheten til å lade opp batteriene sine uten å måtte være hentet tilbake til basen, som betyr at UUVene kunne i stedet lade batteriene sine opp mellom oppdrag ved å dokke inn i stasjonen.

Det foreslått mekaniske designet til stasjonen er bevist til å være egnet for sin planlagte installasjon i Trondheimsfjorden med å møte anbefalte praksiser og standarder til DNV som forsikrer den bærekraftige bygningen av strukturen i tillegg til sin trygge installasjon med ei dekkskran.

Til slutt er et alternativt design til stasjonen foreslått. Dette designet har som hensikt til å egne stasjonen for sin installasjon i andre steder som Kongsfjorden i Svalbard hvor stasjonen også kunne hjelpe utplassere UUVer med høyere pålitelighet.

De neste skrittene i denne arbeidslinja er å bygge den foreslåtte stasjonen, etterpå kan den være installert i sin tiltenkte beliggenhet og å utvikle den induktive modulen som fortsatt er i konsepttilstand.

Preface

This thesis was written in collaboration with the Applied Underwater Robotics Laboratory (AUR-Lab) which is the institution that represents the Norwegian University of Science and Technology (NTNU) within the MarTERA UNDINA project. The original objective of the thesis back when it was conceived in October of 2021 was intended to be the development of an algorithm that would allow a Blueye ROV to dock unto a platform that would integrate the DINA module. However, this proved to be a task somewhat out of the expertise of the writer, which is why at its beginning during February of 2022, the focus was changed to the design of the platform itself.

The reasons behind that change are the fact that the writer of this thesis is more familiarized with the software tools necessary for the development of such a design and that it was a project that would allow for the implementation of the lessons learned in the operations the writer had the privilege of taking part in both in Svalbard during the summer of 2021 and in Trondheim during his collaboration with AUR-Lab.

This thesis is therefore the first effort of integrating the DINA module unto a platform that will actually be installed by NTNU later this year of 2022 in Trondheim. The design was done in collaboration with another student who is undergoing an internship with AUR-Lab Emilie Schoch and the design received constant feedback from all the people within NTNU that is involved in the development of both the MarTERA UNDINA and OceanLab project.

Acknowledgements

Firstly, I would like to thank Professor Martin Ludvigsen for giving me the opportunity to work with him since the moment I asked him whether I could write my thesis about AUVs in Svalbard back in August of 2021. As my supervisor, he gave me very close and crucial support throughout the writing of both this thesis and the specialization project that came before it. He also gave me the opportunity to gain practical experience in the field of underwater robotics and marine operations through AUR-Lab. My other supervisor Professor Pekka Forsman in Aalto also deserves my gratitude as he agreed to supervise me in this project despite the fact that it fell within a field totally outside of his field of expertise and research.

I would like to give a thank you to the directors of my degree Jukka Tuhkuri, Knut Høyland and Gunvor Kirkelund for their support throughout my time as their student. In this same line, all of AUR-Lab deserves a big thank you for their facilities, expertise and guidance that were vital for the development of this thesis. Specially to their Senior Engineers Pedro de la Torre and Kay Arne Skarpnes, regardless of the fact that I will not have the chance to keep working with you after this thesis, your input will always be of help.

Thank you to all my former fellow residents at Tavasttähti for having given me a place in their house during the first year of the program where we had to endure the thickest part of the Covid-19 pandemic and got to learn so much of each other.

The crew of RV Gunnerus also deserves a big heads-up for letting me be a part of their team in the cruises and operations I was invited to take part in, my time on board your ship allowed me to put my Norwegian into practice more than ever as well as to learn how marine operations need to be performed safely and efficiently.

Special thanks to Javier Gómez Subils and Tuomas Romu. The former for his advice back in January of 2022 which helped me get through the specialization project that came before this thesis right when I thought everything was lost and the latter for his contributions which were key for the realization of this thesis.

Lastly but most importantly. I would like to thank my whole family for always being there for me even if I found myself at the other side of the globe. You all are the best, never change. And my biggest show of gratitude is to my mother. This degree is yours as much as it is mine given that it was your effort what supported me all throughout the course if these two years and it was your love what always motivated me to give my best at all times. You are the absolute best.

Jorge Manuel Casillas Rodríguez

Trondheim, July 2022

Contents

Abbreviations

ADCP	Acoustic Doppler Current Profiler
AUR-Lab	Applied Underwater Robotics Laboratory
AUV	Autonomous Underwater Vehicles
CATCHY	Canadian AUV Through-ice Capture and Hold sYtem
CTD	Conductivity Temperature Density
DINA	multimoDal communIcations and Network-Aided positioning system
DP	Dynamic Positioning
DVL	Doppler Velocity Log
LAUV	Light Autonomous Underwater Vehicle
LBL	Long BaseLine
MBARI	Monterrey Bay Aquarium Research Institute
NRCan	Natural Resources Canada
NTNU	Norwegian University of Science and Technology
OSV	Offshore Supply Vessel
PLM	Pig Loop Module
RV	Research Vessel
SIC	Sea ice concentration
TBS	Trondheim Biological Station
UNDINA	Underwater multimoDal communIcations and Network-Aided positioning system
USBL	Ultra-short BaseLine
UUV	Unmanned Underwater Vehicle

Figures

Tables

Equations

Chapter I: Introduction

The purpose of this thesis is to design an underwater docking station for untethered UUVs that fully integrates the UDINA communications module. The advantages that this station offers when compared to already existing underwater docking platforms for UUVs is also discussed as well as an analysis of how this station could allow for better capabilities for AUVs in ice-covered waters.

Motivation

For centuries, the Arctic was considered to be a region where the climactic and environmental conditions were so extreme that rendered most human activities impossible. However, due to climate change, temperatures in the Arctic have experienced an increase up to 3 times more significant hat those observed in other regions of the Earth. This has led to a drastical decline in sea ice concentration; SIC, which saw its lowest level in September of 2012 [1].

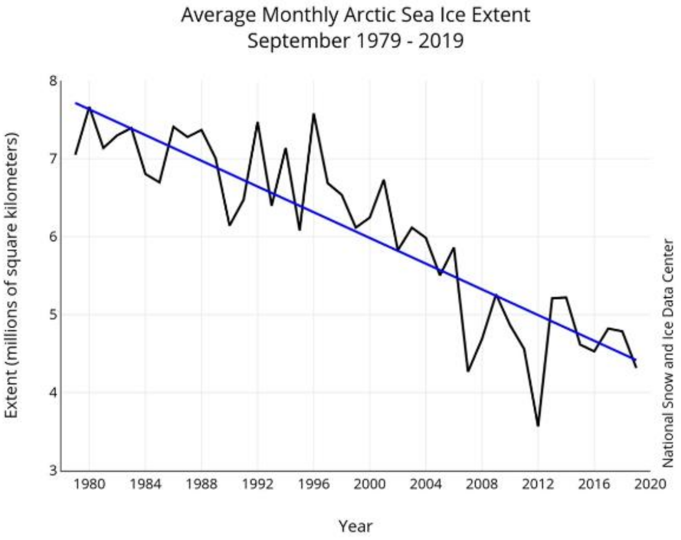

Figure 1: SIC lowest recorded extent in 2012

This decrease in SIC has turned the Arctic Ocean from that for long inhospitable region into one where both economic and strategic values could be obtained. Economic given that the United States Geological Survey has estimated the Arctic region to contain 13% and 30% of the undiscovered oil and gas reserves respectively [2]. And while those estimated reserves are still highly costly to exploit, that has not stopped both state and private owned companies from conducting surveys in search for possible extraction sites like it was the case of Shell plc. In 2012 [3]. Other companies have even begun establishing oil and gas extraction operations in the Arctic region, this has been mainly observed in Russia where state owned companies like Gazprom or Rosneft currently have several drilling operations in the Russian Arctic [4].

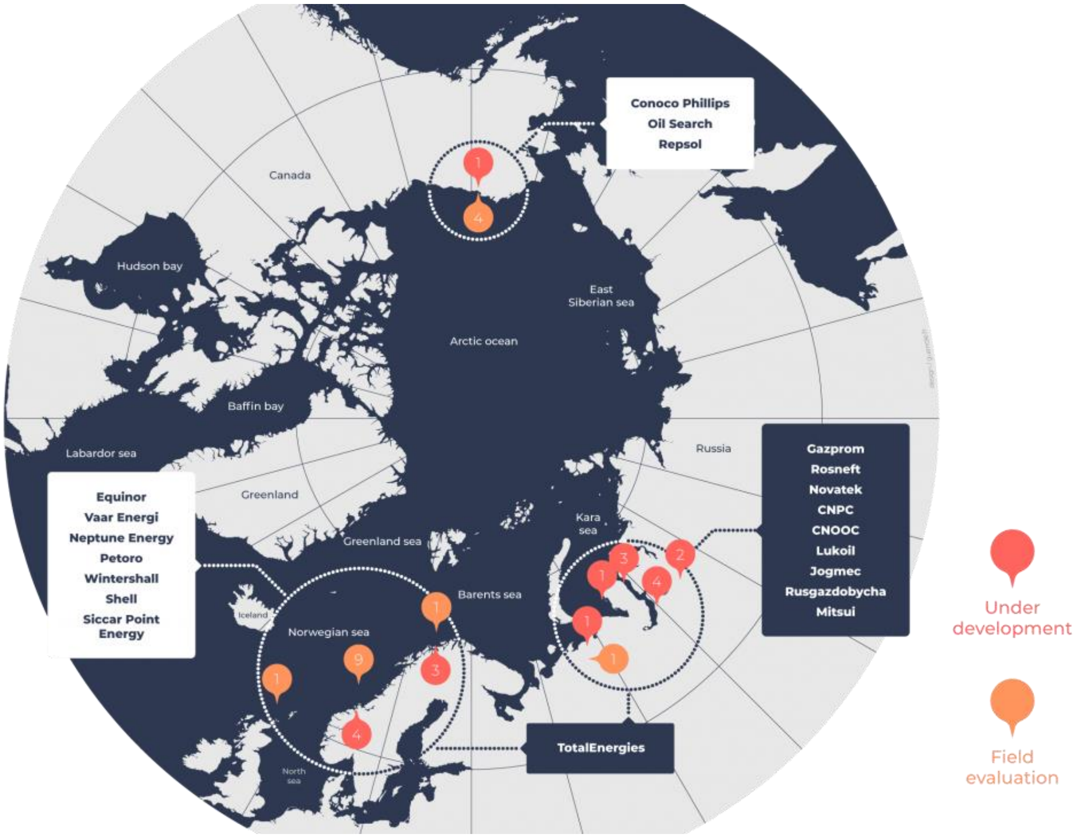

Figure 2: Oil and gas Operarations in the Arctic

The decrease in SIC has also led to widespread changes within the ecosystems in the Arctic that have affected species ranging from large mammals like polar bears or whales to microscopic organisms like phytoplankton or algae [5]. While there is a wide range of studies into the changes experienced by the larger species in the Arctic, the research into the processes that concern the lower end of the food chain in the Arctic marine ecosystems is quite low considering that their study is really challenging with means like satellite remote sensing. With that, understanding of the atmospheric mechanisms behind the Arctic region's climate has become of great importance if sustainability is ever to be found in the region.

Oceanography is one of the areas where the Arctic region has become of great relevance due to the fact that the region is mostly covered by the Arctic Ocean. An ocean that, even with the current climactic situation, is always covered to a varying extent by sea ice that in turn makes surface based oceanographic surveys highly challenging. That is why Unmanned Underwater Vehicles (UUVs) has become very attractive for oceanographic operation in the Arctic Region, because they are flexible mobile sensor platforms capable of covering very wide spatial ranges and that can avoid the challenges surface vessels face when conducting surveys in ice covered waters.

Background

Unmanned Underwater Vehicles are sensor platforms that can function underwater without the need of human occupation. They can be divided into two main categories:

- Remotely Operated Vehicles (ROVs)
- Autonomous Underwater Vehicles (AUVs)

Both AUVs and ROVs trace their origins to the decade of the 1960' when they were first developed for applications closely related to the US Navy. By the decade of the 1990', both ROVs and AUVs had become more commercially available and widely used for industrial purposes; mainly in the oil and gas industry. Currently, they are also used for scientific applications and their capabilities have developed to the point that they can be operated at depths of up to 11 km [6], for periods of up to weeks in the case of AUVs [7].

Nevertheless, UUVs suffer from a significant disadvantage, that being that their operation always conveys a certain level of risk which in the worst-case scenario could leave the vehicle unable to further maneuver. In such case, UUVs can benefit from the fact that they are purposely built with positive buoyancy that can allow them to float back to the surface and await their recovery [8].

However, when operating in ice-covered waters, UUV's do not have the possibility to resurface. This has already led to the loss of two AUVs under the ice in the Antarctic Region. The first of which happened in 2005 when the Autosub2 AUV was deployed under the Fimbul ice shelf, lost communications and was stranded 15km under the shelf of some 180 meters in thickness [9]. The other incident happened in 2019 when the AUV 7 was lost under multiyear ice in the Wedell Sea, after 3 days of search, the vehicle was deemed lost as the ice conditions prevented the SA Algulhas II from searching any further [10].

That explains why Petter Norgren, despite demonstrating how AUVs could be used for under-ice operations such as subsurface ice features monitoring, considers the need for more and better underwater infrastructure and communications as the main factor limiting AUVs from widespread use under ice [11].

The DINA modem proposed in the MarTERA UNDINA project has the potential of solving those inconveniences as it integrates 3 communication types for UUVs to use while underwater. One of them is the already widely used acoustic signals. The other type is optical communication which allows for high-bandwidth data transfer in a range that can span some tens of meters. By integrating these communications, this module would allow for both long-range and short-range communications with the acoustic and optical modems respectively. And, when a UUV were to be within range of both modules, the station needs to determine the amount of data transmitted to and from the vehicle with each of the modules in order to guarantee the best possible data transfer rate and power consumption [12].

The third type of communications that the proposed DINA modem in the MarTERA UNDINA project integrates is inductive communications which allows for data transfer with even higher bandwidths; when compared with its optical counterpart, in addition to the wireless recharging of batteries. With the disadvantage of having an extremely limited range of just millimeters that would therefore require the vehicle to be docked into a station.

Scope and limitations

The main focus of this thesis is to design an underwater docking station that fully integrates the DINA module proposed in the MarTERA UNDINA project.

Two different designs will be proposed in this thesis. The first of which, apart from following the guidelines of the MarTERA UNDINA project, would also need to take into considerations the Ocean Lab project undergone between NTNU, the Norwegian Research Council and SINTEF which is a larger scale project that aims to build a network of marine facilities to accommodate both educational and scientifical activities. The Ocean Lab project consists of 4 phases, the first of which (already in operation) is the one that is of interest for this thesis as one of its modules installed in the Trondheimsfjord is where the proposed station in this thesis is to be integrated. Therefore, the design would need to be adapted to the already existing infrastructure of OceanLab.

The MarTERA UNDINA project has decided to integrate the proposed module into 3 different vehicles. Which are the Poggy AUV currently still in development by EvoLogics and two ROVs, the Seasam Drone (manufactured by Notilo Plus) and the Blueye X3 with the hope that the UNDINA module could in the future allow for the elimination of their umbilical altogether. The vehicle that will be taken as the model for this thesis is the Bueye X3.

The second of the proposed designs is intended for the installation of the proposed station without the presence of the OceanLab infrastructure. The purpose of that second design is intended for the implementation of the proposed UNDINA Platform in other locations apart from Trondheimsfjord where it could be of aid for UUV deployments. One such location would be in Kongsfjord outside Ny Ålesund or Van Mijenfjord outside of Sveagruva in Svalbard where ice can occasionally be present. Of worth clarifying is that such implementation has not been planned, which is why it will be treated as just a possible field of application for the proposed design in this thesis.

The design of such docking station is a vast process, this thesis will focus mainly on the mechanical design of the station. Additionally, the following topics are covered:

- Description of the chosen instruments that will be installed on the station.
- Hydrodynamical analysis of the proposed station when installed in the Trondheimsfjord.
- Description of the chosen material and dimensions for the station.

Other aspects of the design such as the electronical configuration of the instruments, the economic analysis of the project or the necessary modifications needed for adapting the station to other vehicles besides the Blueye X3 will not fall inside the scope of this thesis.

Objective

The main purpose of this thesis is to design an underwater station for UUVs that may serve as a communications base for nearby operating UUVs in addition to giving them possibility of docking into it and recharge their batteries at the end of a mission.

The objective above can be achieved by fully integrating the DINA module which combines acoustic and optical communications. Thereby allowing for both long and short range as well as for low and high bandwidth communications underwater. The DINA module also features an inductive modem that allows for wireless battery charging on top of data transfer while the vehicle is docked.

This design will be created with the help of SOLIDWORKS where the station will be modelled and optimized accordingly to the needs of the project. This includes the design and modelling of the structure, the material choice for the structure, the choices of the instruments for both navigation and communication that the station will feature and the integration of the chosen instruments unto the station.

Once the station is designed, another objective of this thesis is to analyze the possibilities the proposed station would offer for the operation of UUVs in ice covered waters. This analysis will only be based upon the areas of opportunity identified in the reports of previous UUV deployments.

Chapter II: Literature review

Remotely Operated Vehicles (ROVs)

ROVs are UUVs which feature a tether, known also as the umbilical, that connects the vehicle to a control base; most often a surface vessel, where human operators can control the vehicle in real-time. The umbilical has the main purpose of providing the ROVs a communication link to its control base, but depending on their use and characteristics, the umbilical can also transmit power to the vehicle. ROVs can be used for operation where simple visual inspections are required. Such operations can be hull surveying or pipeline inspection. However, most of the ROVs under operation are employed in more complex operations where the handling of materials or equipment underwater is needed. Good examples of such operations can be the installation of underwater infrastructure like blowout preventors or search and rescue missions.

Figure 3: ROV

ROVs are assets that are commonly used for both scientific and, more commonly, industrial purposes due to the fact that they are capable of operating at very extreme depths of up to kilometers with high levels of reliability and overcoming the limitations that human operators would face when diving to such depths. ROVs are very commonly equipped with video cameras, light sources and sonar systems for visual capabilities. Depending on their purposes, some ROVs can also be equipped with manipulators.

However, the main hinder of ROVs is their umbilical [13]. This is best demonstrated by the fact that most of the energy ROVs use for propulsion goes towards dragging the tether which is highly affected by currents. Additionally, the tether itself must be handled with great care as to the contrary it could find itself getting caught by the propellers of either the surface vessel or of the ROV itself. The tether can also be a limiting factor to the mobility of the ROV as it must always be either followed by the surface vessel or tethered to a fixed structure. This explains why ROVs are usually centered towards small-scale studies or operations where precision and accuracy are the priority.

Autonomous Underwater Vehicles (AUVs)

AUVs, unlike their ROV counterparts, do not feature any tethering. This allows them to conduct operations with a larger spatial and temporal range without suffering from the limitation that the umbilical implies. AUVs are therefore commonly used for recollection of geophysical and oceanographic data in marine environments with high levels of reliability and efficiency.

AUVs have experienced great developments since their invention in the late decade of the 1960' [14] to the point that they have allowed for their operation at depths of up to 6km and offer a very diverse range for their applications.

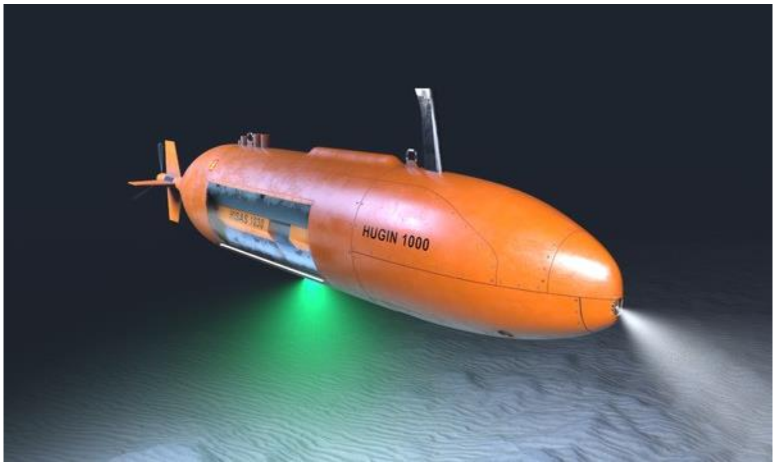

Figure 4: AUV

However, AUVs suffer from some disadvantages. The most significant one being the fact that, while underwater, they face a significant challenge in their communications due to the fact that seawater dampens electromagnetic waves. This renders communications like radio, GPS or Wi-fi completely useless.

While underwater, and with the current technology, AUVs conduct their communication with acoustic signals that have the advantage of having a range that expands to the scale of kilometers. However, acoustic communications have very high levels of power consumption and only offer very low bandwidths which in turn means that they cannot be used to transmit very high amounts of information [12]. When AUVs require higher bandwidth communications, they are programmed to ascend to the surface where they can utilize electromagnetical signals like Wi-fi or GPS. This is commonly done when new mission commands want to be sent to AUVs or when the AUV seeks to obtain accurate position references with GPS fixes.

The other major disadvantage of AUVs, when compared to their ROV counterparts, is the fact that power consumption is a more important factor during their operations given that their only source of energy are their batteries. In order to optimize operational range, both the speed at which the AUV travels as well as the sensors that are to be functional during an operation need to be chosen carefully. This in order to optimize energy consumption by both the propeller and the hotel load induced by the sensors (navigational and payload). That same need for optimal power consumption is what explains the design of AUVs which have the purpose of reducing the hydrodynamical loads of the vehicle.

Previous similar projects

CATCHY

In 2010, NRCan embarked on a survey where they conducted bathymetric surveys in the Canadian Archipelago where they deployed an AUV called Explorer for 12 days under the ice-covered waters outside of Resolute Bay. The Mission's main camp was located in Borden Island while the AUV made use of a remote camp approximately 300 km northwest where it was able to transfer the collected data back to base, receive new mission commands and recharge its batteries [15].

Figure 5: Explorer AUV

This was with the help of a dock called CATCHY which was developed specifically for this deployment by Memorial University. The CATCHY dock consisted of a squared structure of 1,5 m in length, it was fixed to the top of the ice and under the ice, a cradle would hold the vehicle in place while docked. The CATCHY dock allowed for both data transfer and battery recharging, but its disadvantage it that it required the assistance of an ROV to physically connect a tether to the AUV and to fasten the AUV with the help of ropes unto the station [16].

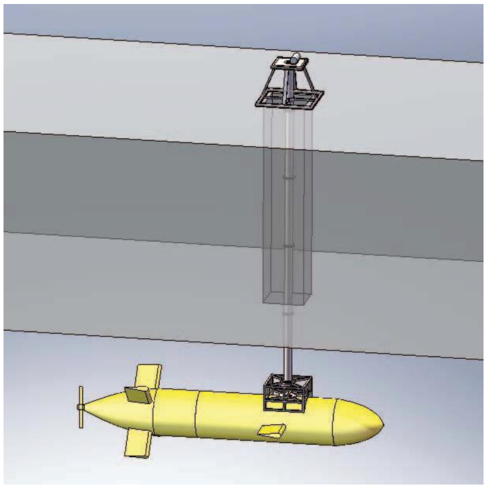

Figure 6: CATCHY System

CATCHY fulfilled its intended purpose of providing a remote base for the Explorer AUV in the area of interest for its deployment. But it had to be relocated after the first mission due to the fact that the ice in the original site began to break and compromised the safety of the dock for both the AUV and the personnel in site.

MBARI AUV dock

MBARI developed in the year of 2007 a docking station for a Dorado/Bluefin 21’’ AUV. The motivation behind this dock was to remove the dependency that the AUVs had upon ship support for power resupply, data transfer and for the acquisition of new mission commands. The dock developed by Hobson. et al. [17] was also part of a larger project that has the objective of collecting both water column measurements and bathymetry maps in the Monterrey Bay.

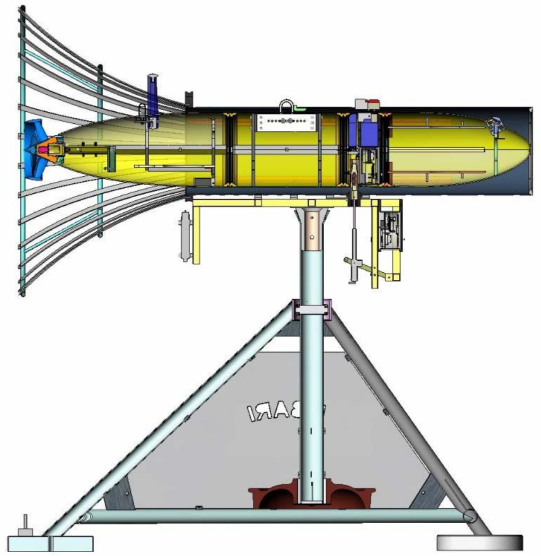

Figure 7: MBARI AUV dock

This docking station is a fixed cone type where the AUV is held in place by a cylindrical structure where all the instruments are located. The entrance of the cylinder features a conical grid to aid the vehicle when making its final approach to the station. This station was operational for 5 months in the Monterrey Bay and demonstrated high reliability when transferring data and mission commands to and from the AUV via a short range ethernet link. When it comes to battery recharging, the MBARI dock made use of pin that would insert itself into the AUV to both hold it in place and to then transfer power to the vehicle via inductive signals.

Figure 8: MBARI AUV dock after recovery

Description of design approach

The chosen design methodology for this project is the Systematic Approach described by Pahl, Beitz, Feldhusen and Grote in their book Engineering Design [18]. Their approach consists of defining a problem or unsatisfactory condition that is sought to be solved. A goal or satisfactory situation is then realized. Throughout the whole design process, the Systematic Approach specifies the presence of obstacles that prevent the reaching of the desired satisfactory condition. Those obstacles can either be identified since the beginning of the project when the problem and the goal are defined, or at different points in time during the design process.

The Systematic Approach, establishes a set of conditions that need to be met in order for the method to be satisfactorily employed. The first of those conditions is the clear definition of the goal that is sought, as well as its further subdivision into more particular and specific subgoals that will need to be considered during the design process.

Once the goal and subgoals are defined, the next condition specified by Pahl. Et al [18]. consists of determining the constraints that will be present during the design process. This has the objective of preventing any possible efforts that need not be part of the project. With the objectives and constraints formulated, the next condition is the search of solutions that help solve the initial problem upon the project's goal was defined.

The next condition for the proper implementation of the Systematic Approach is the evaluation of all of the solutions found based upon the previously established goals and constraints. This with the objective of combining the best aspects of the proposed solutions and of discarding those that do not meet the desired goals or that fall outside of the defined constraints. In order to ensure a proper decision making, both the solutions and objectives need to be evaluated since *"Without decisions and experiencing their consequences there can be no progress"* as Pahl. Et al. state [18, p. 53].

In order to adequately fulfill the aforementioned conditions, Pahl. Et al. consider the dispelling of prejudice as crucial for the Systematic Approach in order to maximize the range of solutions that are sought.

The steps formulated in the Systematic Approach when solving a problem are the following below:

- ***Confrontation.*** Where the designer assesses what is known and what needs to be known.
- ***Definition.*** In this step, the problem is defined more abstractly to determine the best course of action and the constraints,
- ***Creation.*** This is the phase of the process where a solution is developed and; when multiple of them, combined.
- ***Evaluation.*** The proposed solution is analyzed in this step. To determine its advantages and disadvantages.
- ***Decision.*** When more than one solution is proposed, based on the objectives, the best one of them is selected.

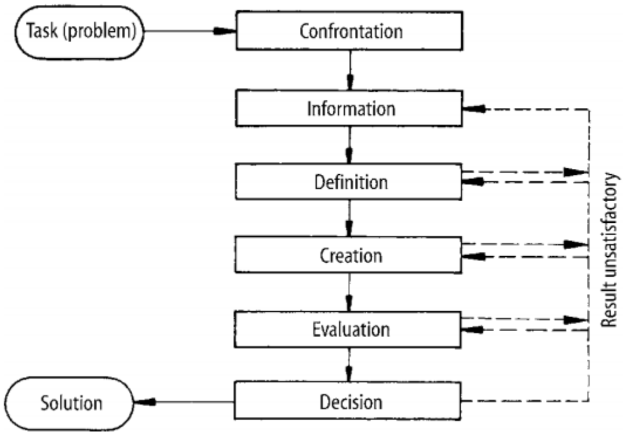

Figure 9: Systematic Approach problem solving process. [18, p. 127]

Given that the solution to problems in engineering require efforts in multiple fields, Pahl. Et al. define the concept of iteration as the method in which a solution is developed [18]. This essentially means that the search of a solution is divided into steps, and each time a step is completed it is repeated to make sure that the step; as well as the previous ones, yield satisfactory results. In the Systematic Approach, the iterations are kept as small as possible to allow for efficiency in the process.

If the correct decisions are to me made, Pahl. Et al. have determined the following considerations. The next step may only be started if the results from the previous step meet the objectives. Otherwise; the previous step needs to be repeated in order to make it fulfill the objectives. When the resources or the prospect do not allow for the step's repetition, the development must be stopped and a different solution must be sought.

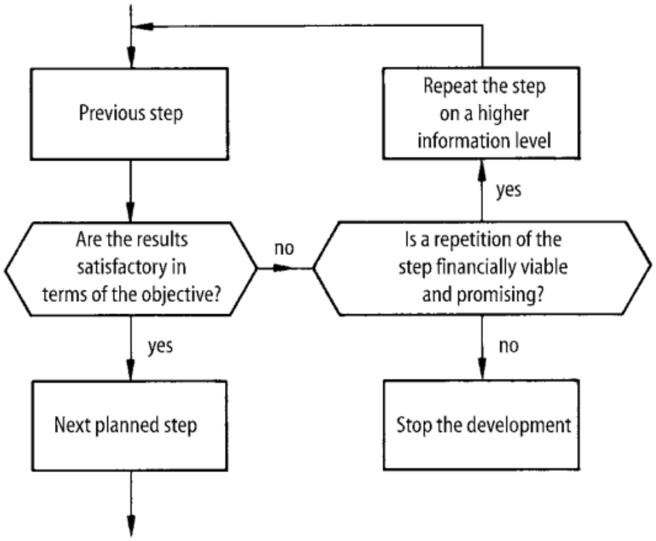

Figure 10: Systematic Approach decision making process. [18, p. 127]

When the development of a solution is stopped, Pahl. Et al. mention that even though the solution did not meet the objective or constraints, its results can still be of use if they yield possible areas of improvement to the objectives themselves. That is why the process of iteration is really necessary throughout the entire design process in order to guarantee the best outcome possible.

Description of use case

The proposed station in this thesis is meant to offer UUVs the already available technology of acoustic communications and USBL navigation, in addition to high bandwidth communications while fully underwater via optical signals and the possibility of docking into the station and recharging their batteries via its inductive module. This station would therefore eliminate the logistical limitations UUVs currently face by depending on surface vessels for their launch and recovery.

This station would also serve as a good alternative for UUVs to receive new mission commands or transfer the data they have collected in their deployment while underwater, which would make them avoid the inconvenience of spending time and energy in resurfacing to make use of electromagnetical communications as they currently have to with the current technology available. This station would thereby mitigate the risk that resurfacing poses for UUVs when operating in an area with very adverse sea states or when operating under ice covered waters which could lead to damage or loss of the vehicle.

While the designs proposed in this thesis will only allow for the docking of a Blueye ROV, their concept and functions could be adapted to the other vehicles considered in the MarTERA UNDINA project as well as other UUVs with similar dimensions like the LAUVs owned by AUR-Lab.

Chapter III: Design methods

As mentioned before, the design methodology chosen for this thesis is the Systematic Approach proposed by Pahl and Beits where they first make an analysis of what is known and what is not yet known and that ultimately is sought to know through a *Confrontation* of the problem. This part was covered in the *Background* section of the thesis.

The next step in the Systematic approach (*Information),* is where the problem that is sought to be solved is disseminated into a more abstract conception that may facilitate the development of a solution. This is the step where the requirements for the will be established based upon the needs of the project, the desired location for its installation, the constraints the OceanLab infrastructure implies upon the design, the successful aspects of the previous similar projects previously described as well as their areas of opportunity that this project may be able to improve.

Once the requirements for the UNDINA Platform are defined, the next step (*Creation)*, is where the instruments for the platform will be chosen and where with the help of SOLIDWORKS the platform will be modelled together with the chosen instrumentation.

The next step (*Evaluation)*, is perhaps the most crucial one given that it is where the created solutions are evaluated in order to determine whether they fulfill the previously established requirements. Additionally, it is in this step where new requirements may be needed to be taken into consideration alongside the already established ones or; if necessary, even modify the requirements.

Of worth mentioning, the hydrodynamical analysis mentioned in the scope of the project will only be performed with the final design iteration as it is the one where all of the aspects of the structure will have been optimized and confirmed to be apt for their installation. The results of that analysis will be included in the Results chapter.

Once the evaluation is completed, the next and final step in the Systematic Approach; *Decision*, is to determine if the best course of action is to continue developing the proposed solution in search of improving it or to the contrary searching for a new solution altogether if its results are not deemed satisfactory enough.

After each decision *Solution* is reached. In the case of this thesis, the result after each iteration will be a design render for the UNDINA Platform. All of the design renders will be included and explained in Chapter IV: Results.

Operational requirements

Based upon the objective above, the following design and operational requirements are identified for the UNDINA Platform.

1. Withstand a pressure of at least 10 BAR.
2. Integrate the acoustic modem of the DINA module to allow for long range communications and navigational aid for UUVs with USBL.
3. Integrate the optical modem of the DINA module for high bandwidth communication with UUVs in its range.
4. Integrate the inductive modem of the DINA to allow for wireless battery charging and high bandwidth communications when UUVs are docked into it.

Structural requirements

Given that; for one of its configurations, the station would have to be integrated with the already installed PLM module in Throndheimsfjord at 91.4 m, the station must feature guiding pins to be properly mounted unto the PLM. For its other configuration without the PLM, the structure needs to feature conical or cylindrical legs to be more stably landed on the seabed. The structure of the station needs to be built either with materials that are not prone to corrosion by the seawater, otherwise, a corrosion resistant coating needs to be applied to the structure.

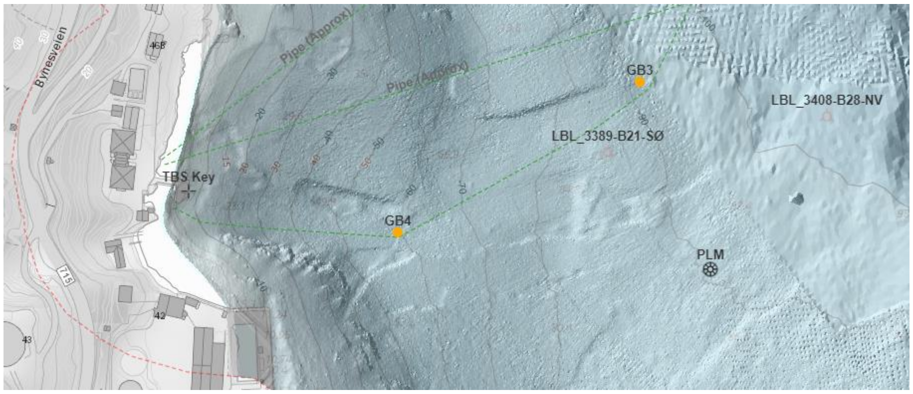

Figure 11: Location of PLM

In order to allow its proper installation, the structure needs to feature hooking points for when it will be lifted by a crane from the dock and then lowered to the installation site by a winch.

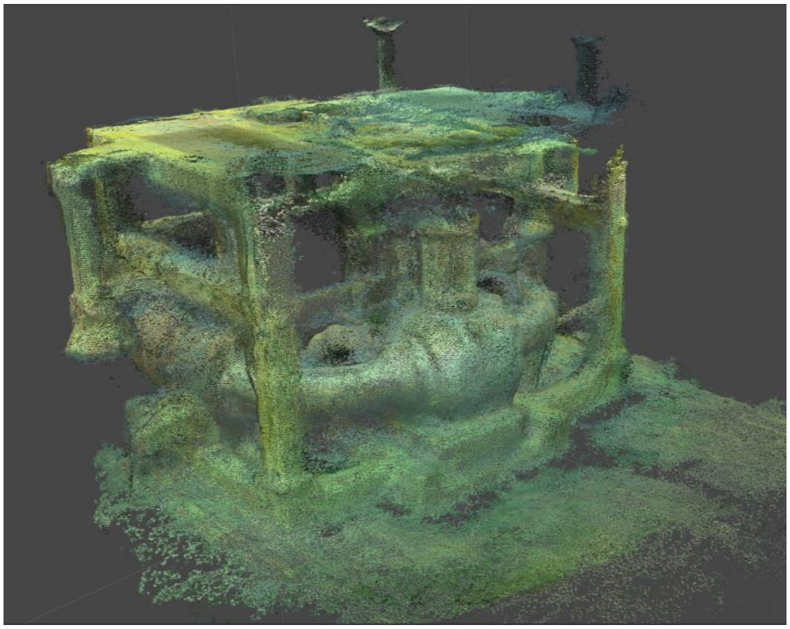

Figure 12: PLM photogrammetry

Navigation, sensor and docking requirements

The station could be equipped with water column measurement instruments such as CTD or turbidity sensors in order to be aware of the environmental conditions of its surroundings. The station could integrate; apart from the communication modules, video cameras to give the control base real time images of the vehicles in the proximity of the station. Those cameras would therefore have to be installed in positions where its vision will not be obstructed by other sensors or instruments.

Due to the fact that the inductive module has a range of just a few millimeters, the station would need to integrate a strategy or mechanism to hold the docked vehicle in place and prevent currents from pushing it away while either recharging its batteries or transferring data with the inductive module. Since; as mentioned before, the Blueye X3 is the model vehicle for this project, this thesis will integrate a holding strategy for that vehicle.

Communications and energy requirements

The station would must be equipped with two junction boxes; one corresponding to the OceanLab infrastructure and the other to the UNDINA Platform, that converts the received power from the umbilical into currents and voltages that the instruments in both the Instrument Rig and the UNDINA Platform can use.

Operational safety requirements and constraints

In order for the electrical systems to remain safe, the water-tight spaces of the station need to be built with high quality to avoid any possible leakages which may lead to the electrical systems short-circuiting or being damaged and thereby compromising the integrity of the station's instruments or to the docked UUVs.

Modes of operation

The proposed station would have two possible uses. The first one consists of a UUV just flying within the vicinities of the station to obtain USBL range measurements or acoustic communications with the acoustic modems mounted in the station or to make use of the optical modem to transfer high amounts of data collected in its deployment or to receive new mission commands.

The second mode of operation would consist of the UUV docking into the station to recharge its batteries. For this mode, the acoustic module corresponding to the UNDINA Platform would have to first serve as a homing beacon by sending the approaching vehicle USBL pings that may allow the vehicle to confirm its approach towards the station, once in range, the optical module could be used to establish a high-bandwidth communication channel between the station and the vehicle to constantly update the vehicle its actual range to the dock and; once in the dock, the vehicle can recharge its batteries and transfer its collected data before embarking on its next deployment.

Installation requirements

The station would need to be installed with the help of an offshore supply vessel (OSV) that can allow for the lifting and lowering of the station to its intended site. When taking care of its landing, an ROV; operated form the OSV would help ensure its proper placement either on the seabed or on top of a previously installed base.

Given the available resources at NTNU AUR-Lab. The OSV would be RV Gunnerus, the research vessel owned by NTNU equipped with a deck crane for lifting operations that can extend up to 14 meters, winches with a capacity of 5 tons and a wire 1000m long intended for deep sea lowering operations and with a DP system that will guarantee a proper station keeping during the installation operation.

The ROV that would be employed for the landing of the designed platform is the 30K, which is the largest underwater robot at the disposition of AUR-Lab weighing approximately 2 tons with a depth rating of 1000m (limited to 600m given its tether length). The 30K ROV is an intervention class ROV equipped with a DVL for both obstacle detection and for bottom tracking as well as with a hydraulic manipulator capable of both sample recollection and instrument handling.

Lifting in the air

The lifting ropes connect to the station with shackles which are mounted to the lifting pad eyes whose design needs to be carefully adjusted to the loads it will be subject to during the lifting operations. The shackles will be placed on the corners of both the Instrument Rig and UNDINA Platform, this with the objective of offering the possibility of lifting either of the structures individually; if needed, or together as they will be for its installation.

In order to guarantee a solid lifting point at the lifting pad eyes, DNV establishes in its 2.7-1 standard [19] two different criteria. The Tear-out criteria and contact criteria. The former (Equation 1) ensures that the yield strength of the material the pad eye is made of R_e must not exceed a certain stress level at the edge of the bolt hole described by the following equation. While the latter (Equation 2) ensures that the yield strength of the pad eye's material R_e is not exceeded by the compressive stress at the contact line between the bolt and the bolt hole.

$$R_e \geq \frac{3 \bullet RSL}{2 \bullet H \bullet t - D_H \bullet t} \left[MPa \right] 14$$

Equation 1: Tear-out stress criterium

$$R_e \geq 23.7 \sqrt{\frac{RSL}{D_H \bullet t}} \left[MPa \right]$$

Equation 2: Contact stress criterium

Where RSL is the is the resulting sling load, H is the distance from the bolt hole center to the eye pad edge, D_H is the bolt hole diameter and t is the pad eye thickness.

Lifting through splash zone

Once the platform is successfully lifted from the OSV deck, it will need to cross the surface of the water. This phase of the installation is the most critical one as it is the one where the loads acting upon the wire have been observed to reach its maximum values. This is due to the fact that it is where the structure interacts with waves which depending on the orientation in which the structure crosses the surface or splash zone can lead to variable loads that need to be taken into consideration if snap loads in the wire want to be avoided.

For this thesis, the method used to calculate the loads to which the designed platform will be subjected to when crossing the splash zone is the Simplified Method described in section 4 of the DNV recommended practice DNV-RP-H103. [20] In that document, two different methods are described; the General and the Simplified Method, the latter of which is based upon the following assumptions [20, p. 61]:

- The horizontal extent of the lifted object in the wave propagation direction is relatively small compared to the wave length.
- The vertical motion of the object follows the crane tip motion.

- The load case is dominated by the vertical relative motion between object and water; all other motions can be disregarded.

The main objective of this Simplified Method is to determine the characteristic total force F_{total} a structure lowered through the water surface exerts upon the lifting line by adding up the characteristic hydrodynamic force generated when the object crosses the splash zone F_{hyd} and the static weight of the object F_{static}.

$$F_{total} = F_{static} + F_{hyd}$$

Equation 3: Characteristic total force

The static weight F_{static} can be determined by subtracting the product between the water density ρ, the acceleration by gravity g and the displaced water volume V from the weight of the object in the air (product of the lifted object's mas sin the air M and acceleration by gravity g).

$$F_{static} = Mg - \rho V g\left[N\right]$$

Equation 4: Static weight

The characteristic hydrodynamic force F_{hyd} is a rather conservative estimation of the loads the lifted object generates when crossing the water surface. In the Simplified Method, the characteristic hydrodynamical load F_{hyd} is determined by the following expression.

$$F_{hyd} = \sqrt{\left(F_D + F_{slam}\right)^2 + \left(F_M + F_\rho\right)^2}\left[N\right]$$

Equation 5: Hydrodynamic force

Where:

F_D is the hydrodynamic drag force.

F_{slam} is the slamming impact force.

F_M is the hydrodynamic mass force.

F_ρ is the varying buoyancy force.

The hydrodynamic drag force F_D originates from the resistance the fluid generates when a solid object moves within it. The magnitude of this force depends upon the projected area of the object normal to the direction the fluid is flowing A_{pi}, the relative velocity between the particles of the fluid and the solid v_r, the density of the fluid ρ and a coefficient that depends on the geometry of the object C_D .

$$F_{Di} = 0.5 \bullet \rho C_{Di} A_{pi} v_r^2 \left[N\right]$$

Equation 6: Drag force [20, p. 68]

$$v_r = v_c + \sqrt{v_{ct}^2 + v_w^2}\left[m/s\right]$$

Equation 7: vertical object-water particle relative velocity [20, p. 68]

Where:

v_c is the lowering velocity; for this case 0.1 m/s

v_{ct} is the single amplitude vertical crane tip velocity

v_w is the vertical water particle velocity.

The Varying buoyancy force is the one that refers to the change in buoyancy of the lifted object as it is in the process of submerging. This in turn leads to a change in the volume of water that is displaced by the object as it crosses the surface. Of worth noting, for this thesis the change in volume will be considered lineal due to the fact that the installation of the platform will be planned in such a way that it may be performed under relatively calm sea conditions.

The change in buoyancy is determined by calculating the submerged volume of the structure with respect to the wave crest δV and then multiplying it by the density of water ρ and the acceleration of gravity g .

$$F_\rho = \rho \delta V g\left[N\right]$$

Equation 8: Varying buoyancy force [20, p. 67]

Where the submerged volume is determined by the projected area of the object in the horizontal plane on the wave surface zone $\tilde{A}_w$, the characteristic wave amplitude ζ_a and the single amplitude vertical motion of the crane tip η_{ct} .

$$\delta V = \tilde{A}_w \sqrt{\zeta_a^2 + \eta_{ct}^2}\left[m^3\right]$$

Equation 9: Change in displaced water volume [20, p. 67]

The vertical motion of the crane tip η_{ct} is the change in height of the crane structure with respect to the water surface in response to the sea state. The simplified Method calculates it by taking into account the OSV's heave η_3 , roll η_4 and pitch η_5 motion, the horizontal distance of the crane tip from the OSV's center line b and the horizontal distance of the crane tip from the OSV's midship l .

$$\eta_{ct} = \sqrt{\eta_3^2 + \left(b \sin \eta_4\right)^2 + \left(l \sin \eta_5\right)^2}\left[m\right]$$

Equation 10: Vertical motion of crane tip [20, p. 137]

$$v_{ct} = 2\pi \sqrt{\left(\frac{\eta_3}{T_3}\right)^2 + \left(\frac{b \sin \eta_4}{T_4}\right)^2 + \left(\frac{l \sin \eta_5}{T_5}\right)^2}\left[m/s\right]$$

Equation 11: Crane tip vertical velocity [20, p. 138]

Following the relation between the tip crane displacement, velocity and acceleration implemented by Sandvik in [21, p. 105]. The acceleration for the crane tip can be expressed with the following equation.

$$a_{ct} = 4\pi^2 \sqrt{\left(\frac{\eta_3}{T_3^2}\right)^2 + \left(\frac{b\sin\eta_4}{T_4^2}\right)^2 + \left(\frac{l\sin\eta_5}{T_5^2}\right)^2} \left[m/s^2\right]$$

Equation 12: Crane tip vertical acceleration

In this Simplified Method, the characteristic wave amplitude ζ_a can be determined using the following equation with respect to the significant wave height H_s.

$$\zeta_a = 0.9 \bullet H_s \left[m\right]$$

Equation 13: Significant wave amplitude [20, p. 64]

The hydrodynamic mass force is the one where the mass of the object in the air as well as the effect that the object's geometry has upon the fluid when it is submerged; commonly referred to as added mass, are taken into consideration. The following equation is the one used in this Simplified Method to determine the hydrodynamical mass force.

$$F_{Mi} = \sqrt{\left[\left(M_i + A_{33i}\right)a_{ct}\right]^2 + \left[\left(\rho V_i + A_{33i}\right)a_w\right]^2} \left[N\right]$$

Equation 14: Hydrodynamic mass force [20, p. 68]

Where:

M_i is the mass of object item in the air.

A_{33i} is the added mass of object item in the heave direction.

a_{ct} is the single wave amplitude of the crane tip vertical acceleration.

ρ is the water density.

M_i is the total volume of object item.

V_i is the volume of displaced water by the object

a_m is the vertical water particle acceleration.

$$v_w = \zeta_a \left(\frac{2\pi}{T_z}\right) \bullet e^{-\frac{4\pi^2 d}{T_z^2 g}} \left[m/s\right]$$

Equation 15: Vertical water particle velocity [20, p. 64]

Where:

ζ_a is the characteristic wave amplitude.

g is the acceleration of gravity.

d is the distance from the waterplane to the center of gravity of the submerged part of the object.

H_s is the significant wave height.

T_z are the zero-up crossing wave periods.

$$a_w = \zeta_a \left(\frac{2\pi}{T_z} \right)^2 \bullet e^{-\frac{4\pi^2 d}{T_z^2 g}} \left[m/s \right]$$

Equation 16: Vertical water particle acceleration [20, p. 64]

The slamming impact force F_{slam} is the one that occurs when an object with a relatively high projected area in the horizontal plane enters in contact with the waves in the splash zone. In the Simplified Method, the slamming impact force F_{slam} is calculated with respect to the density of sea water ρ, the relative velocity between the object and the water particle v_r, the projected area of the submerged object that will be subject to slamming loads A_s and a slamming coefficient C_s determined by the geometry of the lifted object.

$$F_{slam} = 0{,}5 \bullet \rho C_s A_s v_r^2 \left[N \right]$$

Equation 17: Slamming impact force [20, p. 65]

The Simplified Method described in the recommended practice H103 of DNV establishes 4 different load cases when lowering a structure through the water surface. The first of which will not be utilized given that it contemplates the submersion of ventilated buckets, feature that the proposed design in this thesis does not include.

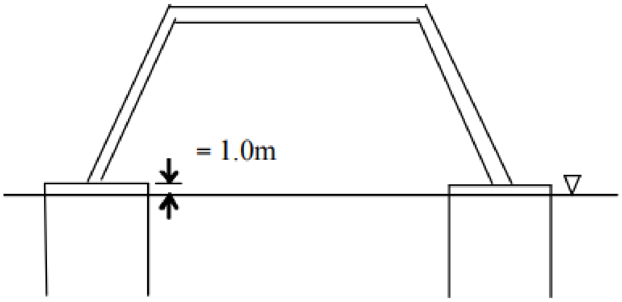

Figure 13: Load Case 1- Still water level beneath top of ventilated bucket [20, p. 71]

The second load case is the one where the more transparent parts of the structure; hydrodynamically speaking, referred to as "legs" crosses the splash zone. For this load case, the slamming impact force F_{slam} is zero, while the rest of the hydrodynamical forces are calculated. However, just like the previous load case, this second load case will not be used as the dimensions of the proposed design do not justify its implementation.

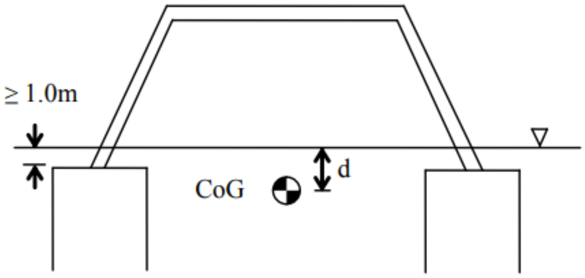

Figure 14: Load Case 2-Still water level above top of buckets [20, p. 71]

The third load case is the one where the water surface is within 1m of the “roof cover” of the lifted object. For this load case, the varying buoyancy force F_ρ must be determined at the wave surface zone. The mass force F_{Mi} and the drag force F_{Di} need to be calculated separately for the “legs” and the “roof cover”. The slamming impact force F_{slam} must be calculated for the roof cover.

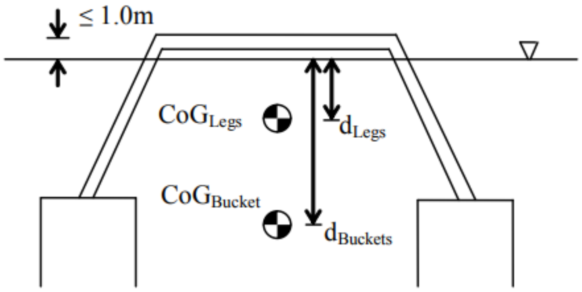

Figure 15: Load Case 3-Still water level beneath roof cover [20, p. 71]

The fourth and last load case is the one where the “roof cover” has been submerged at least 1m and the structure is finally completely under the water. For this case, the slamming impact force F_{slam} and the varying buoyancy force F_ρ are zero while the mass force F_{Mi} as well as the drag force F_{Di} needs to be calculated separately for the “legs” and the “roof cover”.

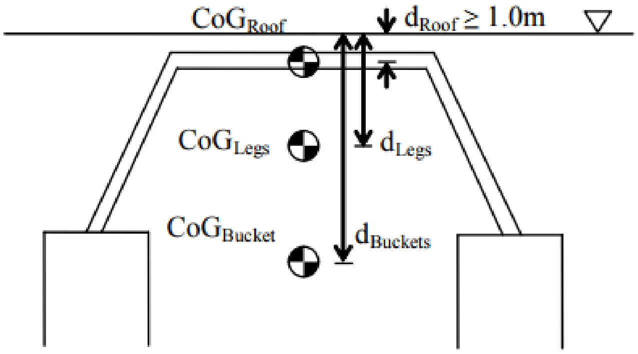

Figure 16: Load Case 4-Still water level above roof cover [20, p. 72]

Landing

Two different designs will be proposed in this thesis. In the first and main design, the proposed UNDINA Platform will be integrated to the already existing Instrument Rig, structure intended for the OceanLab project which will be mounted on top of the already installed PLM which features guiding funnels. The Instrument Rig is therefore equipped with guiding pins in order to facilitate its installation upon the PLM.

Installing that main design would require the help of an intervention or work class ROV to ensure that the guiding pins of the Instrument Rig go into the guiding funnels of the PLM. In order to simplify the operation, the guiding pins of the Instrument Rig are of different lengths with the purpose of lining the longest one with its corresponding guiding pin and then making it stay in place by lowering the structure just enough to then allow the ROV to line up the remaining; shorter pin, with its guiding funnel.

In the case of the other design. The UNDINA Platform would be landed directly onto the seabed. Thereby eliminating the need for lining up any guiding pins. Still, an intervention or work class ROV would be needed to ensure that the station is properly landed on the seabed and, if necessary, leveling it.

Recovery

In order to recover the station from its installation site, the lifting ropes would have to be attached to the winch for it to lower them to the station. Once the ropes are by the station, an ROV would have to attach them to the shackles. Once the station is attached to the lifting line, the winch can lift it to the surface where; like with its installation, the structure will generate the highest loads due to its interaction with the waves. Therefore, the operation must be conducted under a weather state that guarantees a safe retrieval operation. Once the structure is outside of the water, it can be then lowered unto the OSV's deck.

Given that the retrieval would be the inverse of the installation process. By ensuring that the structure is suited to be lowered through the water surface, it would thereby mean that it is also fit for its lifting from the water surface.

Under ice use

As mentioned before, UUVs rely on GPS fixes in order to get accurate position measurements while operating. In the case of ROVs the, the mother vessel can constantly update the vehicle's position based upon its integrated navigation systems. However, the mother vessel needs to be closely following the ROV's course in order to minimize the risk of incidents with the tether, something that can be quite inconvenient when operating in ice covered waters given that the surface vessel would see its maneuverability severely limited due to the ice which could in addition easily lead to damage to the tether.

On the other hand, when underwater, AUVs can rely on dead reckoning navigation. A method where they estimate their position based upon its last global position reference, their speed and the heading measurements of its inertial navigation systems such as gyrocompasses. Dead reckoning can be a useful method for underwater navigation when properly conducted, but its main disadvantages are that it requires very careful calibration of the vehicle's instruments and that it always has a degree of uncertainty in its position estimations that only grows with time and can lead to drastical differences between the desired course and the actual course of the vehicle.

Therefore, AUVs are programmed to resurface periodically in the course of a deployment in order to acquire GPS fixes and that way eliminate the accumulated errors in its dead reckoning navigation (as seen in Figure 17). However, when deployed under ice, UUVs cannot count with GPS position references as resurfacing may pose the risk of a collision with an ice floe in drift ice or brash ice fields. In the most extreme case, resurfacing could be totally impossible like it would be the case when the vehicle is operating under level ice or a permanent ice cap.

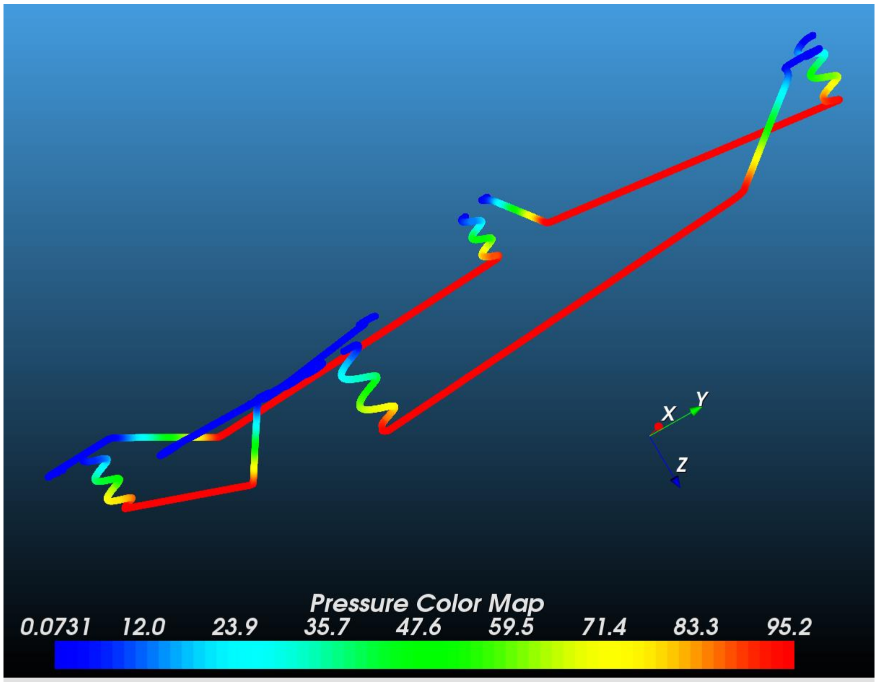

Figure 17: AUV mission 3D pressure diagram in dBAR

An alternative to GPS fixes is LBL navigation where the vehicle communicates with at least 3 USBL transponders located on previously known fixed positions and then by trilateration determines its position within a global reference frame. The main advantage of LBL navigation is the fact that it eliminates the need of resurfacing for global positioning references and the risks that it may imply, but its main disadvantage is that the placement of the USBL transponders can be costly and needs to be very accurate in order to then allow for reliable trilateration. That is why Norgren only considers the deployment of such infrastructure economically justifiable in an area where exploration will be performed for long periods of time [11, p. 31].

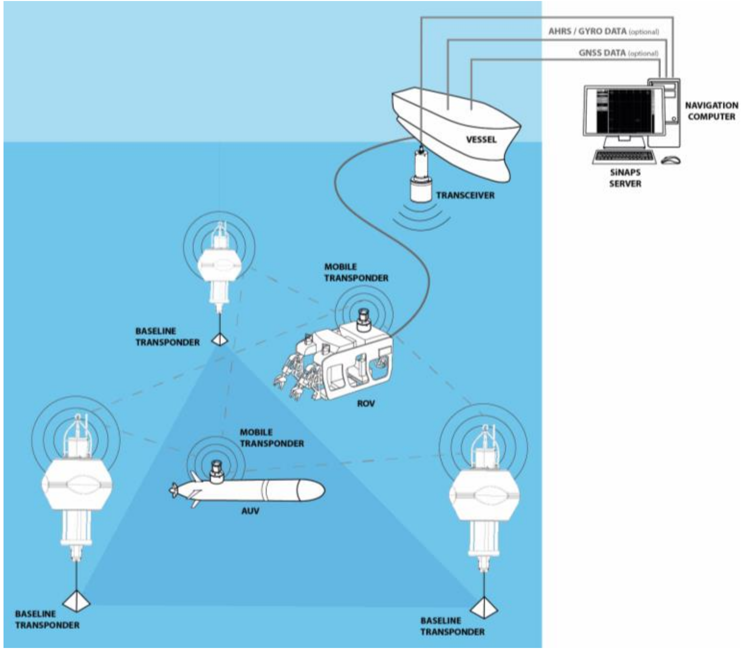

Figure 18: LBL navigation

Hegrenæs et al demonstrate that LBL based navigation can be of great use in under-ice deployment of AUVs after deploying a KM MUNIN AUV in a frozen lake in North America and with the help of 3 USBL transponders fixed to the ice give the AUV reliable position references for pipeline surveying [22].

Chapter IV: Results

Description of the functions

The platform proposed in this thesis is the integration of two different structures, the Instrument Rig corresponding to the OceanLab project and the UNDINA Platform corresponding to its homonymous project which also was the focus of the thesis. The Instrument Rig is equipped with a CTD sensor and an ADCP module, the purpose behind those instruments is to obtain an overview of the environmental conditions surrounding the installation. The ADCP would be able to determine the currents that are present in the water column above the station while the CTD would be able to measure the temperature of the water as well as to determine the salinity of the water from its conductivity measurements as. All of which would allow for awareness about the environmental conditions surrounding the station. The Instrument Rig is also equipped with two acoustic modems that are meant to serve for navigational guidance for UUVs in the vicinities of the station. The reason behind having two of them is to allow for redundancy in case any of them were to malfunction. Another reason is flexibility when it comes to the frequencies they could be programmed to in order to diversify the vehicles they could communicate to.

Table 1: Instruments specifications

Manufacturer Model	**Function**	**Depth rating**	**Mass (in air)**	**Dimensions**
AML **AML-3 RT**	CTD	500 m	1.4 kg	76 X 464 mm
Nortek **Signature 100**	ADCP	400 m	37.5 kg	460 X 354 mm
EvoLogics **S2CR 18/34 H**	USB/Acoustic module	1000 m	6 kg	180 X 383 mm
Hydromea **LUMA X**	Optical module	6000 m	0.53 kg	60 X 126 mm
Sperre **Low Light Subsea**	Video camera	3000 m	1.04 kg	80 X 161 mm
Norce	Inductive module	*	*	145 X 34 mm

The UNDINA Platform proposed in this thesis would be capable of housing one Blueye ROV with the possibility of adapting it to other UUVs such as the other vehicles that are part of the UNDINA project or the LAUVs owned by AUR-Lab. The platform features its own acoustic modem which has the objective of functioning as a homing/docking beacon for vehicles that are approaching the station. Within its docking bay, the inductive module is fully integrated to allow for wireless battery charging and high bandwidth communications. The Inductive modem is also designed with a conical shaped housing that may allow for the docked vehicle to properly connect to it and to help it keep in place while docked.

**This information is unavailable because the module is still in development*

First design render

For the first proposed design, the main objective was to represent both of the structures and the selected instruments in the proposed layout based upon the design criteria described in the Methods chapter. The acoustic instruments corresponding to the Instrument Rig were placed on the top level of the structure to maximize the propagation of their signals, on that same top level, the optical modem was mounted 1.5 m above the top level of the Instrument Rig, this was done to maximize its field of view when a UUV were to approach the UNDINA Platform. The UNDINA Platform itself was modelled with conical legs given that it would be installed directly on the seabed, inside of the structure, the inductive modem as well as the acoustic modem corresponding to the UNDINA Platform were inserted with the idea of having a magnetic mechanism to hold the vehicle in place.

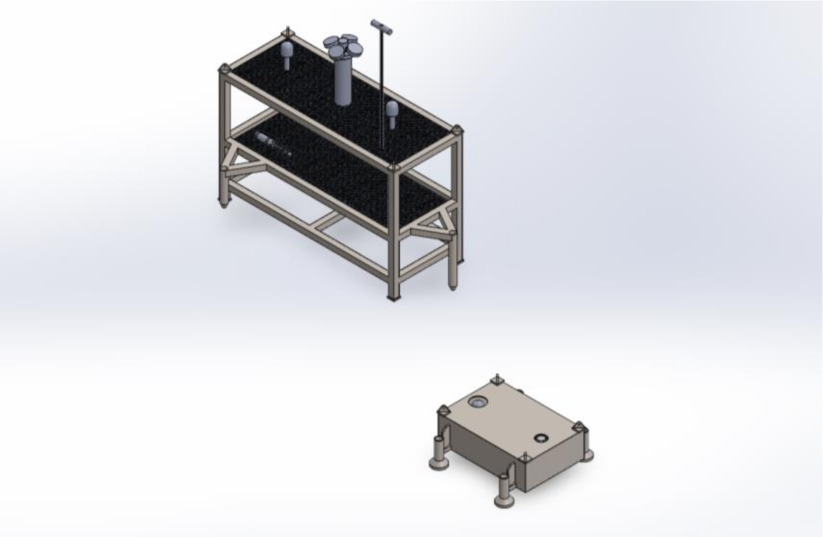

Figure 19: First render

After this first render, it was determined that instead of having the UNDINA Platform and the Instrument Rig as two separate structures, that they would instead be integrated into a single one. It was also determined that the optical modem would not be mounted so high above all else as it would be instead be installed together with the camera in a base whose tilt and pan can be regulated to adapt their orientation and optimize their visual ranges.

Second design render

For this second render, the main objectives were to integrate the UNDINA Platform to the Instrument Rig, to place the camera and the optical module in the pan-tilt unit and to integrate two junction boxes; one corresponding to the UNDINA and the other to OceanLab, in this model represented as simple cylinders in the middle level of the Instrument Rig.

For this second draft the UNDINA Platform was designed as 3 different structures, the base where the acoustic modem was mounted, the garage where the Blueye ROV is intended to dock unto and the top protective box where the inductive module is mounted. For this second render, the docking strategy chosen in which the vehicle is held in place by its own positive buoyancy was already taken into consideration. The UNDINA Platform as it can be observed in the images below was placed in such a way that the garage would be located both under and in front of the camera and optical module which were mounted in a pan-tilt module.

For the joining of the structures the proposed strategy was to use L-profile sections with the objective of then screwing the vertical columns of the structures together. Additionally, a special bracket was designed to provide additional support to the UNDINA Platform in case it were to receive an impact from the side.

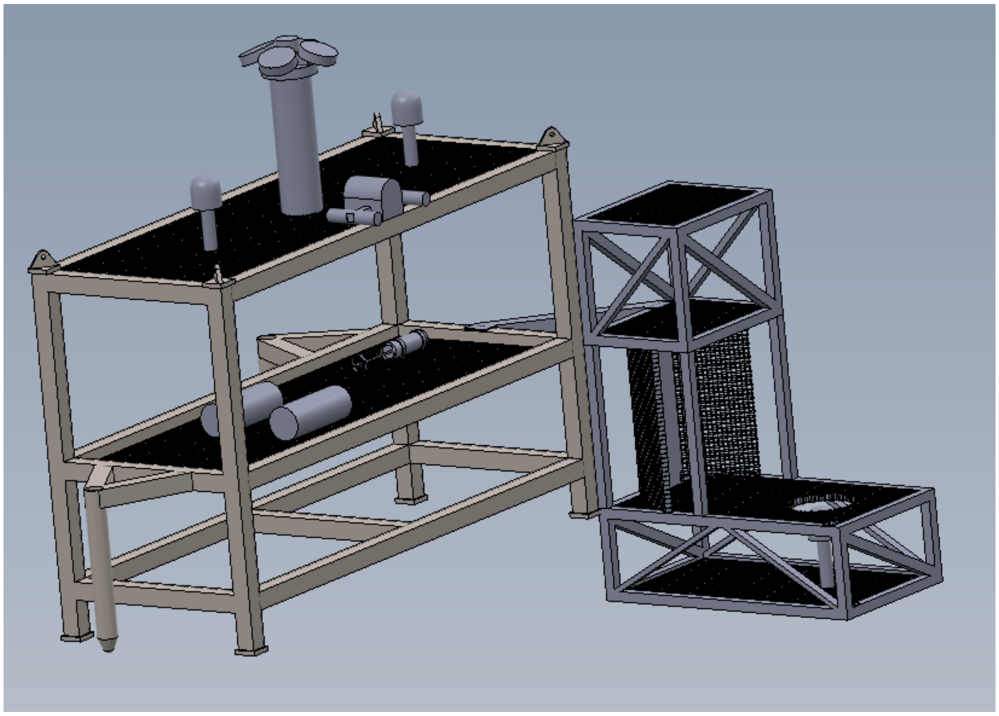

Figure 20: Second design render isometric view

After this second render, it was decided that the UNDINA Platform had to be raised to the height of the first level of the Instrument Rig as it would otherwise make its transport in a OSV's deck unnecessarily complicated with that configuration where it stands out from the bottom of the Instrument Rig, Another modification that was deemed necessary for the UNDINA Platform was its elongation so that its vertical columns aligned with those of the Instrument Rig, This with the objective of providing it with a more rigid joining to the Instrument Rig by making use of pad eyes; similar to the ones were the lifting shackles are mounted, alongside the horizontal beams of both structures in all 3 levels.

Third design render

For this third render, the main objective was to modify the design of the UNDINA Platform as suggested after the second render, in addition, the acoustic instruments in the top level of the Instrument Rig were mounted unto a shelf that would allow them to be under the top grid where they would be better protected from any possible impacts.

Of worth mentioning, for this render, a representation of the Blueye's outer design was finally made available which led to an adapting of the dimensions of the garage within the UNDINA Platform to accommodate for the vehicle possible while keeping the docking strategy proposed in the previous render where the vehicle is held in place by pure buoyancy.

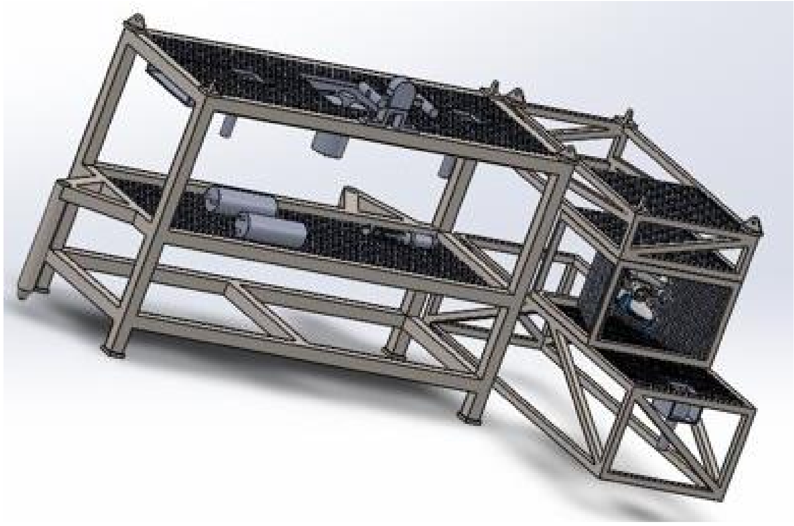

Figure 21: Third design render isometric view

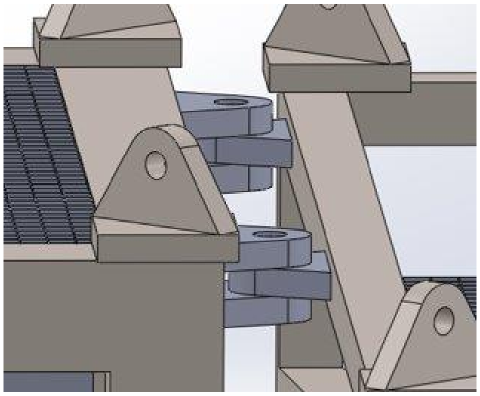

Figure 22: pad eye joining

After this third design render, the main observation was that the UNDINA Platform had to be modelled into a single structure; as opposed to the joining of 3 different ones. The other observation was that, in order to provide a better joining between the two structures, the orientation of the pad eyes would be changed from horizontal to vertical. The reasoning behind this change was that with vertical pad eyes the load generated by the UNDINA Platform would translate into shear stress for the screws holding the pad eyes together as opposed to bending moments unto the pad eyes that their horizontal orientation would imply.

Final design render

Main design

The main priority for this design render was to orient the linking pad eyes vertically. This in turn led to a change in the chosen thickness for the beams that would conform the UNDINA Platform from 45 mm as they had been proposed in the previous two renders to 80 mm. The reason behind this change was to provide the linking pad eyes a solid joining to the UNDINA Platform. With the 45 mm beams, the pad eyes would only have been partially joined to the UNDINA Platform and therefore would have not guaranteed a very firm joining. This change in the beam thickness led to the elimination of the support inclined beams used in the previous two design renders as the beams would have the stiffness enough to not need such supports.

The other priority for this design render was to model the bracket that would support the instruments of the Instrument Rig. The proposed bracket is illustrated in Figure 23: Instrument bracket, it allows for the rigid placement of both of the acoustic modems and ACDP module corresponding to the OceanLab project contemplated in this thesis. As well as for the possibility of adapting other instruments easily if it were to be needed in the future.

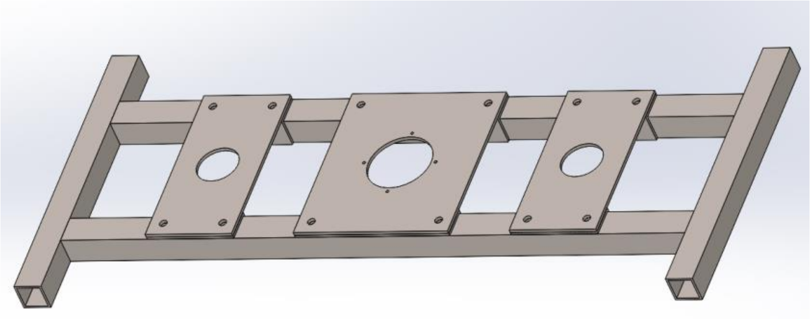

Figure 23: Instrument bracket

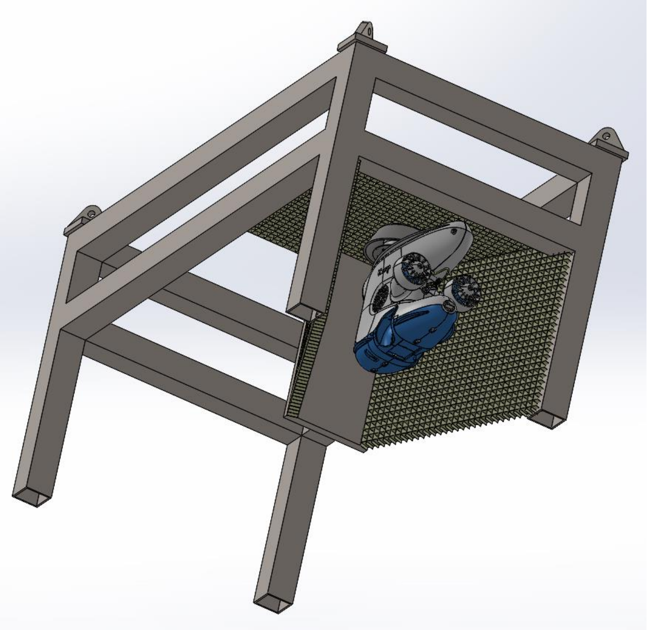

Figure 24: Buoyancy based holding strategy

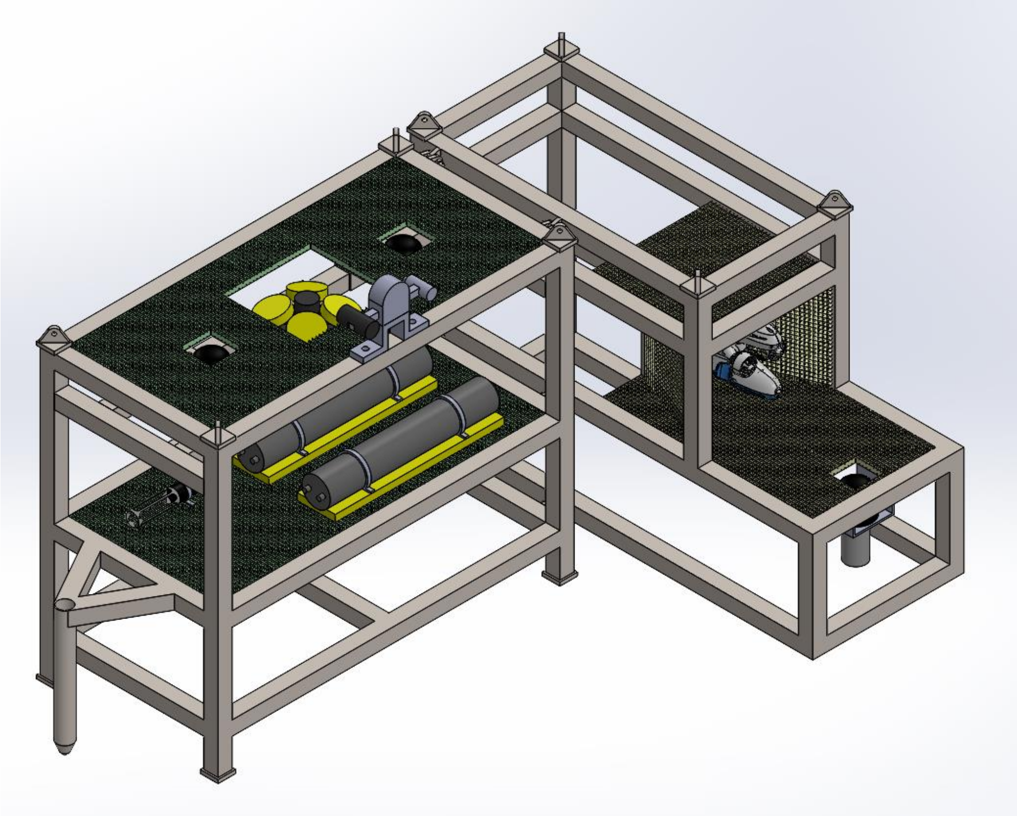

Figure 25: Final design for the proposed station

The pad eyes that were modeled for holding the two structures together (Figure 26) were given a thickness of 2 cm and holes 26 mm in diameter, this with the purpose of fitting 24 mm bolts.

As it can be observed in Figure 25, the components and the grids were given a more aesthetic appearance that would resemble closer their actual versions, something that was purely for visual purposes. This design proved to fulfill all of the previously established design requirements, therefore, it is the design that was input into the hydrodynamical analysis described in the *Hydrodynamical analysis* section.

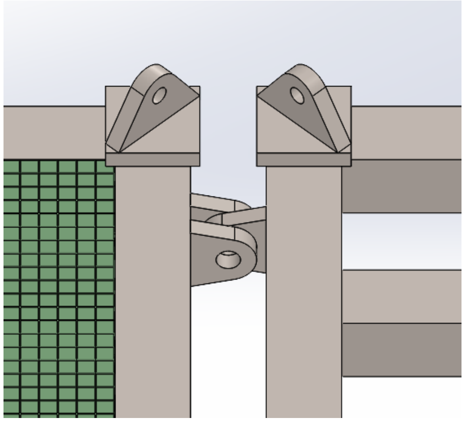

Figure 26: Joining pad eyes

Alternative design

In case the proposed solutions in this thesis were to be implemented in a place other that the Trondheimsfjord, the design illustrated in Figure 27 was created with the main objective of allowing a Blueye to dock into the proposed UNDINA Platform without the presence of the OceanLab infrastructure.

The design for the platform's structure remains the same, with the exception that it features cylindrical legs that would allow it to be stable when landed onto either a sandy or a rocky seabed. In order to accommodate the UNDINA junction box, the top grid had to be enlarged. The pan-tilt unit with the video camera and the optical module is installed directly on the top truss of the platform. While this configuration would not guarantee a view of the vehicle once it makes its final docking approach into the garage, it would guarantee its safe homing and considering that there is no Instrument Rig, there are no instruments that the vehicle could possibly impact.

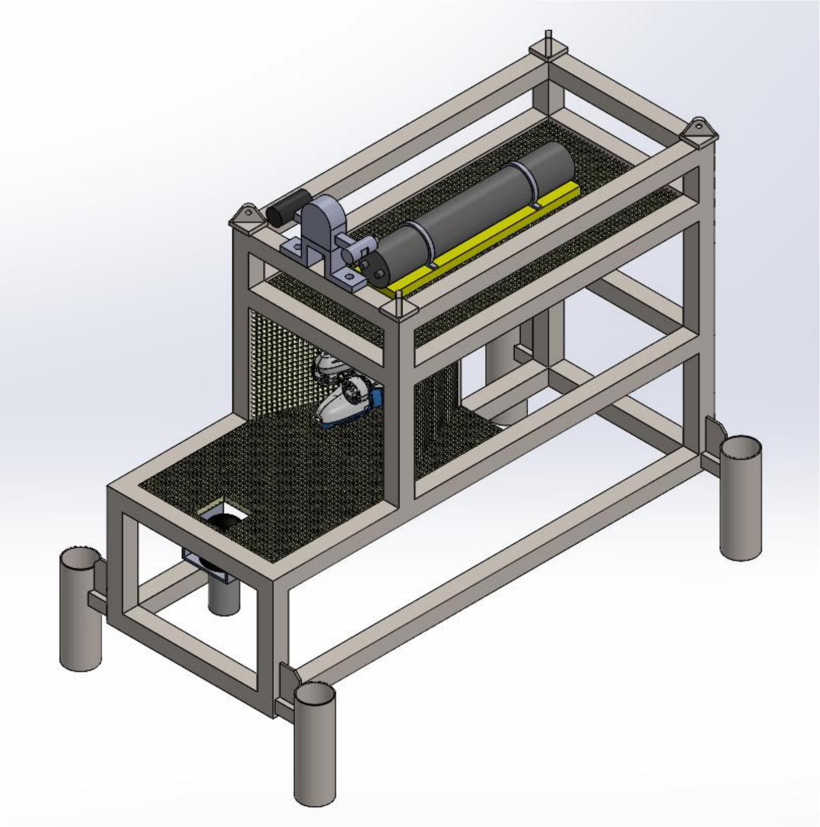

Figure 27: Alternative UNDINA Platform design

Description of chosen solutions

Material

One option for building the UNDINA Platform was plastic given that it would not be prone to corrosion and have very low weight than if it were built with a metal. However, that was quickly discarded due to the fact that any collision with the ROV during its installation (or retrieval) could lead to damage that could compromise the integrity and stability of the structure.

That is why the following 3 materials were considered as options for building the UNDINA Platform:

- Aluminum T6 6082
- Black S355 steel
- AISI 316 annealed steel

Table 2: Proposed material properties

	Density	Yield strength
AISI 316 stainless steel	8000 kg/cm^3	290 MPa
S355 low carbon steel	7800 kg/cm^3	355 MPa
6082 T6 aluminum	2700 kg/cm^3	260 MPa

The T6 6082 Aluminum has the advantage of being the lightest of the materials proposed. But it was discarded due to the fact that its malleability could lead to undesired malformations of the structure during the installation or recovery process because of the loads it would be subjected to while being lifted. Another reason this material was discarded is the fact that its strength decreases in the welded areas.

Black S355 steel is the strongest of the proposed materials for the UNDINA Platform, it is also benefits from excellent weldability. However, it was decided not to build the UNDINA Platform with Black S355 steel because its corrosion resistance is very low, meaning that a corrosion prevention coating would need to be applied to the platform.

Therefore, the material chosen for the proposed UNDINA Platform is the AISI 316 stainless steel. Despite being the heaviest of the proposed materials, it was chosen as the material for the UNDINA Platform due to the fact that the; already existing, Instrument Rig is built with that material, therefore building the UNDINA Platform with the same material avoids the chance for any galvanic or bimetallic corrosion emanating from the contact in the joints between the structures [23], it also offers good weldability and it allows for very effective protection against corrosive substances like alkaline chlorides such as those present in seawater which eliminates the need for applying any treatment or coating to prevent the UNDINA Platform from succumbing to its surroundings.

Lifting Strategy

In order to lift the station form the OSV' deck, the station must be attached to 4 lifting ropes that are connected by a main lifting point which is then attached to the lifting line of the crane or winch. The length of the ropes needs to be adjusted in such a way that the main lifting point aligns vertically with the center of gravity of the station. The length of the ropes must also be adjusted to ensure that the angle between them and the top horizontal truss of the station is equal or more than 45°

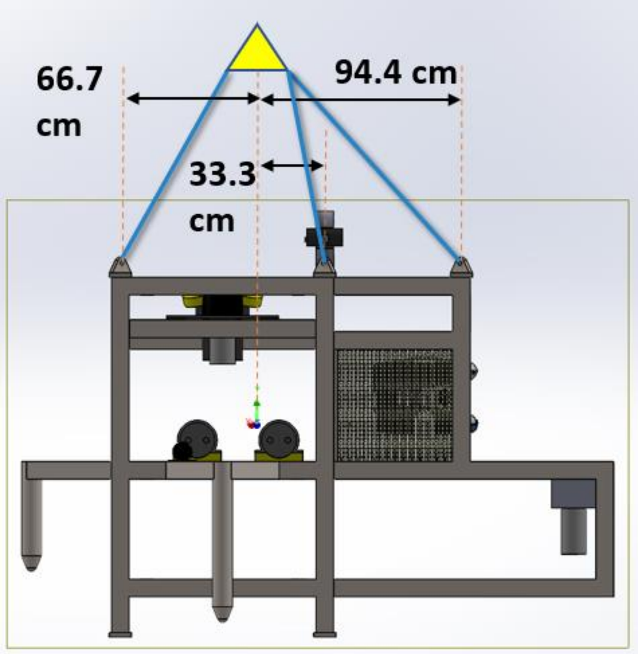

Figure 28: Side view of lifting strategy

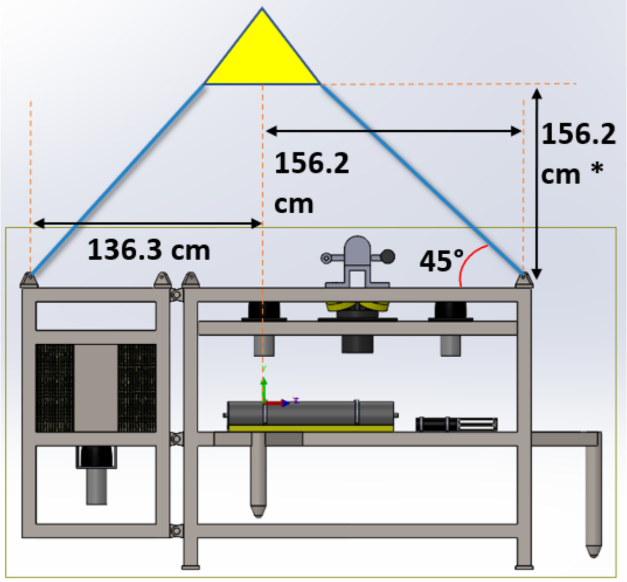

Figure 29: Front view of lifting strategy

**Not to scale*

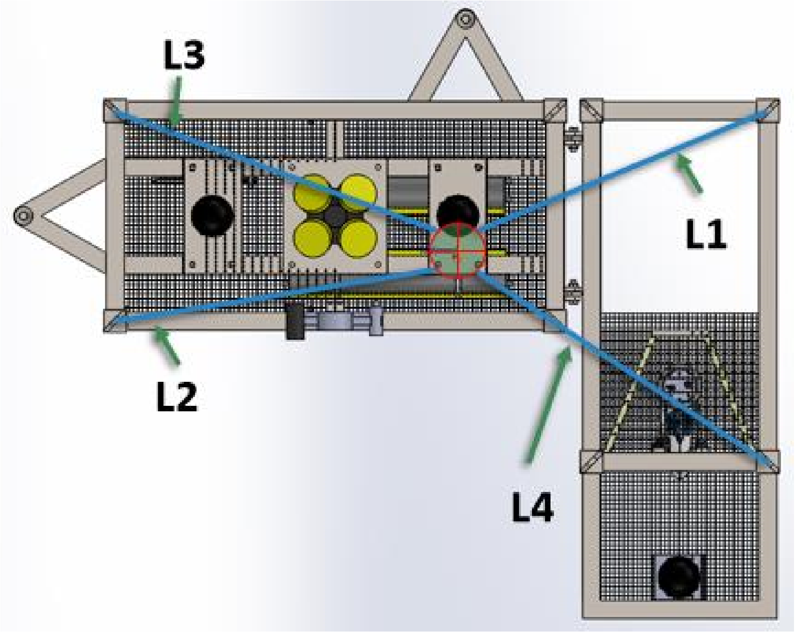

Figure 30: Top view of lifting strategy

The configuration shown in Figure 28 and Figure 29 was chosen because those are the 4 lifting points that would guarantee the best stability when the station is lifted by the crane. Considering the distance of the center of mass of the station to each of the chosen lifting points, the ropes would need to be of the following length:

Table 3:Llifting ropes length

	length
L1	217.7 cm
L2	223.4 cm
L3	230.8 cm
L4	227.8 cm

Volume and weight

The total weight of the instruments would amount to 46.5 kg. The junction boxes; since they did not fall within the scope of this thesis, were not selected, but based upon those installed in similar projects like the SDS of OceanLab, it can be assumed that each junction box weighs 40 kg. The structure would have a weight of 703.2 kg (387.7 and 315.5 from the Instrument Rig and UNDINA Platform respectively). The grids would amount for 6.8 kg, the instrument bracket for 13.1 kg and the bracket that holds the acoustic module for the UNDINA Platform amounts to 8.2 kg. Therefore, the station would have a weight of 847.7 kg in the air if it is assumed that the inductive module amounts for 3 kg.

The Instrument Rig would occupy a volume of 3.2 m^3 given that its main dimensions; as it can be observed in Figure 34, Figure 35, Figure 36, are of 100x200x160 cm. Following that same reasoning, the UNDINA Platform would occupy a volume of 2.7 m^3 given its main dimensions of 226x85x145 cm.

Loads

The most critical part of the installation is when the structure will cross the water surface, therefore, the guidelines established in the DNV Recommended Practice H103 will be used to; very conservatively, calculate the loads the proposed designed will be subjected to.

Something important regarding these calculations, is that the only parts of the station that will be considered are the structural frames and the horizontal grids due to the fact that those are the components that will generate the greatest part of the hydrodynamical loads. The guiding pins of the Instrument Rig will also be disregarded for this analysis as their shapes would require a more sophisticated analysis that is not the focus of this thesis.

Hydrodynamical analysis

The installation that will be supposed for this analysis would be in Trondheimsfjorden on with a significant wave height H_s of 2.5 m and a zero-crossing period T_z of 10 s, the reason for those values is that they represent the most extreme sea state that can be present in the area. So, if the results demonstrate that the station can be installed under such conditions, then the station can be installed in the Trondheimsfjorden regardless of the conditions. For this analysis, the water density ρ will be considered of 1025 kg/cm^3 and the acceleration because of gravity g will be given a value of 9.81 m/s^2. The hoisting velocity that will be supposed for this analysis is of 0.1 m/s.

Three moments will be analyzed in order to determine the hydrodynamical loads the station will generate when crossing the splash zone. The first one is when the waterline is at the midpoint between the bottom trusses and the middle level where the bottom horizontal grids of both the Instrument Rig and UNDINA Platform are mounted. The second moment of analysis is when the waterline is at the midpoint between the middle and top levels of the structures. The third and last moment that will be analyzed, is when the structures are fully under the waterline at a depth of 1m.

The OSV that will be supposed for this analysis is RV Gunnerus as it is a vessel owned by NTNU equipped with a main crane that can tolerate up to 8.6 tons and a winch that can bear a maximum load of 5 tons. RV Gunnerus has already been used for similar operations, among them the installation of the SDS which forms part of the OceanLab project. It has a breadth of 9.6 m, if it is supposed that the crane will extend its tip 2 meters from the deck, then the horizontal distance from the vessel's center line to the crane tip b would equal 6.8 m while the horizontal distance from the midship to the crane tip would be of 11.8 m if it is supposed that the crane's arm is parallel to the midship line during the installation. The values that will be supposed for the motion amplitudes and for the natural periods of Gunnerus on heave, roll and pitch will be the following:

Table 4: Gunnerus values

	Symbol	Value
Single amplitude heave motion	η_3	1 m
Single amplitude roll angle	η_4	5°
Single amplitude pitch angle	η_5	2°
Heave natural period	T_3	4 s
Roll natural period	T_4	10.2 s
Pitch natural period	T_5	6.8 s

For all three moments of analysis, the following values will remain the same:

- The characteristic wave amplitude ζ_a *(Equation 13)*
- The characteristic single amplitude vertical motion of the crane tip η_{ct} *(Equation 10)*
- The characteristic single amplitude velocity of the crane tip v_{ct} *(Equation 11)*
- The characteristic single amplitude acceleration of the crane tip a_{ct} *(Equation 12)*

By making use of their respective equations, their values are the ones indicated in the table below.

Table 5: constant values for hydrodynamical analysis

ζ_a	η_{ct}	v_{ct}	a_{ct}
2.25 m	1.23 m	1.66 m/s	2.5 m/s^2

First moment of hydrodynamical analysis

Instrument Rig

The second load case described in DNV RP-103 is the case that will be used for analyzing the first moment of analysis. In this case, the mass force F_{Mi} and drag force F_{Di} will have to be calculated separately for the legs and the trusses of the bottom level of each structure. The varying buoyancy force F_ρ will need to be calculated at the legs of both structures while the slamming force F_{slam} will have to be calculated on the bottom grids of each structure separately.

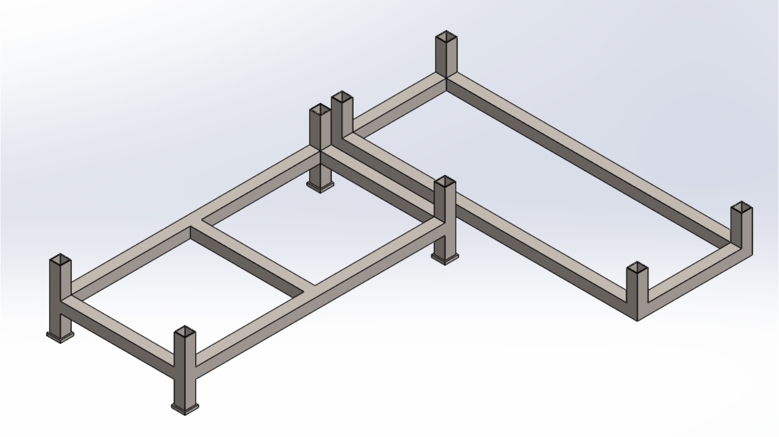

Figure 31: First moment of hydrodynamical analysis

At this moment, the distance between the waterplane and the center of gravity of the submerged part of the Instrument Rig d is of 0.254 m, with that the characteristic vertical water particle velocity v_w and acceleration a_w can be obtained with their respective equations (Equation 15: Vertical water particle velocity and Equation 16 respectively) giving a value of 1.4 m/s and 0.88 m/s^2 respectively. Therefore, the relative velocity between the Instrument Rig and the water particles (Equation 7) would be of 2.27 m/s.

The varying buoyancy force F_ρ (Equation 8) generated by the Instrument Rig would equal 660.6 N given that the mean area at the waterplane area would be the one corresponding to the 4 vertical columns; each of 8 X 8 cm.

The slamming impact force F_{slam} (Equation 17) caused by the bottom grid of the Instrument Rig would be of 1987.4 N given that the surface area of the bottom grid in the Instrument Rig is of 1506.96 cm^2 and that the slamming coefficient will be taken as 5 as recommended in [20, p. 65] given that the geometry in question is not a smooth cylinder.

The drag force F_D (Equation 6) generated by the Instrument Rig at this moment will be divided into two components. The vertical columns which have an area of 64 cm^2 each and a drag coefficient of 1 if they are considered as square rods parallel to the flow [20, p. 154] and the horizontal trusses which will be generalized as a rectangular plate parallel to the flow which would have a total area of 4960 cm^2 and a drag coefficient of 1.20; being conservative according to [20, p. 154], the total drag force generated by the Instrument Rig at this first moment would amount to 1638.5 N (1570.9 N by the horizontal trusses and 16.9 N by each of the vertical columns).

The mass force F_M (Equation 14) generated by the Instrument Rig at this moment would be as well subdivided into the same components as those of the drag force. The mass of the object in the air M_i would be that of the Instrument Rig of 387.7 kg. In order to obtain their added mass coefficients A_{33i}, the DNV recommended practice C205 [24] establishes [20] that for 3D bodies the added mass coefficient is obtained by multiplying a reference volume V_R by the water density ρ and a coefficient C_A depending on the body's geometry. Additionally, in [20, p. 74] the effect that perforation has on the added mass can be roughly estimated by the equation below.

$$A_{33} = A_{33s} \bullet e^{\frac{10-p}{28}}$$

Equation 18: perforation effect [20, p. 74]

Where p is the percentage of perforation. And A_{33s} is the added mass coefficient without perforation.

With all that into consideration, each one of the vertical columns would have a C_A of 0.15 and a reference volume of $0.08^2 \bullet 0.466$ which would also equal its displacement volume $V_{1...4}$, each vertical column would therefore have an added mass coefficient $A_{331...4}$ of 0.46 each according to [24, p. 119]. The horizontal trusses would have a C_A of 0.757 and a reference volume of $0.25\pi \bullet 1^2 \bullet 2$ and; given that p would be of 75.2%, their total added mass coefficient A_{335} would be of 118.8. The displaced volume input into this calculation would be the total V_5 volume the supposed plate would displace without the perforations of $1 \bullet 2 \bullet 0.08$ m^3.

The total added mass force generated by the Instrument Rig at this first moment of analysis would equal; with all legs taken into consideration, would be of 5192 N (1295.2 N by the horizontal trusses and 974.2 N by each of the vertical columns).

The total Hydrodynamic force generated by the Instrument Rig F_{hyd} at this first moment of analysis can now be calculated with (Equation 5) giving a total of 5803.5 N.

UNDINA Platform

At this moment, the distance between the waterplane and the center of gravity of the submerged part of the UNDINA Platform d is of 0.276 m, with that the characteristic vertical water particle velocity v_w and acceleration a_w can be obtained with their respective equations (Equation 15: Vertical water particle velocity and Equation 16 respectively) giving a value of 1.4 m/s and 0.88 m/s^2 respectively. Therefore, the relative velocity between the Instrument Rig and the water particles (Equation 7) would be of 2.27 m/s.

Just as with the Instrument Rig, the varying buoyancy force F_ρ (Equation 8) generated by the UNDINA Platform would equal 660.6 N given that the mean area at the waterplane area would be the one corresponding to the 4 vertical columns; each of 8 X 8 cm.

Considering that the surface area of the bottom grid in the UNDINA Platform has a surface are of 774.55 cm^2, the slamming impact force F_{slam} (Equation 17) generated by the UNDINA Platform would be equal to 1021.4 N.

Following the same reasoning taken with the Instrument Rig, the drag force F_D (Equation 6) generated by the UNDINA Platform at this moment will be divided into two components. The vertical columns which have an area of 64 cm^2 each and a drag coefficient of 1 if they are considered as square rods parallel to the flow [20, p. 154] and the bottom horizontal trusses which will be generalized as a rectangular plate parallel to the flow which would have a total area of 4464 cm^2 and a drag coefficient of 1.20; being conservative according to [20, p. 154], the total drag force generated by the Instrument Rig at this first moment would amount to 1475.7 N (1412.9 N by the horizontal trusses and 165.7 N by each of the vertical columns).

Following the same methodology taken for the Instrument Rig, the mass force F_M (Equation 14) generated by the UNDINA Platform at this moment would be as well subdivided into the same components as those of the drag force. The mass of the object in the air M_i would be that of the UNDINA Platform of 315.5 kg. Each one of the vertical columns would have a C_A of 0.24 and a reference volume of $0.08^2 \bullet 0.305$ which would also equal its displacement volume $V_{1...4}$, each vertical column would therefore have an added mass coefficient $A_{331...4}$ of 0.48 each according to [24, p. 119]. The horizontal trusses would have a C_A of 0.83 and a reference volume of $0.25\pi \bullet 0.85^2 \bullet 2.26$ and; given that p would be of 76.8%, their total added mass coefficient A_{335} would be of 100.4. The displaced volume input into this calculation would be the total V_5 volume the supposed plate would displace without the perforations of $0.85 \bullet 2.26 \bullet 0.08$ m^3.

The total added mass force generated by the UNDINA Platform at this first moment of analysis would equal; with all legs taken into consideration, would be of 4237.4 N (1065.4 N by the horizontal trusses and 793 N by each of the vertical columns).

The total Hydrodynamic force generated by the UNDINA Platform F_{hyd} at this first moment of analysis can now be calculated with Equation 5 giving a total of 4362.2 N.

Second moment of hydrodynamical analysis

Instrument Rig

The third load the case is the one that will be implemented when analyzing the hydrodynamical loads of the second moment. In this moment, the mass force F_{Mi} and drag force F_{Di} will have to be calculated separately for the legs and the trusses of the bottom and middle level of each structure as well as for the already submerged bottom grids. The varying buoyancy force F_{ρ} will need to be calculated at the legs of both structures; thereby remaining the same, while the slamming force F_{slam} will have to be calculated on the top grids of each structure separately.

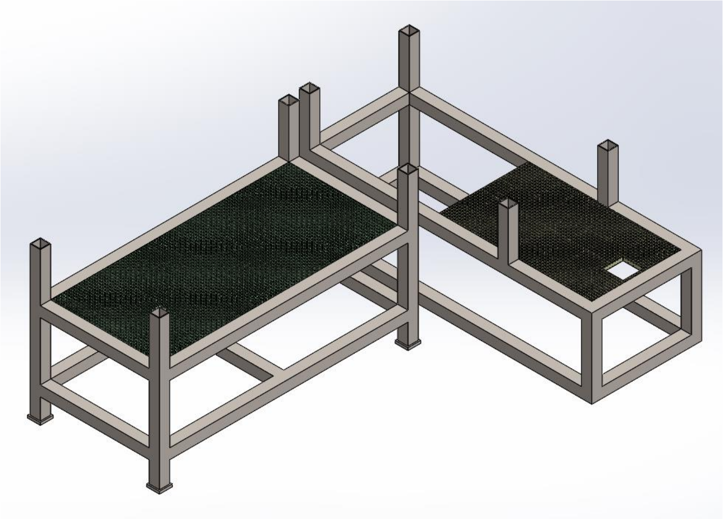

Figure 32: Second moment of hydrodynamical analysis

At this moment, the distance between the waterplane and the center of gravity of the submerged part of the Instrument Rig d is of 0.609 m, with that the characteristic vertical water particle velocity v_w and acceleration a_w can be obtained with their respective equations (Equation 15: Vertical water particle velocity and Equation 16 respectively) giving a value of 1.38 m/s and 0.87 m/s^2 respectively. Therefore, the relative velocity between the Instrument Rig and the water particles (Equation 7) would be of 2.26 m/s.

The varying buoyancy force F_{ρ} (Equation 8) generated by the Instrument Rig would remain the same as in the previous moment at 660.6 N given that the mean area at the waterplane area would still be the one corresponding to the 4 vertical columns; each of 8 X 8 cm.

The slamming impact force F_{slam} (Equation 17) caused by the top grid of the Instrument Rig would be of 1584.1 N given that the surface area of the top grid in the Instrument Rig is of 1214.36 cm^2 and that the slamming coefficient will be taken as 5 as recommended in [20, p. 65] given that the geometry in question is not a smooth cylinder.

The drag force generated by the bottom grid of the Instrument Rig would be calculated by considering the grid as a rectangular plate parallel to the flow which would thereby both have a drag coefficient of 1.20 and have a total area of 1506 cm^2.

The drag force F_D (Equation 6) generated by the Instrument Rig at this moment will be divided into three components. The vertical columns which have an area of 64 cm^2 each and a drag coefficient of 1 if they are considered as square rods parallel to the flow [20, p. 154] and the horizontal trusses in the bottom and middle level which will be generalized as a rectangular plate parallel to the flow which would thereby both have a drag coefficient of 1.20 and have a total area of 4960 cm^2 (for the bottom level) and 4288 cm^2 (for the middle level). The total drag force generated by the Instrument Rig at this second moment would amount to 3434.6N (66.8 N by the vertical columns, 471.6 N by the bottom grid, 1553.3 N and 1342.9 N for the bottom and middle horizontal trusses respectively).

The mass force F_M (Equation 14) generated by the Instrument Rig at this moment would be as well subdivided into the same components as those of the drag force. The mass of the object in the air M_i would be that of the Instrument Rig of 387.7 kg. Following the same methodology and assumptions made on the previous moment of analysis, each one of the vertical columns would have a C_A of 0.08; a conservative estimate, and a reference volume of $0.08^2 \bullet 1.146$ (equal to its displacement volume $V_{1...4}$), each vertical column would therefore have an added mass coefficient $A_{331...4}$ of 0.6 each according to [24, p. 119].

The horizontal trusses in the bottom level would have a C_A of 0.757 and a reference volume of $0.25\pi \bullet 1^2 \bullet 2$ and; given that p would be of 75.2%, their total added mass coefficient A_{335} would be of 118.8.

The horizontal trusses in the middle level would have a C_A of 0.757 and a reference volume of $0.25\pi \bullet 1^2 \bullet 2$ and; given that p would be of 78% a, their total added mass coefficient A_{336} would be of 107.4.

The displaced volume V_5 and V_6 input into the calculations involving the horizontal trusses would be the total volume of the supposed plate would without the perforations of $1 \bullet 2 \bullet 0.08$ m^3.

Additionally, the added mass generated by the bottom grid of the Instrument Rig needs to be considered in this moment. Given its dimensions, it can also be considered a rectangular plate with a reference volume of $0.25\pi \bullet 0.84^2 \bullet 1.84$ and a C_A of 0.757. Considering that its p equals 90.25 %, its total added mass coefficient A_{336} would be of 45. Of worth noting, M_i for this specific calculation would need to be the mass in the air of the bottom grid in the Instrument Rig of 2.2 kg and V_7 would correspond to the volume the supposed plate would displace without the perforations of $0.03 * 0.84 * 1.84$ m^3.

The total added mass force generated by the Instrument Rig at this second moment of analysis would equal; with all components accounted for, would be of 7614.3 N (1984.8 N and 1264.8 N by the horizontal trusses in the bottom and middle levels respectively, 974.6 N by each of the vertical columns and 466.3 N by the bottom grid).

The total Hydrodynamic force generated by the Instrument Rig F_{hyd} at this second moment of analysis can now be calculated with Equation 5 giving a total of 8575.6 N.

UNDINA Platform

At this moment, the distance between the waterplane and the center of gravity of the submerged part of the UNDINA Platform d is of 0.666 m, with that the characteristic vertical water particle velocity v_w and acceleration a_w can be obtained with their respective equations (Equation 15: Vertical water particle velocity and Equation 16 respectively) giving a value of 1.4 m/s and 0.86 m/s^2 respectively. Therefore, the relative velocity between the Instrument Rig and the water particles (Equation 7) would be of 2.25 m/s.

Considering that the mean area at the waterplane area of the UNDINA Platform would still be the one corresponding to the 4 vertical columns; each of 8 X 8 cm, the varying buoyancy force F_ρ (Equation 8) would remain the same as in the previous moment at 660.6 N.

Since the surface area of the top grid in the UNDINA Platform has a surface are of 520.6 cm^2, the slamming impact force F_{slam} (Equation 17) generated by the UNDINA Platform would be equal to 678.1 N.

The drag force generated by the bottom grid of the Instrument Rig would be calculated by considering the grid as a rectangular plate parallel to the flow which would thereby both have a drag coefficient of 1.20 and have a total area of 774.55 cm^2.

The drag force F_D (Equation 6) generated by the UNDINA Platform at this moment will be divided into three components. The vertical columns which have an area of 64 cm^2 each and a drag coefficient of 1 if they are considered as square rods parallel to the flow [20, p. 154] and the horizontal trusses in the two lower levels of the UNDINA Platform which will be generalized as a rectangular plate parallel to the flow which would thereby both have a drag coefficient of 1.20 and a total area of 4464 cm^2 each. The total drag force generated by the Instrument Rig at this second moment would amount to 3099.8 N (66.7 N by the vertical columns, 242.1 N by the bottom grid and 1395.5 N for the bottom and middle horizontal trusses each).

The mass force F_M (Equation 14) generated by the UNDINA Platform during this second moment would be as well subdivided into the same components as those of the drag force. The mass of the object in the air M_i would be that of the Instrument Rig of 387.7 kg. Each one of the vertical columns would have a C_A of 0.08; a conservative estimate, and a reference volume of $0.08^2 \bullet 1.115$ (equal to its displacement volume $V_{1...4}$), each vertical column would therefore have an added mass coefficient $A_{331...4}$ of 0.6 each according to [24, p. 119].

The horizontal trusses in the two lower levels would have a C_A of 0.83 and a reference volume of $0.25\pi \bullet 0.85^2 \bullet 2.26$ and; given that p would be of 76.8%, their total added mass coefficient A_{335} would be of 100.4.

The displaced volume V_5 and V_6 input into the calculations involving the horizontal trusses would be the total volume the supposed plate would displace without the perforations of $0.85 \bullet 2.26 \bullet 0.08$ m^3.

Additionally, the added mass generated by the bottom grid of the Instrument Rig needs to be considered in this moment. Given its dimensions, it can also be considered a rectangular plate with a reference volume of $0.25\pi \bullet 0.69^2 \bullet 1.18$ and a C_A of 0.757. Considering that its p equals 90.48 %, its total added mass coefficient A_{336} would be of 19.3. Of worth noting, M_i for this specific calculation would need to be the mass in the air of the bottom grid in the UNDINA Platform of 1.13 kg and V_7 would correspond to the volume the supposed plate would displace without the perforations of $0.03*0.69*1.18\,\mathrm{m}^3$.

The total added mass force generated by the Instrument Rig at this second moment of analysis would equal; with all components accounted for, would be of 5336.3 N (1049.5 N by each of the horizontal trusses, 793.3 N by each of the vertical columns and 64.1 N by the bottom grid).

The total Hydrodynamic force generated by the UNDINA Platform F_{hyd} at this second moment of analysis can now be calculated with (Equation 5) giving a total of 6011.2 N.

Third moment of hydrodynamical analysis

Instrument Rig

The fourth load case is the case that will be implemented for the third moment. At this moment, both the varying buoyancy F_ρ and slamming impact force F_{slam} will be zero as the structures are fully underwater so there is no surface upon which they could act. the mass force F_{Mi} and drag force F_{Di} will have to be calculated separately for the legs and the trusses of the bottom and middle level of each structure as well as for the already submerged bottom and top grids.

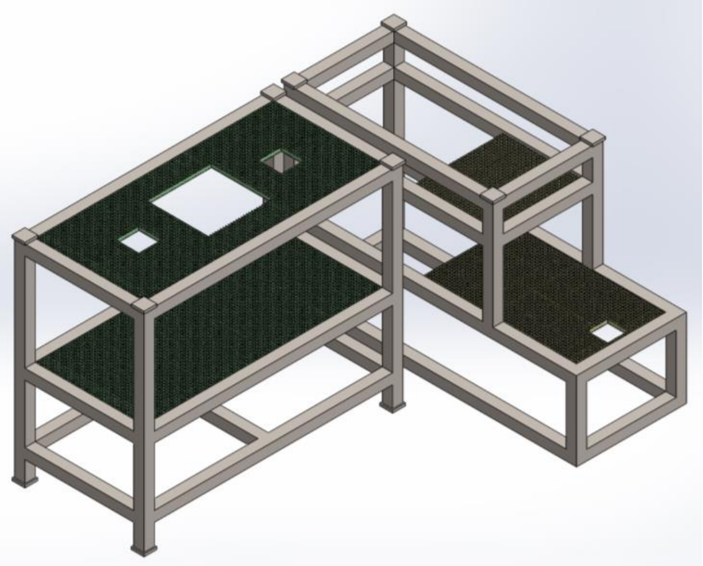

Figure 33: Third moment of hydrodynamical analysis

At this moment, the distance between the waterplane and the center of gravity of the submerged part of the Instrument Rig d is of 1.78 m, with that the characteristic vertical water particle velocity v_w and acceleration a_w can be obtained with their respective equations (Equation 15: Vertical water particle velocity and Equation 16 respectively) giving a value of 1.32 m/s and 0.83 m/s^2 respectively. Therefore, the relative velocity between the Instrument Rig and the water particles (Equation 7) would be of 2.22 m/s.

The drag force generated by the grids of the Instrument Rig would be calculated by following the methods of the previous moment of analysis and considering the grids as a rectangular plates parallel to the flow which would thereby both have a drag coefficient of 1.20 and a total area of 1506 cm^2 and 1214 cm^2 for the bottom and top Instrument Rig grid respectively.

The drag force F_D (Equation 6) generated by the Instrument Rig at this moment will be divided into four components. The vertical columns which have an area of 64 cm^2 each and a drag coefficient of 1 if they are considered as square rods parallel to the flow [20, p. 154] and the horizontal trusses in the bottom, middle and top level which will be generalized as a rectangular plate parallel to the flow which would thereby all have a drag coefficient of 1.20 and have a total area of 4960 cm^2 (for the bottom level) and 4288 cm^2 (for the middle and the top level). The total drag force generated by the Instrument Rig; including the grids, at this second moment would amount to 4946.1 N (16.1 N by each of the vertical columns, 1498.7 N by the bottom truss, 455 N by the bottom grid, 366.8 N by the top grid and 1295.6 N by the middle and top trusses).

The mass force F_M (Equation 14) generated by the Instrument Rig at this moment would be as well subdivided into the same components as those of the drag force. The mass of the object in the air M_i would be that of the Instrument Rig of 387.7 kg.

Following the same methodology and assumptions made on the previous moment of analysis, each one of the vertical columns would have a C_A of 0.08; an even more conservative estimate, and a reference volume of $0.08^2 \cdot 1.6$ (equal to its displacement volume $V_{1...4}$), each vertical column would therefore have an added mass coefficient $A_{331...4}$ of 0.84 each according to [24, p. 119].

The horizontal trusses in the bottom level would have a C_A of 0.757 and a reference volume of $0.25\pi \cdot 1^2 \cdot 2$ and; given that p would be of 75.2%, their total added mass coefficient A_{335} would be of 118.8.

The horizontal trusses in the middle and top levels would have a C_A of 0.757 and a reference volume of $0.25\pi \cdot 1^2 \cdot 2$ and; given that p would be of 78% a, their total added mass coefficient A_{336} and A_{337} would be of 107.4 each.

Just as in the previous moment of analysis, The displaced volume input into these calculations for the added mass of the horizontal trusses V_5, V_6 and V_7 would be the total volume the supposed plate displaces without the perforations of $1 \cdot 2 \cdot 0.08$ m^3.

Additionally, the added mass generated by the both grids of the Instrument Rig need to be considered in this moment. Following the steps of the previous moment, they can be considered as rectangular plates with a reference volume of $0.25\pi \cdot 0.84^2 \cdot 1.84$ and a C_A of 0.757. Considering that their p equals 90.25 % (for the bottom grid) and 92.14% (for the top grid), their total added mass coefficients A_{338} and A_{339} would be of 45 for the bottom grid and 42.1 for the bottom and top grid if the Instrument Rig respectively. Again, of worth noting, M_i for this specific calculation would need to be the mass in the air of the bottom and top grids in the Instrument Rig of 2.2 and 1.77 kg respectively while V_8 and V_9 would correspond to the volume the plates would displace without perforations of $0.3 * 0.84 * 1.84$ m^3.

The total added mass force generated by the Instrument Rig at this third and final moment of analysis would; with all components accounted for, be of 7993.9 N (975.2 N by each of the vertical columns, 1292.4 N by the bottom truss, 142.1 N by the bottom grid, 133.8 N by the top grid and 1262.8 N by the middle and top trusses)

The total Hydrodynamic force generated by the Instrument Rig F_{hyd} at this third and moment of analysis can now be calculated with Equation 5 giving a total of 9099 N.

UNDINA Platform

At this moment, the distance between the waterplane and the center of gravity of the submerged part of the UNDINA Platform d is of 1.76 m, with that the characteristic vertical water particle velocity v_w and acceleration a_w can be obtained with their respective equations (Equation 15: Vertical water particle velocity and Equation 16 respectively) giving a value of 1.3 m/s and 0.83 m/s^2 respectively. Therefore, the relative velocity between the Instrument Rig and the water particles (Equation 7) would be of 2.22 m/s.

The drag force generated by the grids of the Instrument Rig would be calculated by following the methods of the previous moment of analysis and considering the grids as a rectangular plates parallel to the flow which would thereby both have a drag coefficient of 1.20 and a total area of 774.55 cm^2 and 520.6 cm^2 for the bottom and top UNDINA Platform grid respectively.

The drag force F_D (Equation 6) generated by the UNDINA Platform at this moment will be divided into three components. The vertical columns which have an area of 64 cm^2 each and a drag coefficient of 1 if they are considered as square rods parallel to the flow [20, p. 154]. The two bottom horizontal trusses will be generalized as a rectangular plate parallel to the flow which would thereby have a drag coefficient of 1.20 and have a total area of 4464 cm^2 each. And the two top horizontal trusses will be generalized as a rectangular plate parallel to the flow which would thereby have a drag coefficient of 1.20 and have a total area of 3432 cm^2 each.

The total drag force generated by the UNDINA Platform; including the grids and all trusses, at this second moment would amount to 5230.5 N (16.1 N by each of the vertical columns, 1349.6 N by each of the bottom trusses, 1037.6 N by each of the top trusses, 234.2 N by the bottom grid and 157.4 N by the top grid).

Following the same methodology and assumptions made on the previous moment of analysis, the mass force F_M (Equation 14) generated by the UNDINA Platform at this moment would be as well subdivided into the same components as those of the drag force. The mass of the object in the air M_i would be that of the Instrument Rig of 315.5 kg. Each one of the vertical columns would have a C_A of 0.08; an even more conservative estimate, and a reference volume of $0.08^2 \bullet 1.44$ (equal to its displacement volume $V_{1...4}$), each vertical column would therefore have an added mass coefficient $A_{331...4}$ of 0.76 each according to [24, p. 119].

The horizontal trusses in the two lower levels would; like in the previous moment have a C_A of 0.757 and a reference volume of $0.25\pi \bullet 0.85^2 \bullet 1.18$ and; given that p would be of 76.8%, their total added mass coefficient A_{335} would be of 100.4 each. The displaced volume input into these calculations for the added mass of the bottom horizontal trusses V_5 and V_6 is the total volume the supposed plate would displace without the perforations of $0.85 \bullet 2.26 \bullet 0.08$ m^3.

The horizontal trusses in the two top levels would have a C_A of 0.757 and a reference volume of $0.25\pi \bullet 0.85^2 \bullet 1.615$ and; given that p would be of 75% a, their total added mass coefficient A_{336} and A_{337} would be of 69.8 each. The displaced volume input into these calculations for the added mass of the bottom horizontal trusses V_7 and V_8 is the total volume the supposed plate would displace without the perforations of $1.615 \bullet 0.85 \bullet 0.08$ m^3.

Additionally, the added mass generated by the both grids of the UNDINA Platform need to be considered in this moment. Following the steps of the previous moment, they can be considered as rectangular plates with a reference volume of $0.25\pi \bullet 0.69^2 \bullet 1.18$ and $0.25\pi \bullet 0.61^2 \bullet 1.69$ for the bottom and top grid respectively, a C_A of 0.757 and 0.579 for the bottom and top grid respectively. Considering that its p equals 90.48 % (for the bottom grid) and 88.77% (for the top grid), their total added mass coefficients A_{339} and A_{338} would be of 19.3 for the bottom grid and 7.2 for the bottom and top grid if the Instrument Rig respectively. Again, of worth noting, M_i for this specific calculation would need to be the mass in the air of the bottom and top grids in the UNDINA Platform of 1.13and 0.76 kg respectively while V_9 and V_{10} would correspond to the volume the plates would displace without perforations of $0.03 * 0.69 * 1.18$ and $0.03 * 0.69 * 0.61$ m^3 respectively.

The total added mass force generated by the Instrument Rig at this third and final moment of analysis would; with all components accounted for, be of 7352.5 N (793.8 N by each of the vertical columns, 1065.4 N by each of the lower trusses, 978.7 N by each of the upper trusses, 63.1 N by the bottom grid and 26 N by the top grid)

The total Hydrodynamic force generated by the Instrument Rig F_{hyd} at this third and moment of analysis can now be calculated with Equation 5 giving a total of 9023.2 N.

Total hydrodynamic loads

Table 6: Hydrodynamic loads of the Instrument Rig

	F_ρ	F_D	F_{slam}	F_M	F_{hyd}
1° moment	660.6 N	1,638.5 N	1,987.4 N	5,192 N	5,803.5 N
2° moment	660.6 N	3,434.6 N	1,584.1 N	7,614.3 N	8,575.6 N
3° moment	0 N	4,346.1 N	0 N	7,993,9 N	9,099 N

Table 7: Hydrodynamic loads of the UNDINA Platform

	F_ρ	F_D	F_{slam}	F_M	F_{hyd}
1° moment	660.6 N	1,475.7 N	1,021.4 N	4,237.4 N	4,362.2 N
2° moment	660.6 N	3,099.8 N	678.1 N	5,336.3 N	6,011.2 N
3° moment	0 N	5,230.5 N	0 N	7,352.5 N	9,023.2 N

Knowing the loads that each of the individual structures generate when crossing the splash zone under the supposed conditions, the total loads that the proposed platform would exert unto the lifting line at each of the analyzed moments would be the ones displayed in the table below.

Table 8: Total hydrodynamic loads values

	F_ρ	F_D	F_{slam}	F_M	F_{hyd}
1° moment	1,321.2 N	3,114.2 N	3008.8 N	9,429.4 N	10,165.7 N
2° moment	1,321.2 N	6,534.4N	2,262.2N	12,950.6 N	14,586.8 N
3° moment	0 N	9,546.6 N	0 N	15,346.4 N	18,122.2 N

Knowing the volume displaced by the structures at each of the analyzed moments, the static weight of the station F_{stat} can be determined. Having calculated the characteristic hydrodynamical load F_{hyd} , the characteristic total force F_{total} can be obtained for each of the analyzed moments.

Table 9: Characteristic total force

	F_{hyd}	F_{stat}	F_{total}
1° moment	10,165.7 N	6,000 N	16,165.7 N
2° moment	14,586.8 N	4,873.8 N	19,460.6 N
3° moment	18,122.2 N	3,697.4 N	21,819.6 N

Capacity

RV Gunnerus crane

In order to determine whether the crane of RV Gunnerus is capable of lifting the proposed station under the supposed sea state (corresponding to the most extreme weather state possible in the Trondheimsfjord), [20] determines a dynamic amplification factor DAF_{conv}, which then multiplies the total characteristic load F_{total}. The result of that product is then compared to the capacity of the crane to determine if it is safe to lift the object in question under the supposed sea state.

$$DAF_{conv} = \frac{F_{total}}{Mg}$$

Equation 19: converted dynamic amplification factor

Where M is the mass of the lifted object in the air; 709 kg for the structure analyzed in the *Hydrodynamical analysis*. Therefore, the resulting DAF_{conv} would equal 3.13 which multiplied by the highest total characteristic load F_{total} (corresponding to the third moment of analysis) gives a total of 68,450.76 N or 6,977.65 kg. Based upon that resulting amplified load, it can be determined that the proposed station can be safely lowered by the main crane of RV Gunnerus given that it is capable of lifting a maximum load of 8,600 kg at an extension of 6 m.

Lifting pad eyes

To determine whether the lifting pad eyes have the capacity to withstand the installation of the proposed station, both the Tear-out (Equation 1) and the Contact stress (Equation 2) criteria will be used.

Following the guidelines of the DNV Standard 2.22 [25], In order to determine whether the lifting pad eyes are made from the correct material, the resulting load needs to be multiplied by a load factor that for this case will be 2 given that; as demonstrated in *Table 9*, the maximum load the station will generate will be of less than 3 tons (3000 kg). Therefore, the RSL will be of 43639.2 N, t equals 2 cm, H equals 2.7 cm and D_H equals 2 cm.

The resulting tear-out stress equals 192.5 MPa and the resulting contact stress is of 274.5 kPa. Therefore, the lifting pad-eyes would be strong enough to not fail as the yield strength of their material (AISI 316 stainless steel) is of 290 MPa.

Geometry

Arrangement of the components

The CTD sensor as well as the junction boxes were mounted in the middle level of the Instrument Rig since it is a location where they will be protected by the Instrument Rig's structure.

The acoustic instruments corresponding to the OceanLab project were installed in the top level of the Instrument Rig with the help of its instrument bracket which may allow for the adapting of new or other instruments that may be required. The reason behind placing them in the top level, is to give both the acoustic modems and the ACDP a clear field of view to the water column above and that way maximize their beam spreading.

On that same top level of the Instrument Rig, the pan-tilt base was mounted in order to give both the optical module and the video camera a complete view of its surroundings and; most importantly, of any vehicle that may approach the station either to transfer data via the optical module or to dock unto the UNDINA Platform.

The inductive module was mounted on the top of the garage in the UNDINA Platform where the Blueye will dock unto and with the help of its positive buoyancy will be help in place to communicate with the station via the inductive module. In order to give homing aid, the UNDINA also features a USBL transponder located under the garage.

Dimensions

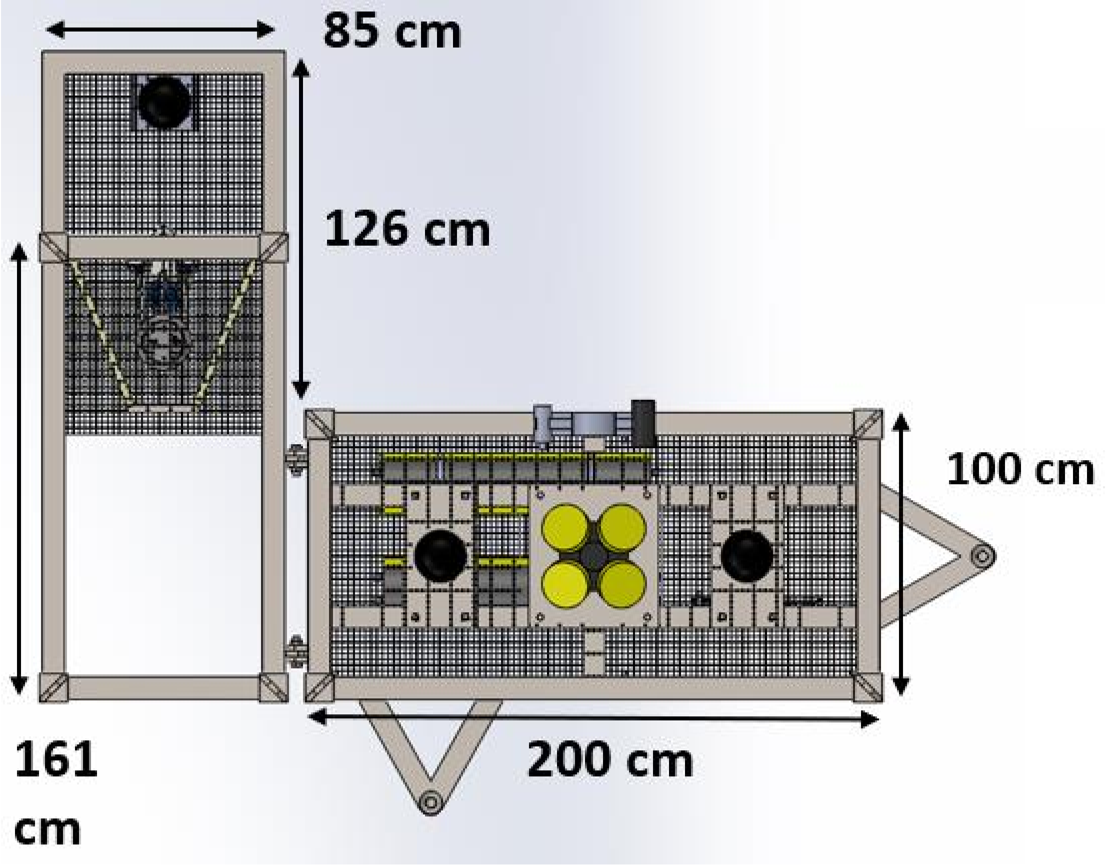

Figure 34: Top view with main dimensions

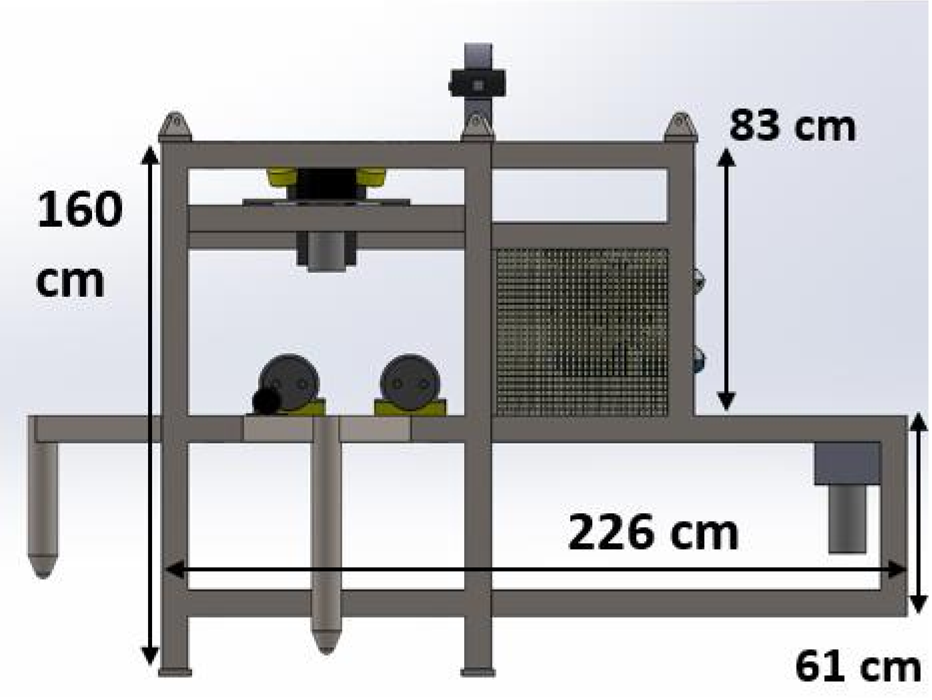

Figure 35: Side view with main dimensions

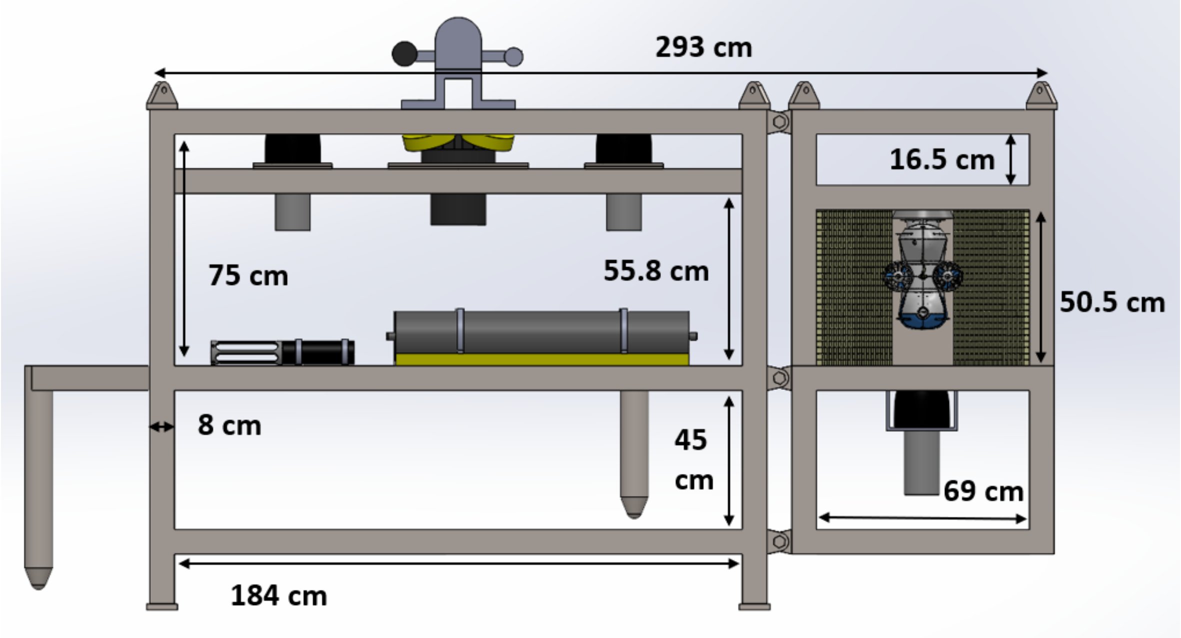

Figure 36: Frontal view with main dimensions

Chapter V: Discussion

The chosen acoustic and optical communication modules fulfill the requirements established as they allow for the communication of the station with both high and low bandwidth to the vehicles that would use the station for communication purposes. The CTD and ADCP modules chosen for the station allow the station to be aware of the environmental conditions in the water column, something that could be very useful for optimizing optical communications or to determine the speed profiles acoustic signals traveling to and from the station will have.

The proposed design for the UNDINA Platform in this thesis allows it to dock a Blueye ROV. This means that the station could either be used for housing that vehicle as a resident ROV, or the Blueye's tether could be removed to instead allow it to operate fully autonomously within the vicinities of the station. The dimensions of the UNDINA Platform were chosen in order to optimize the rigidity of its mechanical joining of the Instrument Rig. However, those dimensions and the holding strategy that makes use of just the positive buoyancy of the vehicle would also allow for the adapting of other UUVs like the other two vehicles considered in the MarTERA UNDINA project (the Seasam Drone and the EvoLogics Poggy) or even the LAUVs owned by AUR-Lab. Meaning that the proposed design for the UNDINA Platform fulfills its requirement of housing a Blueye while offering the possibility of housing other UUVs that could also benefit from it.

The quadrangular shape of the proposed UNDINA Platform further simplifies any future adapting of other vehicles or the modification of its instrumentation considering that any instruments that were to be added to the platform could be mounted without having to do any significant changes to the structure.

The material for the UNDINA Platform, despite being the heaviest and most expensive of the materials proposed for the structure, was chosen in order to prevent any possible compromising of the joining between the two structures that conform the station proposed in this thesis, its good weldability and machinability means that the construction of the structure will not lead to any extraordinary costs during its manufacture. Additionally, if it were to be installed in places where the sea state or environmental conditions make its retrieval more inconvenient, not needing to worry about restoring any coating against corrosion would lead to a more sustainable long-term deployment of the station.

Assuming the most extreme weather conditions in Trondheimsfjord; where the station is planned to be installed, allowed for demonstrating that the proposed design for the station will not cause the equipment of Gunnerus to fail and thereby guarantees a safe installation operation.

The lifting pad eyes of the UNDINA Platform were given the same dimensions as those in the; already existing, Instrument Rig. This resulted as a good choice as the capacity of such pad eyes would guarantee them not to yield while loaded under the assumed operation.

Chapter VI: Conclusions and further work

UUVs have evolved from being just very specialized and exclusive machines in their conception in the middle of the 20th century to sensor platforms that can now be used for multiple application both in the industry and in science. But their main limiting factor is their dependency on either a surface vessel or resurfacing maneuvers which not only limits their operative ranges but also restricts them from more widespread use in environments such as extreme depths, unfavorable sea states or ice-covered waters where depending on the surface is either highly risky, inconvenient or even impossible.

The hydrodynamical calculations; although very conservative, helped prove that the station can be safely installed in Trondheimsfjorden by RV Gunnerus under even the most extreme sea state possible without risking the vessel's crane to damage or failure.

As expected, the moment when the station will generate the most hydrodynamical loads is shortly after it is fully submerged as it is when all of the elements of the structure are contributing to the drag and added mass force. Which demonstrates how; even without any slamming impacts unto the structure, the waves still lead to the horizontal parts of the structures to generate a lot of loads because of their added mass.

The station proposed in this thesis has the possibility of fixing the inconveniences UUVs currently encounter with the current technology given that it still offers long range communications and navigational aid to UUVs with its acoustic module on top of allowing for high bandwidth; albeit very low range, communications with UUVs while underwater via its optic module. Additionally, with its inductive module, the station proposed in this thesis gives UUVs a possibility of recharging their batteries while docking into the station. Thereby eliminating the need of either a tether or recovery for the extraction of the data the UUVs have collected during an operation or for the recharging of their batteries, factors that currently limit their range and practicality to a very high degree.

The next step in the development of this station would be the construction of the UNDINA Platform as well as the integration of the instruments into both the Instrument Rig and UNDINA Platform. Once the station has been fully built and assembled, the next step would be its implementation in Trondheimsfjord where it is planned to be installed later during this year of 2022.

Another very important step in the development of this project would be the integration of the DINA module into the Blueye in order to finally determine with field deployments how the module improves the autonomy of the vehicle. And; if possible, determine whether it is enough to fully remove its umbilical.

In case the project was to be wanted to be implemented in places where ice can be found either seasonally or all year round, a thorough analysis of how the proposed complementation with an LBL navigation network would be pertinent as it would be the next step in providing UUVs the necessary infrastructure they currently lack for better reliability in ice covered waters. In that same line, the umbilical connecting the station to its base back on land would need to be designed to withstand; apart from the usual wave and current induced loads, the loads that both land fast level ice and brash ice floes would generate.

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