Master's thesis

NTNU
Norwegian University of Science and Technology

Mathias Gjone

Set-Based Development of an Autonomous Waste Collection System for Unmanned Surface Vessels

Master's thesis in Mechanical Engineering (MIPROD)
Supervisor: Geir Ringen
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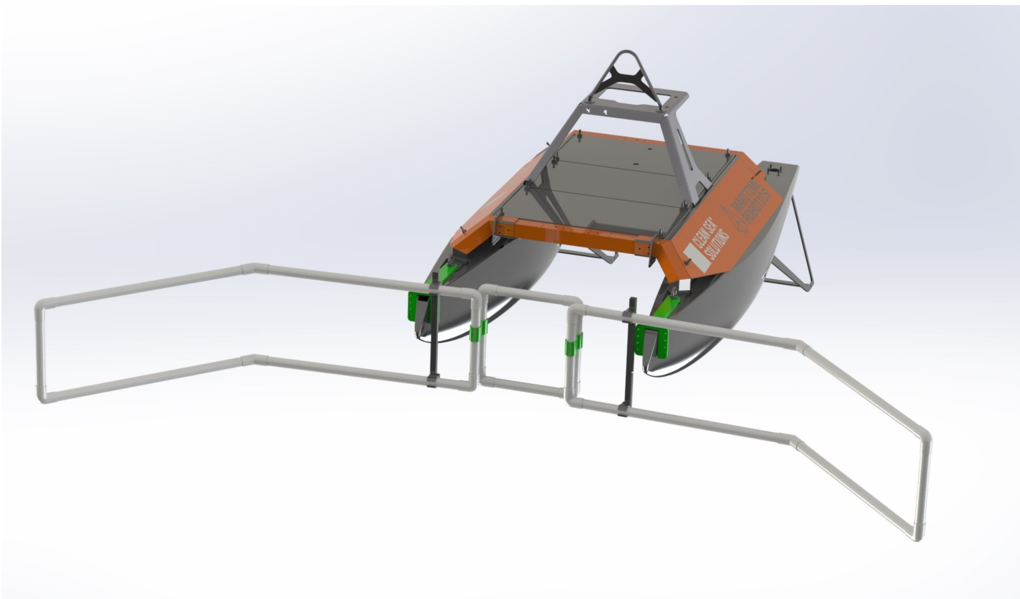

Mathias Gjone

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Abstract

The escalating challenge of marine waste presents a significant threat to our ecosystems and climate. Each year, millions of tons of waste, end up in our oceans, causing harm to an extent we do not yet know the consequences of. Innovations in technology provide a unique opportunity to combat this issue. The development of autonomous Unmanned Surface Vessels (USVs) for waste collection is a proposed solution to help address the problem. This work is motivated by a commitment to leveraging technology to the global efforts towards a cleaner, healthier marine environment and, ultimately, a more sustainable future for our planet.

This thesis explores the exciting potential of managing marine waste using USV's, focusing specifically on developing a mechanical system for a specific USV. This unique system is designed to actively find, collect, transport, and dispose of objects floating on the water's surface. The project is part of ongoing research by Clean Sea Solutions, linked closely with the Norwegian University of Science and Technology (NTNU). The study looks into rational function, user, and performance requirements to create an optimal design. The study combines existing product development approaches with innovative solutions, that result in a design proposal that is unique, innovative, and more efficient than similar projects. Set-Based Concurrent Engineering (SBCE) has been employed as the primary product development strategy, which allowed for exploring and narrowing down multiple design options concurrently, reducing design risks and making well-informed decisions. This research approach could potentially be an inspiration for corresponding physical product development projects. While the project still is prone to some technological gaps, this project illuminates a promising path for using technology to address environmental challenges. This design not only tackles physical waste but also leaves room for discovering other possible applications. The final design proposal has proven its validity by performing testing under realistic operating conditions. It also emerges that the project has contributed to lifting the Technology Readiness Level (TRL) several steps through this development.

Sammendrag

Den økende utfordringen med marint avfall utgjør en betydelig trussel mot økosystemer og klima. Hvert år havner millioner av tonn avfall I alle verdens hav og forårsaker skade i en grad vi ennå ikke vet konsekvensene av. Innovasjon innen teknologi gir en unik mulighet til å bekjempe dette problemet. Utviklingen av autonome ubemannede overflatefartøyer (USV) for avfalls håndtering er en foreslått løsning for å hjelpe til med å løse problemet. Dette arbeidet er motivert av å utnytte teknologi for bidra mot et renere, sunnere marint miljø og, til syvende og sist, en mer bærekraftig fremtid for planeten vår.

Denne oppgaven utforsker det spennende potensialet ved å håndtere marint avfall ved hjelp av USV-er, og fokuserer spesifikt på å utvikle et mekanisk system for en spesifikk USV. Dette unike systemet er designet for aktivt å finne, samle, transportere og deponere gjenstander som flyter i vannoverflaten. Prosjektet er en del av et pågående prosjekt av Clean Sea Solutions, tett knyttet til Norges teknisk-naturvitenskapelige universitet (NTNU). Studien ser på rasjonelle funksjons-, bruker- og ytelseskrav for å skape et optimalt design. Studien kombinerer eksisterende produktutviklingstilnærminger med innovative løsninger, som resulterer i et designforslag som er unikt, innovativt og mer effektivt enn lignende prosjekter. Set-Based Concurrent Engineering (SBCE) har blitt brukt som den primære produktutviklingsstrategien, som gjorde det mulig å utforske og begrense flere designalternativer samtidig, redusere designrisiko og ta velinformerte beslutninger. Denne forskningstilnærmingen kan potensielt være en inspirasjon for tilsvarende fysiske produktutviklingsprosjekter. Selv om prosjektet fortsatt er utsatt for noen teknologiske hull, belyser dette prosjektet en lovende vei for å bruke teknologi for å møte miljøutfordringer. Denne designen takler ikke bare fysisk avfall, men gir også rom for å oppdage andre mulige bruksområder. Det endelige designforslaget har bevist sin gyldighet ved å utføre testing under realistiske driftsforhold. Det kommer også frem at prosjektet har bidratt til å løfte Teknologimodenheten (TRL) flere steg gjennom denne utviklingen.

Preface

This Master's thesis marks the completion of a five-year educational course at the Norwegian University of Science and Technology (NTNU), where I have pursued the field of Mechanical Engineering. The thesis summarizes the knowledge, skills, and insights I have amassed throughout my academic education. The primary objective of this thesis is to create new insights within a specific technological domain that meets my field of expertise and interest. That's why I focused my thesis on something that could have an impact, a subject where we still have much to learn. This project has concentrated product development within a small technical segment. Significant changes can only be achieved gradually, step by step. This project contributes as one of these small steps towards a greater change. Overall, this thesis is about shining a light on sustainable technical solutions and showing the potential of rapid prototyping to achieve quicker results. I believe that in recent times, environmental projects have been prone to slow development processes, lots of talks, and little physical innovation. This project stands in contrast to that type of approach. I hope this research can inspire others to pursue more rapid development approaches and encourage decision-makers to make a difference with action and not with words. Finally, I would like to show my gratitude to the individuals that have been vital to the quality and completion of this project:

> First and foremost, my academical-supervisor, Geir Ringen, for valuable guidance, patience, and insightful critiques, which have profoundly shaped the thesis's growth and outcome.
>
> To Clean Sea Solutions, for providing the resources needed to complete this project. Helping with a collaborative spirit and real-world insights has been vital. An extra thanks to Matthias Van Middentorp, my technical supervisor from Clean Sea, as well as Gulleik Olsen, who has been a valuable sparring partner throughout the project.
>
> Lastly, to my fellow students and friends, your companionship and camaraderie have been my lifeline during the most challenging times. Our shared struggles have immeasurably enriched this journey. Your support and friendship have made all the difference.

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PART I

INTRODUCTION

1 Background for thesis

The world's lakes, rivers, and oceans are increasingly exposed to more pollution as a result of human activities. Plastic trash, harmful chemicals, and other forms of harmful man-made waste present a severe threat to marine life and ecosystems[1]. The inappropriate waste disposal by individuals, corporations, and enterprises contributes to this problem. Plastic garbage, in particular, is a major source of worry because it does not biodegrade and can be present in the environment for generations. The global problem of waste in lakes and oceans is something that affects all parts of the world in ways researchers are still determining. Microplastics have been a highly discussed topic in the latest years. Generally, one is still determining the consequences of microplastics, and we know that it is rapidly increasing and accumulating in the maritime environment[2][3]. According to a UN assessment, an estimated 8 million tons of plastic waste enter the world's oceans each year[1], the equivalent of dumping a garbage truck full of plastic into the ocean every minute. This amount is expected to double over the next decade[1]. A recent study also shows that the number of microplastic particles in the ocean has skyrocketed and that these large amounts follow rivers, outlets, and ocean currents[4]. The scope of this problem is so enormous that it cannot possibly be solved in a specific way. Instead, various active and passive measures will be needed to deal with this. When focusing on active measures, one method is collecting or retrieving waste that has found its way into the environment. The challenge with collecting waste is that it is often time-consuming and very repetitive, in addition to being very unprofitable. In later years, robotic technology and autonomous systems saw significant development. One proposal is to utilize this technology to deal with the specific tasks of active waste management.

Motivation
UN has stated an agenda for sustainable development within 2030[5]. As individuals, we are all responsible for protecting and preserving our planet's natural resources for future generations. We all have different ways of contributing positively through our ways. This thesis focuses on how product development within mechanical engineering can be used to benefit an important issue. Developing new technologies that can effectively collect waste from lakes, marinas, rivers, and other bodies of water is one step in addressing the growing problem of waste pollution in oceans and waterways. This is, therefore, a good opportunity to help protect marine life and ecosystems and ensure a sustainable future for our planet. As stated by the UN, many challenges must be solved, and providing useful technology is an important part of reaching these goals.

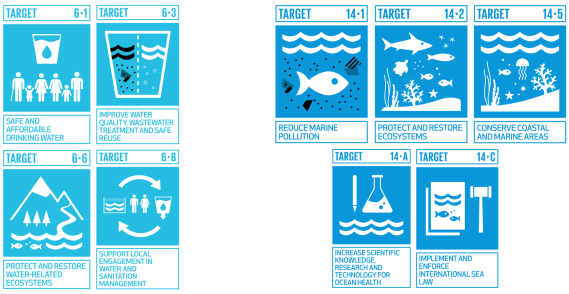


Figure 1: Some of the relevant sustainability goals provided by UN[5]

2 Problem description

As a response to the issue of waste in the marine environment, the potential for using autonomous drones has occurred. This thesis aims to research and develop a dynamic mechanical system that will benefit the working of an autonomous USV (unmanned surface vehicle). This mechanical system should enable the USV to actively target, collect, transport, and dispose of objects on the water surface. The intended USV utilizes sensors and novel path-planning algorithms to detect, target, and navigate to the desired locations. In addition to navigation, the system must also be able to physically collect objects on its way. To achieve this, navigational software and a mechanical system must be developed. The mechanical system will be specially developed to collect, transport, and dispose of objects. This problem focuses solely on the mechanical system that should provide this operation. While the main goal is towards physical waste, the development is open to discoveries of other application areas. The waste collection USV is an already ongoing research and development project under the auspices of Clean Sea Solutions (CSS), which again has close ties to NTNU. The development of the mechanical system is a subsystem to the already ongoing project, meaning the framework of the project is relatively detailed. The subsystem should eventually provide the right functions to benefit the USV's way of working. The project focuses on investigating rational function, user, and performance requirements for such a system so that an optimal design can be conceptualized. This should be achieved by using appropriate product development methodologies. A part of the research includes investigating how existing product development approaches can be utilized for optimizing the process of developing such defined products. The project should make use of dimensions and specifications that can be directly linked to the USV's (in particular the Otter USV) that are developed by Maritime Robotics. As a part of the project, the Otter USV was made available for testing throughout the project.

Some initial research questions that were raised prior to the project:

1. Explore how physical product development methods can be evaluated, designed, and applied based on a specific case study.
2. Identifying the current state of autonomous waste collection methods and evaluating their effectiveness.
3. Identify key functionalities for developing a waste collection system in relation to a USV.
4. Identify requirements that can be used to measure such a system in terms of its efficiency.
5. Research the potential of a USV system design that is more optimized for its application.

Figure 2: The Otter used by Clean Sea Solutions during early-stage development (summer 2021)

2.1 Objective and scope for the thesis

The long-term goal of this project is to contribute to the task of reducing waste in waters by developing a system that can successfully collect waste autonomously. The corporate goal for Clean Sea Solutions is to develop and commercialize an autonomous USV system capable of performing such advanced operations. Using novel data-vision and path-planning algorithms, the system should operate independently. In addition to the mechanical and navigational development, a docking station for charging is needed, very much similar to the now very-common robotic lawn-mover. To achieve full autonomous operation, the system must also be able to dispose of its collected content(disposal station). Clean Sea Solutions have already an ongoing project on this, which will be further detailed in a later chapter. Over the long term, this system should reach a technology readiness level of 8, meaning it both are standardized and approved for commercial use[6]. The road toward developing a system with a TRL of 8 for such an advanced system would acquire extensive research, development, verification, and validation.

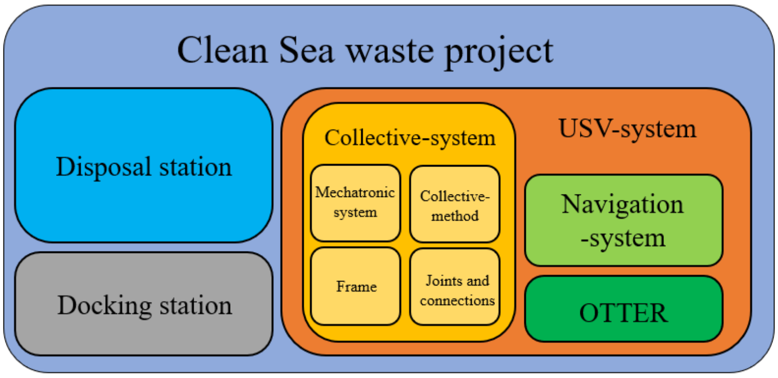


Figure 3: Scope of the case study

This thesis is solely focused on the development of the mechanical waste collection system. Therefore the thesis will not cover any USV-related technical issues or navigation and control systems. However, these topics will be presented if feasible for the current development. The thesis assumes that a fully developed navigation system is provided so that the Otter and the collective system will present a fully working concept. This project is also completed under relatively restricted time and workforce, meaning certain decision-making has been influenced by these conditions. From 3, it can be seen how the intended collective system is only a subsystem in a larger project and that the collective system also be divided into subsystems. This thesis will not focus on raising the subsystem to a TRL of 9(commercialization), but rather towards a 6-7(full-scale prototype testing). To achieve this, a conceptual design should be detailed, and a prototype should be tested under real-life conditions to make a proof-of-concepts statement. The author was free to develop the project in the most sensible direction. While also CSS expressed a desire to receive a proposal on the design geometry of such a system at the end of the project.

Two MSc projects were carried out in parallel, focusing on object recognition of objects located on the water surface and the optimal path planning toward these objects. The product of these three MSc projects shall (if successful) be able to target objects, navigate towards, collect, transport, and dispose of objects at a designated location. Clean Sea Solutions aims to perform a summer project based on the proposed design. The summer project will use the Otter drone and a collective system to perform tests in marinas along the Norwegian coast. This leads to extra motivation to provide both working and sensible solutions that can be utilized in further research and development.

2.2 Structure of thesis

The thesis is structured in a way that is considered sensible to the specific case study, with six main parts, each covering an essential segment of the thesis.

- Introduction
- Literature Review
- Method
- Case Study
- Discussion
- Conclusion

The thesis structure is designed to provide a clear and logical flow of information, making it easy for the reader to follow the research process and the traditional documentation practice of academic work. Each part is further divided into multiple sections and subsections. This structure guides the reader through the research process, presenting relevant background information, methodology, findings, and analysis, leading to a well-reasoned conclusion. Beyond infographics, drawings, screenshots, and photographs, this document also incorporates links to video content where applicable. These videos, which are clearly indicated, are strongly recommended for viewing. They offer a depth of understanding that exceeds what static visuals convey, bringing additional insight to the material.

The **Introduction** part sets the context for the thesis, providing background information, motivation, and defining the problem this research will address.

A **literature review** provides an overview of relevant literature related to the Case study, both in terms of Product development approaches and a case-specific study covering topics such as prototyping, existing technologies, and USV systems. This is done to establish a good foundation for the upcoming case-study

A **methodology** part is presented as part of planning for the Case-study. This part presents, justifies, and evaluates the chosen approach for the case study. This will hopefully be useful to enlighten and explain why specific methods and approaches were prioritized above other available methods.

The **Case study** is the main part of the thesis. It includes the status of the project, the Otter drone (USV) development, project assumptions, and the various stages involved in the project, such as requirement research, conceptual design, design process, subsystem prototyping, and system integration.

The **Discussion** part will evaluate the research approach used in the thesis, assessing the suitability of the case study, the applicability of the thesis framework, and addressing the final result of the case study. This section allows for reflection on the study's limitations, contributions, and implications.

Finally, a **conclusion** will present the last part of the thesis. Which summarizes the main findings, draws conclusions based on the research, and suggests topics for further work. It provides closure to the thesis, showing how the research contributes to the field and what future directions it may take.

PART II

LITERATURE STUDY

2.3 Introduction to literature study

The literature study presented in this section provides a comprehensive overview of the research deemed relevant for the given case study. The literature review is divided into two main parts: (1) Product Development (PD) approaches and (2) Case-specific study on existing technologies. The literature review aims to achieve the following:

- Research appropriate technologies/projects in relevance to the case study.
- Evaluate case-specific parameters and information that can be used for future decision-making(including USV parameters and climatic factors).
- Research and evaluate relevant methodologies, strategies, techniques, and tools applicable to physical PD approaches.
- Evaluate and propose fitting PD approaches for the specific case study.

Combining the insights gained from both sections, this literature study aims to provide a solid foundation for the subsequent case study. The analysis of PD approaches will guide the selection of an appropriate framework and method for the development process, while the case-specific research will inform the design choices and technological considerations for the collective system. Overall, this literature study establishes the theoretical background and contextual understanding necessary, leading towards the development of an innovative and effective collective system for waste collection.

3 Case-specific study

This section focuses on conducting a case-specific study to examine existing technologies and obtain an understanding of the issue. The aim is to gain a comprehensive understanding of the current methods, technologies, and systems employed in this segment. By analyzing the literature on the effectiveness, limitations, and areas for improvement of existing technologies, findings are summarized. The literature search in this section primarily involves finding literature related to waste collection, autonomous systems, unmanned surface vehicles (USVs), and the case-specific USV (the Otter). It's important to keep in mind that the field of robotics is constantly evolving. Therefore, having an updated insight into these fields is vital to achieving valuable and relevant results.

3.1 The Environmental Impact of Marine Waste

Marine waste, as defined by the United Nations Environment Programme (UNEP), encompasses any human-made objects that are irresponsibly disposed of in marine and coastal environments[7]. Predominantly, it comprises oil-based products like plastics, styrofoam, and rubber, which pose the most significant environmental concerns. These materials' popularity as consumer products are owed to their low cost and high durability[1]. However, these attributes also tend to make them non-biodegradable, leading to their accumulation in environments such as lakes and oceans. UNEP states that 22 percent of produced plastic turns to litter due to improper management [7]. Marine garbage has rapidly escalated into a pervasive global environmental issue, with no part of the world left unaffected[3]. Over time, waste, particularly plastics, degrades into tiny fragments known as microplastics. These micro-plastics have been observed to intrude all trophic levels, although the long-term implications of such accumulation still are unknown[2]. This pervasive issue has been acknowledged as a global threat, yet the degree of its recognition varies vastly across nations and governments.

The root of marine plastic pollution lies in societal production-consumption patterns and the approaches different countries adopt toward their waste management[8]. To address this issue, various initiatives are in place, including legislation and regulations aimed at reducing plastic waste generation and enhancing waste management strategies. These measures, however, vary significantly between regions, and while they are improving, they could be better. Considering the magnitude and implications of this issue, urgent improvement in marine waste management solutions is needed. The primary focus should be restraining the flow of waste into the marine ecosystem and cleaning up the waste that has already entered these waters. Prevention at the source is undoubtedly the most effective solution. However, when preventive measures are insufficient, or the problem becomes overwhelming, waste must be actively extracted from the environment[8]. Active extraction involves physically removing waste from its original environmental location, typically by human or machine intervention. This method, although slow, is sometimes the only sensible method.

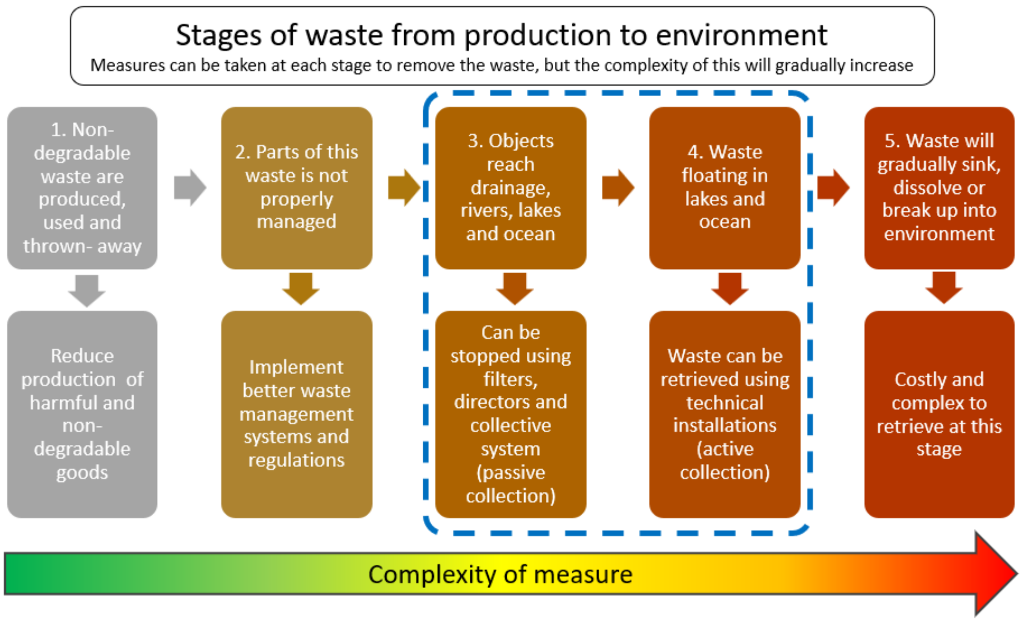


Figure 4: Stages of waste and potential measures to mitigate waste

An illustration that summarizes the stages of waste from production to environment is designed in 4. The active mitigation of waste, as detailed in stages 3 and 4, is a labor-intensive and expensive process, calling for innovative technical solutions. Stage 5 is considered the last phase in the life cycle of waste, at this point, it is no longer considered sensible/possible to retrieve.

3.2 Marine waste management

Marine waste management projects that actively target waste have emerged globally in recent years. However, a significant challenge for these initiatives is their lack of profitability. Traditionally, the scientific and research communities have been the key actors in this project[9]. Although this benefits research and development, it often results in projects fading once their timelines, budgets, or success criteria are met. As documented by [9], only some of these projects achieve a technology readiness level (TRL) that would allow for efficient transfer to society at large. However, in the past decade, private investors, often supported by donations and government incentives, have begun to enter the field. One such organization is The Ocean Cleanup[10], which is a non-profit environmental engineering organization. Another relevant organization is, of course, Clean Sea Solutions, which seeks to commercialize a product portfolio of technical solutions for waste management. One of the challenges with such projects is the significant costs associated with construction, operation, and labor. Costs can vary greatly depending on the targeted segment, making it complex to calculate the overall cost of a waste management system. As [11] notes, collection and transportation alone can account for at least 70 percent of the total cost of managing municipal solid waste (MSW). A general assumption is that the farther an object is from its original location, the more complex and costly it becomes to retrieve. For example, waste collection costs generally increase when transitioning from designated areas, such as trash bins, to rivers and even more so to the seafloor.

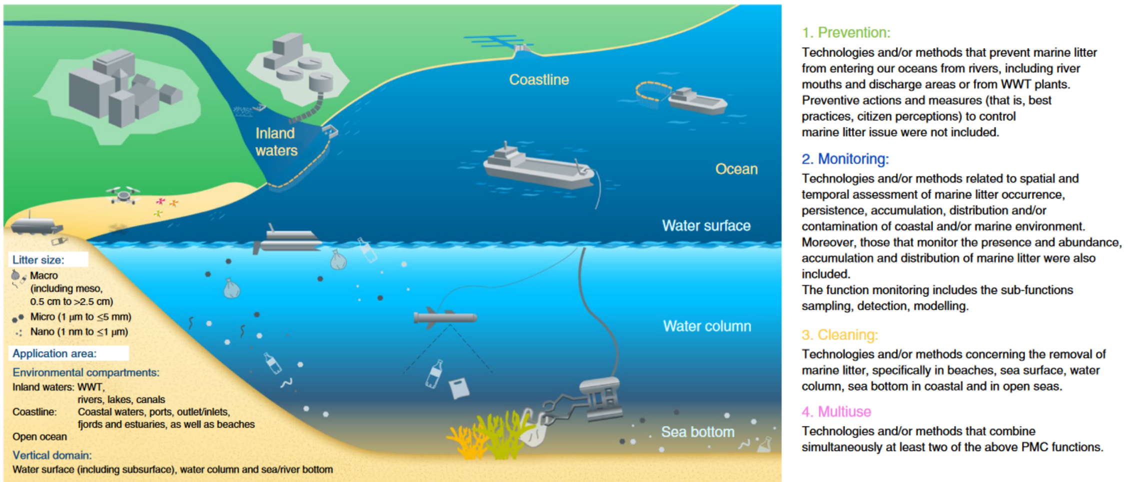


Figure 5: Summary of waste management segments [9]

A systematical waste management overview where presented in [9]. The waste location is divided into environmental compartments; inland waters, coastline, and open ocean. Where of which the water is divided into vertical domains; Water surface, water column, and sea bottom. Waste is also categorized as macro, micro, and nano, depending on size. Given the inefficiency and increased costs associated with retrieving waste from the environment, an essential focus for such projects should be on reducing costs related to manufacturing, operation, and maintenance. One obvious solution should be minimizing labor hours through automation. As waste management often involves repetitive tasks, it is a field that could benefit significantly from automation technologies. This will only be possible by developing affordable, efficient, and reliable technical solutions.

3.3 Unmanned Surface Vessels (USVs)

The technology readiness level of Autonomous Unmanned Surface Vessels (USVs) has significantly improved, particularly in environmental monitoring and management[12]. Due to their lightweight structure and potential for alternative fuel use, USVs are poised to contribute positively to these sectors. An emerging solution involves developing a collection system attached to a USV, specifically designed to efficiently collect and remove pollutants from coastal environments[13]. Unmanned Surface Vessels (USVs) are systems designed to navigate on water surfaces. They can be equipped with sensors, actuators, and other mechanical equipment for executing various tasks, such as mapping, monitoring, analyzing, and collection in the marine environment. USVs are particularly suited for dangerous or repetitive work environments. As they are unmanned, these vessels can be designed and dimensioned in innovative ways[12]. A USV system, like any vessel, can be divided into different subsystems. Each subsystem is designed for a specific purpose, and their collective operation results in the functionality of the entire Vessel[12]. The common subsystems of a USV are:

- Propulsion System: Provides the Vessel's propulsion, typically through electric engines.
- Power System: Supplies power to the Vessel, often using electric batteries.
- Hull Design: The structure of the vessel, which can be a monohull, multi-hull, keel, etc.
- Communication System: Facilitates communication via GPS, WiFi, Bluetooth, 3G, 4G, 5G.
- Navigation, Guidance, and Control System (NGC): Manages the Vessel's navigation and controls.
- Payload/Mechanical System: Customized for specific applications.

3.3.1 The Otter drone

An example of a USV is the Otter drone, engineered and manufactured by Maritime Robotics [14]. The Otter drone has been developed modularly, making it versatile for many applications. This versatility stems from its ability to accommodate various sensors and actuators. Additionally, the size and propulsion power of the Otter enables it to carry relatively large mechanical structures.

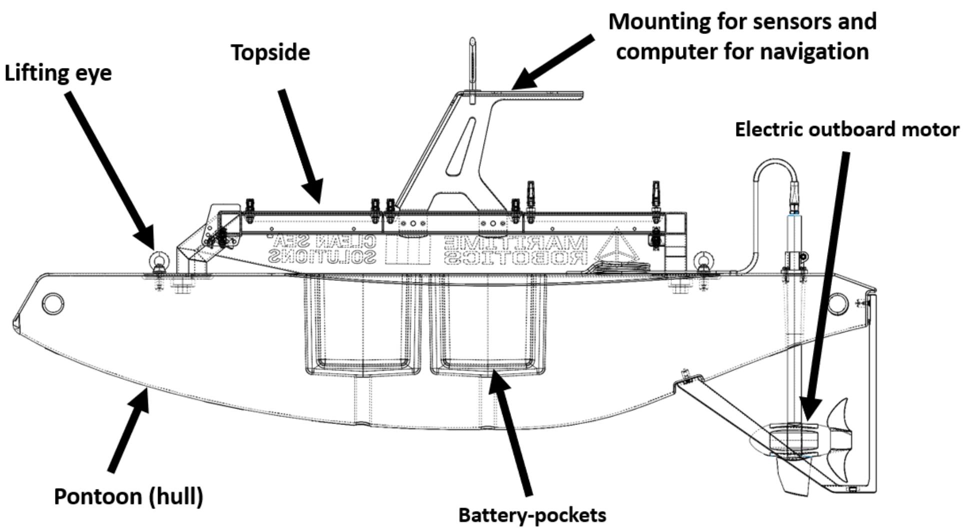


Figure 6: General overview of the Otters subsystems(which will be used for this project)

3.3.2 Specifications: The Otter

Specification	Value
Weight	65 kg
Speed	4 kn(very dependent on USV-setup)
Propulsion system	2 x 915 mAh, 12V-output
Battery Life	20 hours (2kn)
Dimensions	200 cm (L) x 108 cm (W) X 106.5 cm (H)
Draft	32 cm
Communications	wifi, 4G
Electric Propulsion Thrust	Dual electric thruster (Propulsive power: 180W each) [15]
Hull material	Polyethylene

3.4 Development and integration of systems into USVs

While Unmanned Surface Vessels (USVs) are not a new concept, these systems have been predominantly reserved for military projects. This trend can be attributed to the military sector's less restrictive budget and regulations compared to other sectors. Over the past decade, Navigation, Guidance, and Control systems have been extensively researched, making information on the topic readily accessible[12]. Concurrently, the cost of sensors related to such systems has significantly decreased. This price reduction has increased the affordability of these systems, especially for projects with tight budgets [13]. It's worth noting that there have been significant advancements in propulsion and power system technology for USVs. These improvements have made them lighter, more efficient, and cheaper, substantially enhancing their performance.

3.4.1 Autonomy

A particular segment within USV technology that has received significant attention is the research and development of autonomous operations. Like all marine vessels, USVs have a limited range, necessitating monitoring, and recharging. As autonomous systems become more prevalent, the research community and industrial actors are attempting to standardize various levels of autonomy. Lloyds Register, for example, has developed a scale for ships [16], which can be applied to describe a USV's level of autonomy.

Autonomy Level (AL)	Description
AL0	Manual operation – no autonomous function.
AL1	On-vessel decision support system (human-control)
AL2	Off-vessel decision support system (human-control)
AL3	Semi-autonomous vessel with an active human in the loop.
AL4	Vessel operates autonomously but with human monitoring
AL5	Fully autonomous with room for human interference
AL6	Fully autonomous with no need for human interference

Table 1: Levels of Autonomy for Unmanned Surface Vessels (USVs).

3.4.2 Regulations and Standards

A significant constraint on developing autonomous systems is the presence of regulations and restrictions. These apply to all types of autonomous operations, whether on land, in the air, or at sea. The primary goal of autonomy is to reduce physical human interaction (and hence cost) while increasing operational safety. However, the journey towards a safe autonomous society is challenging. USV's present a substantial opportunity for marine operations due to their scalability. Operating small autonomous Vessels poses a minimal risk compared to using large ships without human interaction. This can also be observed on land, where autonomous lawnmowers are allowed in gardens, but autonomous Vessels are strictly regulated by Norwegian law [17].

3.4.3 Data Vision and Path Planning

A USV must be equipped with the appropriate sensors to operate autonomously. Global navigation satellite systems (GNSS) like GPS can be used for localization[18]. However, as this is only suitable in a perfect environment, collision avoidance is crucial for any autonomous system. To achieve this, the system must typically have components capable of analyzing the immediate environment. Sonars, radars, cameras, and LiDAR are typical systems that examine the environment. For objects in close proximity, cameras, and LiDAR are often preferred[18]. However, both cameras and LiDAR can be affected by certain environmental conditions, such as poor visibility. When designing a mechanical sub-system for the USV, it's crucial to ensure that any added equipment does not obstruct the sensors' field of view or interfere with their operation.

3.4.4 Navigation

For the specific case of the Otter USV, its navigation system is managed through software that sends control inputs to the onboard computer. These control inputs are commands that instruct the USV how to operate. The Otter uses GPS for localization, and AIS data (Automatic Identification System) can be retrieved during operations[19]. The Otter communicates with an operator or an on-land computer using WiFi or 4G. Maritime Robotics has primarily developed this software. An external path-planning system has been designed and implemented through a thesis organized by Clean Sea Solutions[19], which will be discussed later. Path planning(PP) and collision avoidance(CA) are typically based on pre-determined mapping and data vision algorithms that process data from a camera or a LIDAR sensor. Detailed information about the status and development of the navigational software can be found in [19]. The USV developed by CCS currently operates at an AL3, as shown in 1. There are a few different ways of navigating a USV, in relation to the case-specific USV(the Otter) the following approaches can be used:

- Manual Control - Just like a remote-controlled boat
- Course Mode - Providing a heading, which the USV will try to follow until told otherwise.
- Station Keeping - Provide a GPS location, which the USV will locate, transport, and keep stationary until told otherwise.
- Point-to-point (P2P) - Following a "leg" to navigate along a particular predefined path segment between two points.

3.5 Existing research projects of waste collection using USVs

In this case study, we concentrate on the application of USV technologies, specifically within waste management, primarily focusing on the water surface segment. Consequently, it is pertinent to narrow the scope to projects similar in design and objective, namely those centering around USVs. The literature survey reveals a surprisingly high number of such projects, most conducted and organized by academic research and development. Interestingly, these projects exhibit diverse design geometries, supporting the earlier assertion that waste management solutions can significantly vary depending on their application segment and area[20],[21],[22]. Three particularly relevant projects have been further looked into for closer examination and evaluation. Two central factors in assessing the projects are the technology readiness level (TRL) [6] and their current autonomy level (AL) [16] of the projects. As described by [9], many relevant projects were primarily conducted at an academic level and hence had lower TRL. The three projects are chosen due to their considerably higher TRL than other academic work. The subsequent analysis of these technologies aims to benefit the development process and, possibly, address potential weaknesses inherent in these systems.

(a) Waste-shark (b) Jellyfish (c) SMURF

Figure 7: Overview over similar USV projects

Table 2: Estimated specifications on similar USV-projects

Project	**Wasteshark**	**Jellyfish**	**SMURF** [22]
Autonomy Functions	P2P, CA	P2P	P2P, CA
AL (estimated)	Lvl. 3	Lvl. 2	Lvl. 4
TRL (estimated)	8	8	7
Speed	1kn (max 4kn)	1kn (max 2kn)	2kn (max 4 kn)
Capacity	160 liter	Net-based (adaptive)	approx: 200 liter
Collection-Width	114cm	70 cm	150cm
Mechanical system	Cage-net	Bag-net	Cage-net
Range	10 hours	6 hours	8 hours
Covered Area/Per Hour (m2)	1000	1000	N/A

Throughout the investigation of various USVs, one common trait stands out - the use of multi-hull catamaran design. This holds not only for the described projects but also for other similar initiatives that have been explored. Alongside this standard hull design, there's a recurring theme in navigation and guidance capabilities: all USVs examined have Point-to-Point (P2P) path planning capabilities. This feature allows the preprogramming of a specific route for the USV. Among these, the SMURF USV distinguishes itself by possessing the highest level of autonomy. While the other projects claim autonomous capabilities, they appear to be primarily automated to follow a predetermined path from point to point. Although this does demonstrate a degree of automation, it falls short of complete autonomy. One significant limitation across the board is that none of the systems have self-charging or self-disposal capabilities. As such, they are not capable of unsupervised operation over extended periods. The collective mechanical subsystems are evaluated primarily by observing and analyzing the available visual content.

Table 3: Evaluation of the mechanical collection subsystem

Wasteshark USV	
Collective-system	The wasteshark contains a metal cage/basket that filters water when moving. The USV must be lifted on land, which seems inconvenient. The system also has the function of locking the cage while operating.
Strengths	Good, minimalistic design and low complexity Waste locking mechanism (enable forward/reverse operation)
Weaknesses	Low capacity (width and storage of bin) Weak propulsion and power system capacity Must be retrieved from water to dispose waste A cage made of metal doesn't seem sensible
Jellyfish USV	
Collective-system	The Jellyfish have a bag attached on the backside, which can be disconnected while in water. The system is modular, with a wide specter of attachable systems.
Strengths	Highly modular design for multi-purpose operations Small, compact design, easy to launch and retrieve
Weaknesses	Low propulsion and power system capacity The small size seems to limit the potential The bag must be disposed by an operator The navigational system provides a low level of autonomy (AL 2)
SMURF USV	
Collective-system	The SMURF has a larger collection capacity, meaning longer operations between the manual disposals. In addition, the navigation and control system is more sophisticated than other projects.
Strengths	High storage capacity Leading on autonomous operation(AL 4)
Weaknesses	Not efficient for waste disposal Low width capacity Do not seem ready for commercial use

Two central observations can be summarized from this assessment. First, the autonomy level of these systems is generally quite low. All projects require an operator within proximity to oversee and, to varying degrees, intervene in the operation. Second, all systems have a relatively low collection capacity and efficiency. Imagine these systems working in an area with a high concentration of waste; they would likely have to return for disposal and charging very often, limiting the efficiency(and also costs) for such processes. In addition, are the design of the collective systems best suited for continuous movement in one direction and seems less competent when tasked with more complex operations. It is evident that there is considerable room for technological improvements in the field.

3.5.1 Operating conditions

The working conditions of an Unmanned Surface Vehicle (USV) are dependent upon its specific application. Climatic factors, particularly waves, and wind, play a significant role in the functionality of a USV. Depending on wind strength and direction, it can lead to a USV veering off course, complicating navigation and task execution. Thus, it is critical to consider the effects of wind and other environmental factors when designing/changing a USV system. All the USV systems examined during this research are powered by electric batteries, which inherently have a limited range. As such, these USVs must therefore operate near charging stations or an operator. It is also noted that all the similar USV projects evaluated are operated in calm water, for the initial development calm water will be a condition.

4 Product development approaches

This study dives into product development (PD) approaches applicable to the case study. The aim is to identify and analyze different frameworks, models, and methodologies employed in PD. The insights gained will be used to choose an appropriate method for the USV development process. The literature search includes research on keywords such as product development, design, prototyping, physical PD, design thinking, and mechanical design.

4.1 Intro to Product Development

Product Development (PD) involves designing, developing, and introducing new products into the market. Traditionally, PD approaches, particularly in early manufacturing industries, were sequential and lacked agility, flexibility, and efficiency[23]. This limitation is notably highlighted by Takeuchi's argument that, "Today's fast-paced, competitive arena of new product development has limited the viability of the traditional sequential approach to new product development" [24].

The modern era has witnessed the emergence of diverse methodologies and strategies, adapting to the unique conditions of individual PD processes, including factors such as budgets, timelines, stakeholders, project participants, and product types [25]. While no universal approach to PD exists, comparing and understanding different methodologies can guide choosing the most suitable approach for a specific case. Wynn's mapping of design and development models shows a systematical overview of PD models(Figure 8), where procedural PD processes are considered to be of the highest relevance.

Figure 8: Map of PD processes as described by [25]

This study seeks to provide insight into various PD approaches. While there are a wide set of models described, many of them fall under certain methodologies. In this study, the methodologies have initially been separated into three domains. After these are presented will a separate chapter discuss general design and development strategies for physical PD processes.

- Traditional Product Development
- Agile Product Development
- Lean and Set-based Product Development
- Design and development strategies

4.2 Traditional Product Development

Traditional product development (TPD) is a sequential and structured method for developing products in the manufacturing industry. Traditional PD follows a structured and linear approach, with commonly known models such as the waterfall or stage-gate model, pioneered by Dr. Robert Cooper in the late 1980s, and has since been widely adopted by businesses worldwide[26].

Stage-Gate Model

The stage-gate model, inspired by the traditional PD approach, consists of several stages a product must pass through, from conception to market launch[27]. Its popularity stems from its simplicity, predictability, and logical governance model. Progress within this model requires passing through a set of gates, with each gate leading to either progression to the next stage (Go) or process termination (Kill).

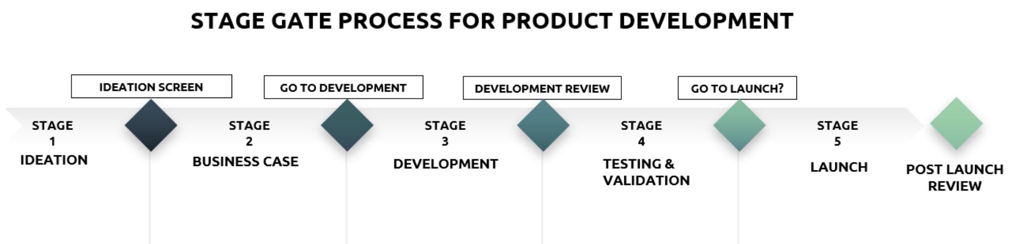


Figure 9: One variation of the stage-gate model, illustrating the sequential way of developing

Point-Based Development

Point-based (PB) development is an approach that emphasizes achieving specific objectives or requirements with often one point as a final goal. A "point" refers to a crucial or essential product feature, capability, or component. PB prioritizes decisions based on customer needs, market expectations, technological requirements, and other vital elements by these pre-defined points. However, this emphasis can limit creativity and flexibility, potentially leading to inefficiencies and rework. The term point-based thinking is often categorized together with TPD[28].

Strengths and Weaknesses of Traditional PD

The development process is made easy to understand and manage with a clear roadmap that outlines specific objectives, tasks, and outcomes for each stage. This level of clarity minimizes uncertainty, while the defined inputs and outputs for each stage enhance control and predictability. It enables managers to forecast project outcomes and manage risks proactively. However, the traditional PD approach also has several limitations. It lacks flexibility and may struggle to adapt when changes or unforeseen challenges arise during the project. This inflexibility may result in missed opportunities and increased costs due to rework. Testing typically occurs late in the process, which may lead to late-stage errors that are costly and time-consuming to fix.

Fit for Purpose

Traditional Product Development (PD) is known for its systematic approach, predictability, and comprehensive documentation, which is particularly suited to sectors with strict regulatory standards. Despite its sometimes rigid nature, modern adaptations have enhanced traditional PD with agility and flexibility, enriching its application, such as the modified stage-gate model described in Ettlie 2007[29]. Traditional project development is ideal for high-risk, complex projects with stable requirements that necessitate thorough documentation and strict regulatory compliance. However, for projects that are rapidly evolving and have uncertain requirements, Agile or Lean PD methodologies may be more suitable. These methodologies are more adaptable and can reduce the risk of errors in the final stages.

4.3 Agile Product Development

The need for a more agile and flexible approach occurred in a volatile and globalized world. Agile Product Development is (in contrast to traditional PD) a non-linear, iterative approach that prioritizes flexibility and customer feedback over strict planning and control[30]. Agile PD was primarily raised towards software development. The methodology has since spread to various other sectors due to its adaptability and efficiency. Agile product development emphasizes flexibility and collaboration, with teams working in sprints, which are short, time-boxed iterations[24]. A well-known principle within agile PD is "the Agile Manifesto", created to meet the fast-phased software developing sector[31]:

"Individuals and interactions over processes and tools
Working software over comprehensive documentation
Customer collaboration over contract negotiation
Responding to change over following a plan" [31]

Flexibility at all costs

One of the main benefits of Agile PD is its adaptability. Since development is iterative and incorporates regular feedback, changes, and improvements should be possible at any point in the process without significantly disrupting the project timeline. This makes Agile particularly suited for projects with changing requirements or in fast-paced industries, as stated in [30]:

"The later one can make changes, the more flexible the process is.
The less disruptive the changes are, the more flexible the process is" [30]

By adopting a more flexible and adaptable approach, teams can increase efficiency, decrease the chances of repeating work, and better adapt to changing requirements and market conditions. Using digital tools and technologies can help with communication and teamwork and improve the efficiency and effectiveness of product development[30].

Scrum Framework

A well-known implementation of Agile methodology is the Scrum framework. Scrum employs short, time-boxed iterations called sprints, usually lasting between 2-4 weeks[32]. Each "sprint" begins with a planning meeting where the team decides what to work on during the sprint, this ends with a review to assess the work done and plan for improvements in the next sprint.

Agile in Modern physical PD

In today's fast-paced world, the need for agility and flexibility has also been raised towards developing physical products, enabling teams to respond swiftly to changing requirements and market conditions. The application of agile principles in physical product development is challenging to model. As the principle is proven for software development, challenges occur due to the fundamental discipline differences between software and physical PD[33]. Instead, approaches have been translated into mechanisms that retain the principles[33]. With careful planning and a commitment to Agile principles, it can benefit significantly in speed, flexibility, and customer satisfaction. An example of such integration is [34], which combines the sequential stage-gate model with agile principles.

A relevant approach of Agile in physical product development is prototyping. This approach rapidly turns ideas into tangible objects, tests them, gathers feedback, and iterates on the design in short, agile cycles [35]. This helps minimize the risk of product failure and ensures that the final product closely aligns with customer needs and market demands[36]. To summarize, Agile methodology is becoming more prevalent in today's physical product development, resulting in faster iterations and a stronger focus on customers. This ultimately leads to more successful and innovative products. By combining Agile with rapid prototyping technologies, developers can quickly adapt to feedback and create products that accurately meet market demands.

Adapting Agile Principles to case-study

One of the main strengths of Agile is its emphasis on team collaboration and customer feedback, but the principles can be adapted for individual projects or projects with limited time-frames. With limited time, the iterative nature of Agile development can seem counter-intuitive, and when there is only one participant, these collaborative dynamics can be more challenging. It can be difficult to obtain diverse perspectives or feedback. In such cases, the single participant might have to actively seek feedback from stakeholders or potential users to maintain Agile's customer-centric focus. Also, Agile principles help manage time more effectively by prioritizing work that delivers the most value. The use of sprints or iterations can provide structure and keep the project on track. The challenge lies in accurately estimating the amount of work that can be completed in each sprint and ensuring that the highest priority tasks are completed first[30].

In a single-participant project with limited time, it can be beneficial to adapt Agile principles to suit specific circumstances. For instance, instead of having daily stand-up meetings, the participant can have a daily check-in with themselves, reviewing progress, setting goals, and identifying any obstacles. Retrospectives can be a time for self-reflection and planning for improvement. User stories and backlogs can be used to keep the project user-focused and to prioritize work.

4.4 Lean Product Development

Lean Product Development (LPD), mindset or philosophy, originated at the Toyota Motor Company in the 1950s[37]. Which at the time focused on Lean manufacturing (LM) since optimizing manufacturing processes where considered vital in a competitive market. A Lean process focuses on minimizing waste and maximizing value for the stakeholders. For the PD approach, Lean PD aims to increase efficiency and effectiveness in product development, ultimately leading to a better product delivered faster and at a lower cost[37].

Lean Principles in PD

Much like Agile PD, it is built on more of a mindset and principles rather than an explicit working method. This mindset has also been adapted to the PD methodology. However, LPD and LM are somewhat different processes that value conditions differently. Lean PD applies the principles of Lean manufacturing to the product development process. Five well-recognized principles to eliminate waste were described by Womack [38]:

- **Identify Value:** The goal is to maximize value while reducing waste by defining value from the perspective of the end-user or client in order to understand the importance of products and services to customers.
- **Map the Value Stream:** The second idea is to detect waste by identifying and evaluating all value-adding activities throughout the product life cycle, all the way from idea to the final product.
- **Create Flow:** Efficient value generation requires eliminating unnecessary steps. This means changing the office layout, team structure, and work methods. In product development, anything that doesn't add value for the customer is waste. Examples include excessive meetings, documentation, wait times, and rework. Client pull is providing what the client wants when they want it. Continuous flow minimizes batch sizes and lead times.
- **Establish Pull:** Enable the customer to obtain the maximum benefit from the producer. Actual customer needs and requirements should drive the product development process.
- **Pursue Perfection:** The fifth principle is all about constantly improving to achieve excellence. The goal is to add more value and reduce waste in the product development process.

It is worth mentioning that these principles were initially developed for the manufacturing industry, they have been modified and utilized in other sectors. This also may indicate that not all are directly translatable to a physical PD process.

Lean PD in Modern Context

Using modern technology, one may more efficiently apply Lean concepts to product development processes. Tools like simulation software, digital twins, predictive analytics, digital meetings, and cloud computing can assist projects in reducing waste, improving flow, and increasing value delivery in their product development processes. Regarding lean prototyping, it's sensible to focus on quickly testing and validating design concepts to avoid wasting time on rework. Prototypes can be used to gather user feedback and confirm assumptions, and prioritize the most critical elements for further development[37].

Front-loading

Front-loading is a strategy that emphasizes investing time and effort early in development. At the start of a project, it focuses on gathering and evaluating information (such as the literature study), establishing requirements, and making early-phase models/prototypes to eliminate unfeasible pathways. Front-loading may be used to increase the efficiency and effectiveness of the development process in the context of this thesis on physical product development[30].

4.4.1 Set-Based Concurrent Engineering

Set-Based Concurrent Engineering (SBCE) is a method entwined within the principles of Lean methodology, where the emphasis is on eliminating waste, improving process efficiency, and focusing on customer value while keeping flexibility. SBCE principles have emerged as a highly flexible approach. SBCE is characterized by the parallel exploration of multiple design concepts, the gradual narrowing of solutions based on suitability, and the eventual selection of an optimal solution. Unlike point-based methods, which involve a linear, singular progression towards a specific goal, SB thinking embraces diversity and iteration and hence enhances the flexibility of the PD process[39]. In SBCE, the concept of concurrent engineering also comes to the forefront. Instead of following a sequential point-based model, concurrent engineering advocates for parallel task execution. The approach aims to create synergies, optimize product design, reduce costs, and expedite the development timeline[40]. SBCE places significant emphasis on customer involvement. Therefore, the sum of set-based design, concurrent engineering, and customer involvement is a powerful approach to modern product development.

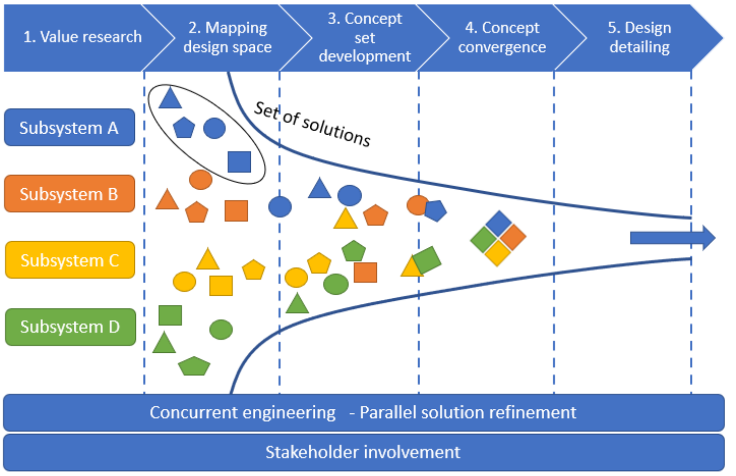


Figure 10: A visualisation the of SBCE-baseline model described in [39]

A model of the SBCE approach can be presented using the 5 phases described above[39].

1. Value Research
Understanding the project's needs wants, and the value it seeks to create. The goal is to clearly understand values/requirements to guide the product development process.

2. Mapping design space
One of the initial steps in the design process is to identify all possible solutions, which may be visually represented as a "design space." This may require brainstorming sessions to establish a framework for the process.

3. Concept set development
Create multiple design concepts within the defined design space. In each set, a cluster of design ideas is developed and explored concurrently. This approach allows for comprehensive design space exploration.

4. Concept convergence
Narrowing down the concept sets based on further analysis, testing, and evaluation. The goal is to progressively reduce the number of design concepts being considered by eliminating those that could be more promising or feasible.

5. Design detailing
Detailing the design specifications for the chosen concept. It includes technical detailing required to turn the design concept into a final product.

4.5 Strategies for physical PD processes

While TPD, APD, and LPD are well-known methodologies utilized in many professional fields, strategies, concepts, and approaches are considered relevant regardless of methodology. For physical product development, some specific strategies and thought processes are considered relevant to include.

4.5.1 TRIZ - Theory of Inventive Problem Solving

Putting PD methodologies aside for a minute, another take on the study is looking at the fundamental issue related to PD, which can be generalized to the *theory of Inventive Problem Solving.* Also now as TRIZ, invented by the Russian inventor and engineer Genrich Altshuller in 1946[41]. Which offers a structured set of tools and principles to overcome technical contradictions and find inventive solutions. While these tools and principles will not be thoroughly evaluated, are templates like the "creativity triggers" provided in Gadd 2011 [42] methods that should be included in any PD process.

4.5.2 Identifyieng values

A consistent topic for LPD and SBCE methodology, but also somewhat TPD and APD, is to identify values related to the project. A central question is: *Who determines value? Depending on point-of-view, will the value of a project will differ?* Each stakeholder group has different, and sometimes competing, values and interests. The challenge in product development lies in balancing these diverse perspectives to create a product that satisfies all stakeholders. Effective communication, stakeholder involvement, and a clear understanding of stakeholder values are crucial for product development. In terms of a physical PD case study, it is sensible to identify stakeholders to organize this:

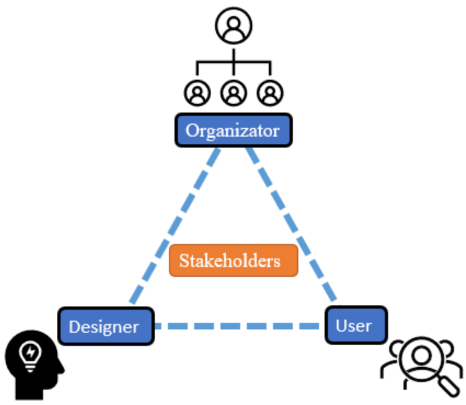


Figure 11: Example illustration of stakeholders in a PD process

The designer in a PD process is tasked with creating the product according to the requirements and constraints defined. A designer might value clear communication, understanding the users' needs and organizational goals, and having the creative freedom to explore and implement innovative solutions.

The organization, whether a corporation or a startup, is the stakeholder with the primary responsibility for the product's commercial success. Organizations value efficiency, profitability, and product results.

The user is the individual or group will use the product. Users value functionality, usability, reliability, and value for money.

4.5.3 Prototyping in PD

Another consistent topic, specifically in terms of physical PD, is prototyping. Prototyping is essential to product development because it allows one to visualize, test, and iterate on ideas before committing to a final design[43]. It can assist in identifying potential issues early on, gathering user feedback, and refining the product concept, resulting in a more successful outcome. Prototypes, as defined in Ulrich and Eppinger 2012[23]:

> *"We define a prototype as an approximation of the product along one or more dimensions of interest"*
> *"Prototyping is the process of developing such an approximation of the product"*

Types of prototyping

Different prototyping approaches serve different purposes and have their strengths and limitations. The most appropriate method will depend on the project's current state and which resources are available. The list includes approaches considered relevant, presented from low to high fidelity:

- **Sketching**
  The simplest and earliest form of prototyping is usually done by hand on paper to get a rough idea of the design and layout. Quick iterations at extremely low cost.
- **Storyboarding and Paper Prototyping**
  A sequence or single, more detailed drawings to visualize a user's interaction with the product. It is a step up from sketching and provides more context. Interfaces or products are drawn on paper to simulate the product in detail.
- **Digital Prototyping**
  This approach uses software tools to create virtual representations of a product, allowing designers to test and refine designs without needing physical materials. In later years, this has been proven as an industrial standard for most physical product development approaches, as it limits the need for costly and time-consuming physical prototyping[44]. Digital prototypes can range from simple 2D line frameworks to highly realistic augmented reality prototypes. Common for all is their dependency on software and hardware. Examples: Digital prototypes built in CAD software such as AutoCAD and SolidWorks.
- **Rapid prototyping**
  Rapid prototyping involves creating physical models quickly and iteratively to proceed efficiently in a PD process. This approach allows developers to iterate on designs faster and identify potential issues early in development. This can include low-fidelity mockups of cardboard or highly detailed 3D-printed product. Detail is not a measurement for this approach but rather the time it takes for each iteration cycle. Rapid prototyping, acknowledged in the early 1990s, just recently saw its potential with new additive manufacturing technologies[45]. In the late 2000's decade, low-cost additive manufacturing (3D printing) exploded in popularity. This is due to its powerful capability of creating quick, cheap, and complex models with relatively few design limitations[46]. Utilizing such manufacturing methods opens up a new world within rapid prototyping.

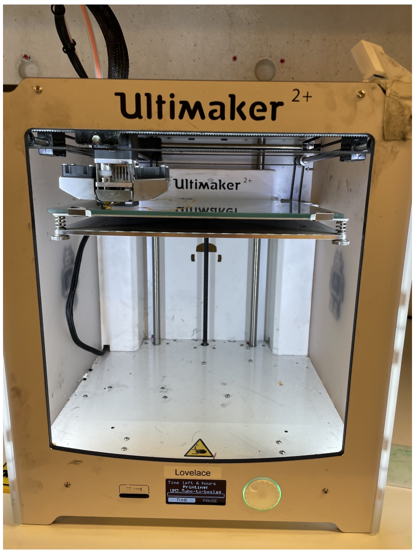


Figure 12: Ultimaker 2+ 3D-printer (from MakerWorkshop at NTNU)

- **Functional and experience prototyping**
  Functional prototypes are working models of a product that include all the essential features and components, simulating the actual user experience[47]. These prototypes are used for testing and refining the product's functionality, performance, and usability. While experience prototypes can be very low-fidelity, they can also include fully working concept versions. Often being the last stage before commitment.

- **Proof-of-Concept (POC) Prototypes**
  These prototypes focus on validating the feasibility of a specific technology, idea, or feature. A POC prototype is typically built to test a single aspect of the product, ensuring that it works as intended before moving forward with development[36].

4.6 A take on digital vs. physical PD approaches

Deciding whether to employ a predominantly physical or digital approach for a PD process will significantly impact the outcome. This section discusses the strengths and weaknesses of both approaches, with a particular focus on their application in academic and real-world contexts.

Digital Approach

The digital approach to product development can be considered a standardized way of working. It allows designers to rapidly iterate designs and test multiple concepts without needing physical materials or manufacturing facilities. This approach is cost-effective, time-efficient, and offers considerable flexibility. Simulation software and digital modeling can help predict product performance and detect design flaws early in development. However, the digital approach has its challenges. Digital models, being often precise, often fail to capture the full complexity of real-world conditions. Simulations may only account for some possible variables, potentially leading to unanticipated problems during physical production. A study at Cambridge found that too-complex digital prototypes tended to score worse than a physical one[48]. Furthermore, digital tools often require specialized skills and can be inaccessible due to high costs or steep learning curves.

Physical Approach

The physical approach involves creating prototypes and conducting real-world tests. This hands-on approach provides an immediate sense of the product's functionality, aesthetics, and user experience and reflects more of the traditional approach. Physical prototypes can be more readily understood by a range of stakeholders, including those without technical expertise. Real-world testing provides highly reliable data and can expose issues overlooked in digital simulations, such as unexpected material behavior or real-world user interactions. Some obvious drawbacks are its tendency to be more time-consuming and expensive, as it involves material costs and manual labor. It may also be less suited for exploring a wide range of design variations due to these resource constraints.

Bridging the Gap

Given each approach's strengths and weaknesses, balanced integration of digital and physical methodologies is often sensible. Digital tools can be used for initial design explorations, quick iterations, and theoretical testing. In contrast, physical prototyping and testing can be reserved for verifying design assumptions and evaluating the final product under realistic conditions. This dual approach leverages both methodologies' benefits while minimizing their shortcomings[49]. In an academic context, there's often a strong focus on digital methodologies, which provide valuable skills and knowledge. However, real-world engineering often requires a blend of both digital and physical processes.

PART III

METHODOLOGY

5 Method

The methodology employed to carry out a case study plays a crucial role in crafting a consistent and understandable thesis, thus facilitating an improved understanding of the report's purpose, approaches, and outcomes. The theoretical frameworks and insights from the literature review will be employed to address this problem effectively.

5.1 Introduction to case-specific characteristic

For any given project which involves distinct and unique factors and conditions, there is a need for a customized methodological research approach to achieve the best possible result. This chapter evaluates the case-specific characteristics of the given case study in terms of factors that have been raised in the literature study. The conditions framing in the case study are given in a list of factors characterizing the Case study:

- **Timeline**
  As shown in fig 14, the Product development phase for this project is limited to about 12 weeks. This is a constraining factor, as it will affect what type of PD approach is feasible within such a timeframe.
- **Participants**
  In most PD processes, it is sensible to include a team, covering different aspects of the process and creating a good discussion environment. Throughout the case study, both Clean Sea Solutions and a supervisor from NTNU have been included to discuss challenges and pathways. Valuable stakeholder input should be available, but one person still carries out the project. The author also specializes in mechanical engineering, which puts limitations on the project's scope.
- **Resources available (tools/techniques)**
  To ensure the completion of a good project, it was essential to have access to relevant resources. Resources such as workshops, manufacturing methods, USVs, software, budgets, and expertise are significant. It will also be important when deciding on the most feasible PD technique. Through NTNU and Clean Sea Solutions, admission to these resources was mostly covered. In addition, provided Clean Sea Solutions with a flexible budget within reason (no specific limit was set).
- **Case-study outcome**
  From both the author and Clean Sea Solutions, it was a strong desire to perform a functional prototype test, which could be used to make a conclusion and recommendation on design geometry. Since the system would likely be used within the summer of 2023, an actual working concept was valued. This could also mean that certain complex variations were eliminated.

- **Case complexity**
  Counting only one participant for the project, all segments of the development summed, results in a relatively complex process. This votes for a more organized method, such as the stage-gate model, which may be required to guarantee that all areas are appropriately handled.

- **Customer/market uncertainty**
  For the framework of this thesis, it is not anticipated that the market or other surroundings will change quickly. The framework of the product development is also rather detailed.

- **Stakeholder Involvement**
  Focusing only on the case study, Clean Sea Solutions can somewhat be considered the user/customer, as the outfall of the case study is a product delivered to CSS. Which also makes the author the supplier. The literature review clearly indicated the importance of good dialogue between supplier and customer. Meaning dialog with CSS is highly prioritized.

- **Nature of case-study**
  Many uncertain factors and conditions around the given case study, related assumptions, and preliminary work were addressed. This justifies a prototyping-driven product development approach to compensate for the lack of controllable variables.

5.2 Research approach

Overall, the research approach should involve a combination of qualitative methods, such as literature review and analysis, and quantitative methods, such as performance evaluation from prototype building. This hybrid approach allows for gathering both qualitative insights and quantitative data to support the research questions raised towards the development of a collective system for waste collection.

Qualitative approach

Qualitative data will be collected through a thorough literature review and case-study analysis and will aid in understanding the context of waste collection, existing solutions, shortcomings, and potential areas of improvement. This comprehensive review will also help outline design considerations and technical requirements for the proposed waste collection system. The case study should generate context-specific insights, providing a deep understanding of the problem space and how different variables interact. This includes feedback from stakeholders, observations of the problem environment, and lessons learned during the stages of development.

Quantitative approach

On the other hand, quantitative data will be obtained mainly through prototyping and testing. Prototypes will be constructed using CAD software, rapid prototyping, and additive manufacturing techniques. These prototypes will then be subjected to controlled testing to measure their performance against defined metrics. Performance metrics may include measures of effectiveness, efficiency, and reliability of the waste collection system. Quantitative data will provide objective and measurable evidence of the system's performance, which can be used for comparative analysis, system refinement, and validation of the proposed solution.

In summary, combining qualitative and quantitative data gathering should allow for a well-rounded understanding of the problem, the development process, and the performance of the proposed solution. The qualitative approach offers a broad, context-rich perspective, while the quantitative approach delivers precise, measurable evidence of system performance.

5.3 Designing a PD approach

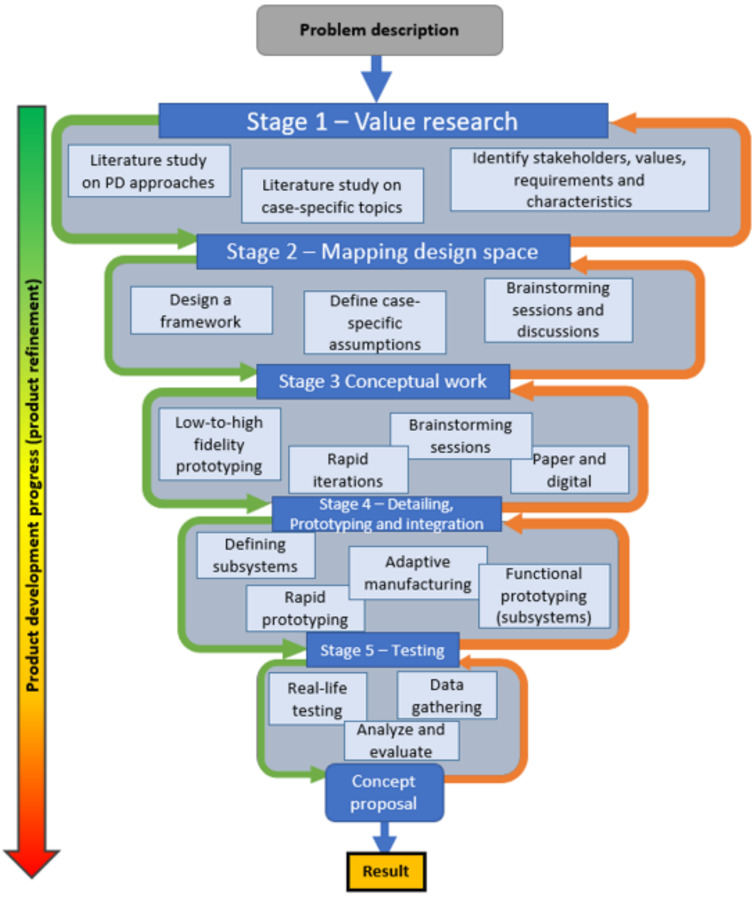


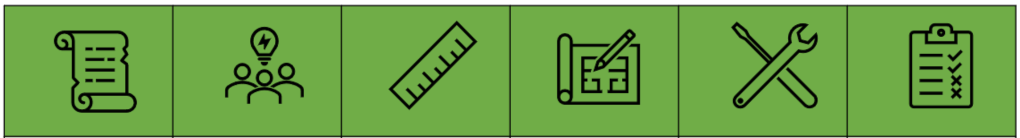
Figure 13: Early-stage development plan for case-study

With the case study's characteristics described, it's possible to evaluate a feasible product development approach for the study. From the mentioned conditions, a tentative PD process plan is designed. Given the relatively defined description and the opportunity to perform real-life testing for product validation, it was considered to use a stage-gate model. Where particular, the kill/go feature was a sensible approach for having a sequential development approach. While instead of doing a "kill", is an iterative approach added, meaning that the stage is repeated until considered sufficient. At the same time, this doesn't support much flexibility and agility in the process. This resulted in implementing the principles from SBCE, having many concept solutions developed in parallel, which would allow for better flexibility. In addition, is front-loading a strategy that already is present(through a literature study). Throughout this customized model, rapid prototyping will be essential to ensure good decision-making. Eventually, concentrating on a final high-fidelity prototype, which should be possible to test in real-life conditions. Additionally, should the mindset from TRIZ and Lean be applied to all stages of development. The research approach of the study can be said to be a combination of different approaches, with extra emphasis on structures from the stage-gate model and SBCE structures. It's concluded that factors such as timeline and participants are some obvious limitations and concerns affecting the proposed design. The approach is designed to meet to following objectives:

- *The combination of stage-gate and SBCE should be able to handle a short timeline and few participants better than a "traditional" approach*
- *By prioritizing physical prototyping and testing over theoretical simulations, should the development achieve more insight(empirical approach over theoretical)*

6 Framework of case study

A systematic and structured approach is presented by 5 defined stages. The provided stages have close similarity to the SBCE baseline model presented in [39], and the stage-gate model from [50]. This initially values a wide set of solutions, which through stages are limited and converged into a detailed design. A similar figure14, illustrates the steps, and the estimated schedule related to each stage. A zero stage is added, which illustrates preliminary work(could also be included in stage 1).



Preliminary work (stage 0)	Value Research (stage 1)	Map design space (stage 2)	Conceptual work (stage 3)	Detailing and prototyping (stage 4)	Testing (stage 5)
--	2 weeks	2 weeks	2 weeks	4 weeks	2 weeks

Figure 14: Overview and time schedule of the development process

6.1 Stage 1 - Value research

The quality of a case study can be greatly improved if there is performed a good evaluation of existing, available information of relevance. In addition to the already presented literature-study will also an assessment be presented based on preliminary work (mainly from CSS).

6.2 Stage 2 - Mapping design space

When a fundamental knowledge base on the topic is built, the next process prior to a PD approach, is to classify the values/requirements raised to the project. Exploring these values means analyzing the gathered information on the topic. From this available information certain conditions, objectives, and goals can be identified. The case study began with a brainstorming process which lead to the identification of requirements mainly related to function, performance, and user. The value of these identifications where a combination of soft/hard constraints. Some of the tasks included:

- Classifying case study type, what type of innovation are looked into?
- Identifying customer value
- Identifying stakeholder value (Clean Sea solution)
- Quantify performance requirements, which later can be used as objectives or checkpoints.

With a list of pre-defined requirements related to the case study, the next step is to map the design space. This is done primarily through a brainstorming session in collaboration with Clean Sea Solutions. This includes the following topics:

1. Identifying case-specific conditions.
2. Evaluate how the determined requirements are feasible, and create compromises when they conflict.
3. Establish constraints and design compromises.
4. Defining design objectives.

6.3 Stage 3 - Conceptual work

As the scope of the design space, and related regiments are established the first conceptual work can begin. Initially, the conceptual work is on low detail high variety level. This technically means that no concept should be left untouched. To avoid an endless process of conceptual iterations a rapid "design and eliminate" process is conducted. By using the predetermined requirements, quick eliminations can be made based on feasibility estimates. Brainstorming, sketching, and computer-aided design (CAD) are methods to visualize and evaluate different solutions. The most promising design concepts are selected for further refinement. The work followed a similar structure as following:

- Iterate different functional geometries, no concept is wrong.
- Evaluate more feasible iterations, by making more detailed drawings, but still with a focus on high volume iterations with low complexity.
- When conceptual drawings are becoming more detailed, conceptual designs can be systematized. This should only be performed in a way that allows for later adaptations and design changes.
- Concentrate the process down to a few feasible designs, that later can be brought into the prototyping phase.

Unlike the SBCE-model proposed in [39], where sub-systems are identified at an early stage, this approach valued the research of functional-model iteration. By not identifying any subsystem, but rather evaluating the total performance and functionality of the system. So when a geometric design with apparently satisfying performance and functionality was established, the case study could move over to the next stage.

6.4 Stage 4 - Detailing, prototyping, and integration

Parallel to conceptual work will also be a more physical approach occur. The development process was centered around rapid experimentation and iterative prototyping, which allows for quick evaluation and refinement of design ideas. An essential method for ensuring high-quality development in an efficient manner is to utilize modern (and traditional) tools for development, such as CAD, additive manufacturing, and simulations. The use of 3D printing and simple materials facilitated the efficient production of prototype iterations, facilitating testing and optimizing subsystems quickly. Physical prototypes should be included early and tested to evaluate their performance and suitability to match the requirements.

6.5 Stage 5 - Testing and evaluating prototypes

When a functional prototype is available, testing should be conducted as early as feasible. However, it is believed that the best results and data observations are made during testing that are as close to reality as feasible. It was therefore desirable to perform a test using the Otter drone to validate and gather relevant data. The after-work includes systematizing, analyzing, and evaluating the tests.

6.6 Applicability of approach

The case study can be considered a classical physical product development case. This also makes it possible to assume that an already defined PD approach would be applicable, but as with most PD processes, special adaptations will be needed. The approach is designed to fit best the conditions expected to meet, and the set values should always be in front during decision taking. However, a fair part of the methodological decision taking throughout the project is based on external factors such as deadlines, insight into the project, other participants (Cleans Sea Solutions, NTNU, Maritime Robotics, etc.), available equipment, budget, and objective expertise. There would be no limitations on such things during an ideal product development process. Developing a fully autonomous waste collection system is a multi-discipline project that has to cover many technology gaps. At this stage, it is unclear how far the case study will reach, but the quantity of the research approach will most definitely be affected by these limitations.

6.6.1 Validation of research

The validation of the "chaotic" process of PD can be challenging to determine, as the "outcome" of the process is hard to predetermine. In comparison to, for instance, a constructional study, where results often are highly measurable, a PD study is difficult to replicate. If the problem description and related requirements were given to another participant, the individual would likely develop a completely different design. If the individual were given the same framework and research approach for the case study, the case study might be more similar but still likely different. It isn't easy to validate such a case study since process decisions are highly impacted by subjective views. The following case study will eliminate many concepts based on subjective decision-making. These decisions should be justified as well as possible. For many eliminations are a feasibility matrix introduced, valued, and presented, but valuing these matrices will also be subjective to some extent.

The validation of research findings is a collaborative effort among all stakeholders. Each stakeholder, in this case, the university, the individual researcher (author), and the subject company (Clean Sea Solutions) has a unique perspective and, therefore, can assess the research outcome differently. The university typically emphasizes theoretical rigor and innovation, expecting research that extends the boundaries of existing knowledge and challenges established norms. The researcher seeks to ensure that the findings align with these expectations and also has a responsibility to stay vigilant about this. The collaborative company, on the other hand, is primarily interested in the practical implications of the research findings. By considering all these perspectives, one can ensure a comprehensive validation of the research, leading to a more robust and impactful study. Future discussions may explore how these different evaluations affect the overall perception and applicability of the research.

6.6.2 Outcome of research approach

As the case study is classified as a PD project, it should be mentioned the actual scope of this research. A classic PD process starts with an idea and ends with a final, commercialized product. However, this approach is different, as this case-study focus on the conceptual design of a subsystem that must be integrated into the main USV system(as shown in the project scope3. The case study focuses on a proof-of-concept approach, seeking to find the answer to what a feasible design could be. After this project's completion, extensive engineering work will still be needed to detail a concept to reach a commercialization level. Comparing this to the TRL scale[6], this means the case study might only raise the TRL up 1-2 levels.

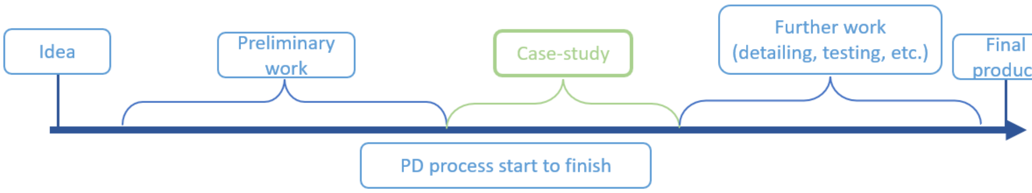


Figure 15: Case-study role in the PD process timeline

6.6.3 Summary of method

A PD approach has been designed, inspired by different PD methodologies, to deal with the relatively strict limitations affecting the case study. A combination of set-based concurrent engineering and traditional product development have been used to make a customized systematized PD process plan. The available resources allowed for a prototyping approach, which was driven by the expected learning outcomes from carrying out physical testing. Rapid prototyping, experience prototyping, and function model testing are methods that are expected to be of high relevance to the case study.

PART IV

CASE STUDY

7 Stage 1: Value research (status of the project)

Prior to this thesis, there has been an ongoing project of developing a waste collection drone since 2021. The long-term goal of this project was to develop a USV with the capability of navigating autonomously in coastal environments while collecting, handling, and disposing of targeted objects (waste, litter, biomass, etc.). This project has its origin in a start-up called Clean Sea Solutions. Which specializes in developing technical solutions for waste management in coastal environments. Through student-involved projects such as this thesis, Clean Sea Solutions have established a well-working collaboration that is based on mutual knowledge sharing and development. Maritime Robotics is an additional partner, which delivers some of the technical solutions to Clean Sea Solutions. Maritime Robotics is specialized in Unmanned Operations, mostly in waters. One of which is the Otter drone, which features the capability of adding a wide variety of actuators and sensors. Clean Sea Solutions have a goal of reducing waste in the coastal environment. Their technical solutions are mainly focused on collecting waste that has found its way into the water. This method is based on the same statements mentioned in the literature study([9]), that waste is concentrated along river outlets, marinas, and harbors, where there, in general, is a lot of human activity. Waste that is below the surface is highly complex to retrieve. These technical solutions will therefore serve as a last measure for avoiding waste from reaching lakes and oceans. Gathering waste can also have value from doing analyzes and research, to further expand the knowledge of the origin and effects of marine waste.

7.1 Clean Sea waste project

Clean Sea Solutions have a complementary parallel developing project. One is a jetty with an integrated water pump/filter system called the Aquapod. The Aquapod is designed to work as a boat dock as well as a waste collective system. The concept is based on pumping surface water into a basket containing a filter. Relying on the assumptions that marine waste is generally located on the water surface, this creates a current towards this pump. This concept has reached a high TRL level (7-9), and with already a few in production. Further on it can be assumed that this system is a working reliable system.

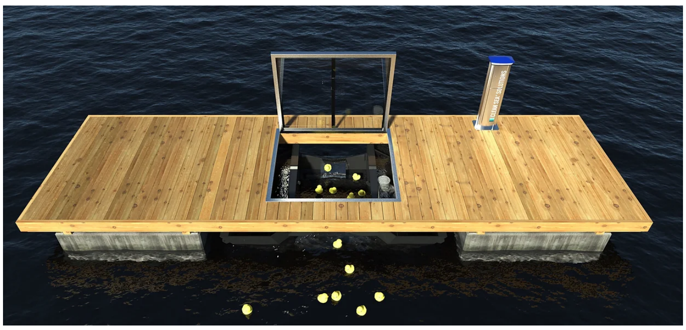


Figure 16: The Aquapod

One major weakness of this system is the short working range. The targeted objects located just a few meters away from the pump system will hardly be affected by the pump current, and likely not be collected. As a response to this, the need for a system to direct waste closer to the Aquapod occurred. Additionally, the idea of developing a USV that actively will target, collect and dispose of objects in close proximity to the Aquapod was already on the drawing board. This would work so that the Aquapod serves as a disposal station for the USV, with drastically better storage capacity.

Figure 17: The Otter drone used by Clean Sea Solutions

Maritime Robotics, already specialized in remote maritime operations had already developed a USV that provides great opportunities for such a system. Maritime Robotics provides a wide specter of different-sized USV systems. In an early phase, it was considered most feasible with the smallest USV system, the Otter. This USV was built on a modular system, which allows for easy mounting of additional sensors, actuators, and mechanisms. Clean Sea Solutions initiated a collaboration with Maritime Robotics, which involved using one of their USVs in a research and development project. Clean Sea Solutions, therefore, started in 2021 with a long-term goal of developing a fully autonomous waste collective USV system, given the name; Aquadrone. To achieve a working integrated system some essential technology gaps must be fulfilled.

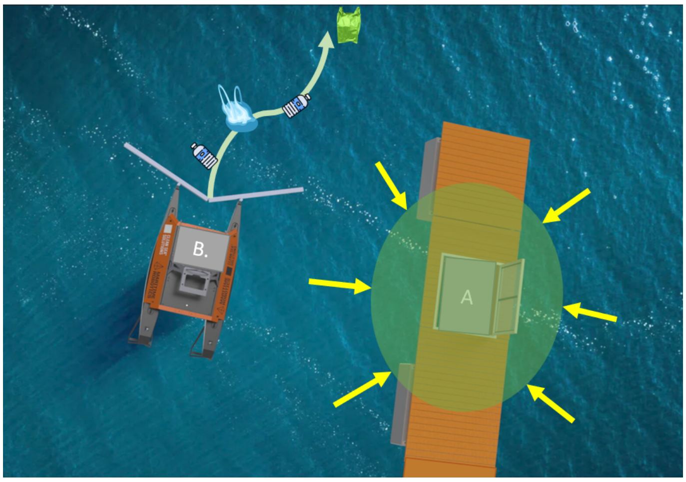


Figure 18: The Clean Sea solutions waste project visualized: The Aquapod as a disposal station (A.), and Aquadrone (the Otter) as an active collector (B.)

In addition to a USV system and an Aquapod (waste-disposal location), it would also be a need for a docking-station. Very much like a station for robotic lawn movers, which has a designated station for charging. Ideally, this would work similarly to robotic lawn movers, so that the USV can allocate, navigate and connect to a docking station without any human interaction.

7.1.1 Progress

The progress of the Clean Sea collective system has been separated into many different research and development projects. Often covering different technological topics. The Otter is already a working USV system, that can be assumed to have a sufficient TRL level. The remaining technology gaps can be generalized into two different technological fields, as shown in the project scope figure3. Mechanical system and the navigational system. The mechanical system serves as the physical system that together with the Otter will be able to perform the physical operation. The Navigational system covers all software and sensor development that are needed to ensure safe, reliable, and efficient autonomous navigation. There are still many technology gaps related to the Aquadrone. There have been, and currently are other projects working on navigation systems based on data vision. With the completion of these projects, the Aquadrone is closing in on working autonomously in terms of waste collection. A short update of previous and current projects in related to the *Clean Sea waste project*:

- **2021, Summer:** Development of the aquadrone v1, the project was developed to observe the potential of further pursuing this research and development of the aquadrone.
- **2022, June:** Design of an Optimal Path-Planning System for a Trash-Collecting USV [19].
- **2023, Present**: Set-Based Development of an Autonomous Waste Collection System for Unmanned Surface Vessels (current thesis).
- **2023, Present**: ("A Novel Path-Planner for a Waste-Collecting USV")
- **2023, Present**: ("Recognizing objects in water surface using data-vision")
- **Future**: Development of a docking station, which allows for autonomous charging.

7.2 Aquadrone v1

The first generation Aquadrone was developed in 2021 in collaboration with the municipality of Oslo. Where a standard Otter drone was installed with a rectangular perforated box. This project was an early-phase development process, with empathizing on proof-of-concept and gathering insight. As a first-generation, the USV was remotely controlled by an operator, as there was no autonomous software system developed. The integrated mechanism was also not developed for autonomous operation. The first generation had two inbuilt linear actuators, where the first was used for opening/locking the collective bin and the second was used as a push-out mechanism during disposal.

Figure 19: Aquadrone v1 with a early-phase collective system

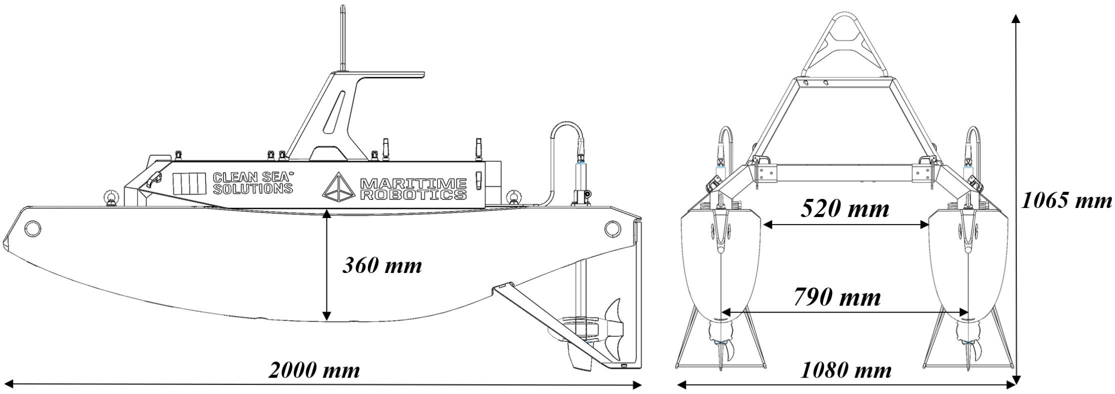


Figure 20: Dimensions of the Otter

The more recent project [19], focusing on optimal path planning of the USV system also developed a state diagram, which divide the USV into different states which would order to USV to perform different task. These states are highly relevant for further development. From[19] a state diagram was presented using if-statements.

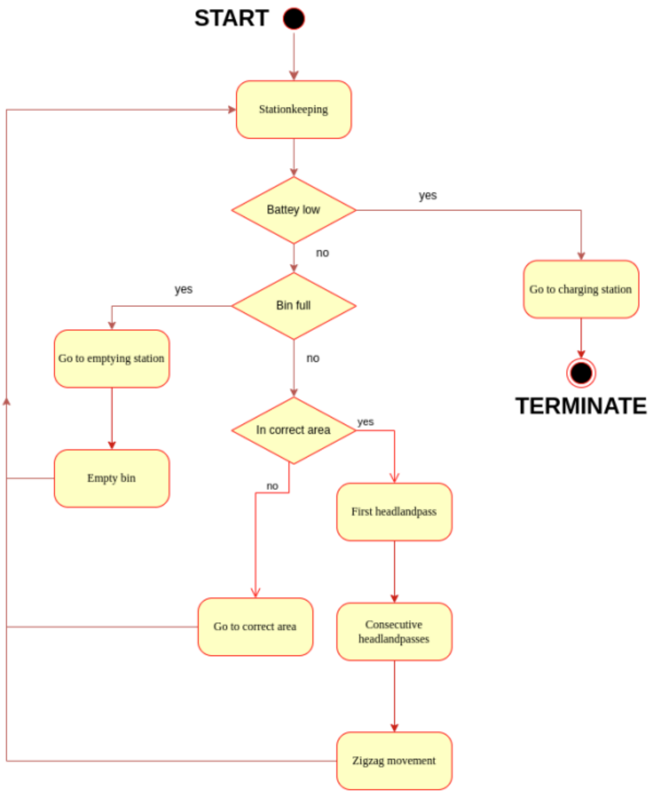


Figure 21: The previously developed state diagram for USV operation[19]

- If the battery is low, transport to the charging station (transport)
- If the Collective system is full, go to the disposal location (transport)
- If the USV is in the correct area, start to collect (object targeting)
- If USV is NOT in the correct area, go to the correct area. (transport)

7.2.1 Observations made the Aquadrone v1

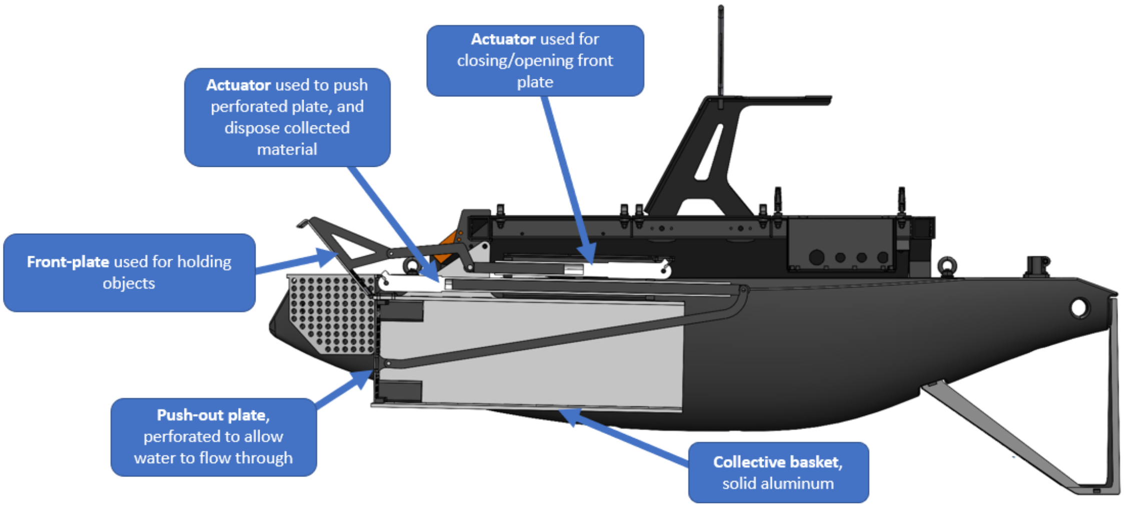


Figure 22: Section view of Aquadrone v1 and the collective system

Through discussion with Clean Sea Solutions, a brainstorming session was performed to evaluate just this. This was both to discover, discuss and evaluate the strengths and weaknesses of the previous design. From the first-generation aquadrone, some challenges were noted. These issues are mostly focused on the collective system in terms of its capabilities to perform its given tasks. As the hardware/software of the drone (pontoons, topside, battery, propulsion system, computers, sensors, etc.) are already provided. Relevant observations and conclusions are gathered in table 4.

Challenges	Description
Collective Capacity	The rectangular collective box had a limited volume, drastically reducing the USV's range before having to return to the disposal location. It was measured to be around 100 liters.
Collective width	With a width of about 500mm, the aquadrone had relatively low collective capability.
Water drag	The collective box was made of perforated aluminum, which caused high water drag, resulting in low energy-efficiency and difficulty to operate.
Materials	The materials used for the collective system were not ideal for long term dynamic movements in corrosive environments.
Mechanism	The mechanism seemed to be unnecessarily complex, with two linear actuators prone to getting stuck due to small tolerances.
Navigation	Projects are currently undergoing to increase the Aquadrone's autonomy level. Testing of Aquadrone v1 was however manually controlled.

Table 4: Issues observed from Aquadrone v1

7.3 Assumptions and indication from preliminary work

For a research project of this kind, there is a wide specter of unknown and unpredictable factors that will greatly affect development, testing, and final results. To narrow down the scope of the project it has been established a set of assumptions prior to the project, to justify some of the decisions and actions that's been made throughout the thesis. These assumptions are based on knowledge from the preliminary work with the Clean Sea waste project as well as the already presented literature study. The following conditions are evaluated and some relevant assumptions are made:

7.3.1 Targeted waste geometry and size

Waste collection at marinas and inshore areas can be difficult due to the unknown geometry of waste that may be present, such as plastics, wood, organic matter, and other unknown debris. It is critical to evaluate the targeted size, shape, and weight of the waste to ensure that the USV is properly suited to collect and store it. Furthermore, the targeted waste is also important as a sale/commercialization argument. It may also be suitable to include a modular system, that easily can be adjusted to different applications including different waste types as well.

7.3.2 Waste location

An early-phase assumption has been to target objects on the water surface, and not by any means further down the water column. The density of an object (ρ_{obj}) and the volume of an object (V_{obj}) will determine whether it floats or sinks. If the density of the waste is less than the density of water ($\rho_{obj} < \rho_w ater$), then the buoyant force (F_b) will be greater than the gravitational force (F_g), and the waste will float on the surface of the water. This will apply to all objects following this equation:

$$F_b = \rho_w V g > F_g \tag{1}$$

Objects with gravitational force (F_g) greater than the buoyant force (F_b), will sink, and hence also not be possible to target for surface collection. Waste that sinks will be much more complex to retrieve. An assumption can therefore be that objects in water can be in two states, floating or sinking. It can therefore be argued that it's only sensible to target the water surface, and not be any mean any deeper.

7.3.3 Environment

An initial assumption is that the system will be operating inshore, marinas, lakes, and slow-running rivers. Meaning rough waves can be avoided. This environment can be complicated and dynamic, with constantly shifting collision objects (boats), water currents, wind, and waves. The USV should be able to operate safely and effectively under these conditions, without creating any potentially dangerous situation for neither humans, animals, or equipment. The mechanical collective system must also be designed in such a way that it will not propose any unnecessary danger to the surroundings.

7.3.4 Navigation

It is important to guarantee that the USV can operate through a well-working navigational system. In terms of navigation, the USV must be equipped with state-of-the-art collision avoidance algorithms. The USV should be outfitted with sensors and guidance technology to maneuver around obstacles such as docks, boats, and other installations. The USV collective system should also be capable of autonomous navigation, meaning it should be operational without human interactions.

7.3.5 Waste management

The objects collected by the USV must be effectively managed to guarantee that it does not find its way back to the environment. At this stage of the project, it is assumed that any collected object can be disposed in close proximity to the Aquapod(disposal location) without any further liability of the objects. The USV must however be able to collect and safely store objects during transport. Sorting and recycling of waste by type and size will fall under the aquapod project responsibility, and can therefore be overlooked.

8 Stage 2: Mapping design space

As mentioned in the previous chapter, there were some issues related to the previous design. Utilizing this knowledge from preliminary work, is possible to conduct a good evaluation method. To systematize requirements for the design process, it was considered feasible to categorize and comment on these values. This will help to evaluate different design alternatives and identify the best solution. Firstly it was identified the key aspects and requirements that should be considered for the waste-collection system. These could be systematized into categories. The following requirements should form the basis for any decision that has been made throughout the product development phase.

8.1 Identifying requirement

Firstly it was identified the primary categories that value the developer, company, and customer. Each category is also divided into specific requirements. It should be noted that not all of these categories are feasible to quantify or measure. The importance/value for each requirement is also highly variable.

Category	**Specific Requirements**
Functionality	- Compatibility with USV - Object operations - Handling of irregular movements - Adaptability to different types of waste
Performance	- Waste size ability - Maneuverability - Water drag - Collection width - Collective capacity
User experience	- Ease of use - Reliability - Safety
Cost	- Manufacturing cost - Development cost - Maintenance cost
Time aspect	- Development time - Production time and Ease of assembly
Material and environmental impact	- Material properties - Material/manufacturing sustainability

Table 5: Early phase proposal of requirements for the collection system

8.1.1 Functionality

Description of the key features and functions the waste collection system should provide in order to work together with the Otter USV. Also discussed is the identification of any technical constraints or dependencies to other subsystems.

- **Compatibility with USV**
  As the collective system will work as a subsystem in collaboration with the Otter and the navigational system, it's important to design a compatible system. This applies to the navigational system in terms of not blocking any sensor's visuals and disturbing navigational plans. It also applies to the Otter drone mechanical design, in terms of the connection between the Otter and subsystem, weight distribution, propulsion, etc.

- **Object operations**
  The collective system should be able to perform a "self-emptying" process. Without this feature, the goal of autonomous operation will be unlikely to reach. Meaning that any collected objects should eventually be possible to dispose of at a pre-determined location (e.g. the Aquapod). This should be possible without any human interactions.

- **Handling of irregular movements**
  It's expected that the USV will perform navigational operations that deviate from its original straightforward path-planning. This could be due to collision avoidance procedures, special operations, or weather. This includes 90 and 180 degrees turns around its own center of rotation, standby positioning, and reversing. In these cases, it is essential that the USV have the possibility to obtain its collected content. Possibly leading to a function of locking or holding objects.

- **Adaptability to different types of waste**
  The sizes of waste are to be specified underneath performance requirements. The collective system should however be possible to target a different set of object geometries as mentioned. This can be in terms of biomass, algae, plastic, hazardous material, and even possibly chemicals. Having the potential of a modular design will make the collective system adaptive to different targets.

8.1.2 Performance

In terms of performance, it can be possible to quantify some of the performance requirements using metrics and values. Including identification of any performance constraints and what trade-offs might be suitable.

- **Waste size ability**
  The targeted waste, are in general not specified in any sizes and dimensions. It's desirable to maximize the geometrical specter of targeted waste. This will apply to the smallest bits such as micro-plastics under 5mm ([3]), and larger items such as cans, and bottles(above 10cm in diameter). An initial goal av handling ability is set to the range of **1mm to 30cm**. With an additional possibility of handling chemicals if feasible. This requirement must be re-evaluated after later-stage testing.

  $$1mm < target_{waste} < 300mm$$

- **Maneuverability**
  Adding an additional mechanical system, such as the waste-collection subsystem, to the USV will impact its maneuverability by affecting its stability, center of buoyancy, mass, and water drag. The center of buoyancy represents the center of the upward buoyancy force acting on the submerged part of the object. It is the point of the volume displaced by the object in the fluid. The addition of a semi-submerged mechanical system may change its buoyancy characteristics. To address this, the volume and density of materials as well as design should be carefully evaluated, to distribute the weight evenly to maintain the USV's original buoyancy characteristics. The Center of Mass represents the location of the weight distribution of the object. The increased mass may require more energy to propel the USV and longer distances to stop or change direction. Careful consideration of the weight and placement of the mechanical system can help minimize these impacts on the USV's maneuverability. Having a center of mass centered lower than the center of buoyancy will generally increase stability as it makes the object less exposed to tip-over or rolling. At this stage, it is not very feasible to quantify these requirements.

- **Water drag**

  The hull of the Otter is designed for minimal water drag, and any additional system entering beneath the waterline will create additional drag. This was one of the major issues addressed for the v1 Aquadrone. Valuing a design that provides minimal water drag while also allowing for longer and more effective operations. This will most likely be a conflict of interest between other requirements, where trade-offs must be made. Without diving too deep into the theory of fluid-dynamic, a very general formula for drag is presented[51]:

  $$F_d = 0.5 \cdot \rho \cdot v^2 \cdot C_d \cdot A \tag{2}$$

  F_d is the resulting drag force in the net, and therefore also the opposing force at the USV.
  ρ is the fluid density, which for water is around $1g/ml$
  v is the velocity of the net relative to the fluid, this will also be the USV's velocity.
  C_d is the drag coefficient, which is decided by the geometry of the net and the flow regime (which is stated using the Reynolds number). This coefficient is highly complex to compute correctly.
  A is the area facing the fluid (which simplified would be the total area of the USV system in the direction of flow)

  Some implications from this: The gain in speed would result in a square gain in water drag, while the area and drag coefficient are linear variables. One early assumption is that a larger slow-moving system is more efficient than a smaller fast-moving system.

- **Collection efficiency**
  The feasibility of expanding this size could potentially increase the efficiency drastically. To quantify this requirement, we focus on collective width as a line (one-dimensional). Since it is assumed that targeted waste is located in a horizontal line. A major issue with the v1 Aquadrone was the low collective efficiency. With only a collective span of around 500mm. Larger collective width should result in better efficiency and accuracy(higher chance of passing a certain location).

  $$System - width >> 500mm$$

- **Collective capacity**
  Since the targeted waste is assumed to be located in a plane, it's concluded that it is possible to measure capacity in 2D, as an area and not volume. This is a daring assumption and can lead to unintended and undesirable results, while at the same time simplifying several estimation processes. The last generation had an areal capacity of $0.4m^2$, which was not sufficient.

  $$Collective - capacity >> 0.5m^2$$

8.1.3 User experience

User experience is a crucial aspect of any product that is scheduled for commercialization, as it directly influences user satisfaction and adoption. Addressing these key aspects of user experience through easiness of use, reliability, and safety is important.

- **Ease of use**
  A well-designed system should be intuitive and easy to operate, even for users with little technical knowledge or experience. By simplifying controls, providing clear instructions, and using familiar design elements, it's possible to effectively implement the system.

- **Reliability**
  Users expect a system to perform consistently and dependably. A reliable system should have minimal downtime, few errors or malfunctions, and deliver consistent performance across various operating conditions. To enhance reliability, it's essential to use feasible materials and components, and thoroughly test the system under different conditions.

- **Safety**
The safety of users and the environment is a hard constraint when designing a system that will operate close to third parties. A safe system should minimize risks to users and protect the environment from potential hazards. This includes safety features, such as emergency stop buttons, warning systems, and protective barriers, as well as designing the system to comply with relevant safety standards and regulations.

8.1.4 Cost

Cost requirements play a significant role in the design and development of any product or system, as they can directly impact profitability, market competitiveness, and customer adoption.

- **Development cost**
Development costs encompass the expenses related to research, design, prototyping, and testing throughout the development process, and are very much dependent on the chosen research approach. These measures are already well-discussed.
- **Manufacturing cost**
To minimize manufacturing costs, it's essential to optimize system design, material selection, and production methods. Low-complexity design is a highly desired feature.
- **Maintenance cost**
Maintenance costs refer to the ongoing expenses associated with the repair and servicing of a system. A well-designed system should be easy and cost-effective to maintain. Low complexity also supports this requirement.

8.1.5 Time aspect

The timeline has already been mentioned as a crucial requirement. From this is development and production time considered.

- **Development time**
Development time encompasses the time needed to research, design, prototype, test, and refine a system throughout its development process. Initially been set to 12 weeks.
- **Production time and Ease of assembly**
This refers to the duration required to manufacture a system or its components, from the start of the production process until completion. Once again, favors low complexity.

8.1.6 Material and environmental impact

This can be evaluated for factors such as material properties and sustainability. Is unsure how central these requirements will be for the current PD process.

- **Material properties**
The properties of the materials used in a system will influence its performance, durability, and overall quality. When selecting materials, it's crucial to consider factors such as strength, weight, corrosion resistance, and compatibility with other components.
- **Sustainability**
Environmental sustainability is an increasingly important consideration in product design and development. Designing for sustainability involves considering the environmental impact of materials, manufacturing processes, and the system's life cycle cost (LCC), from production and use to disposal or recycling.

8.2 Brainstorming session

Before the conceptual development, a brainstorming session was performed based on the described requirements and values.

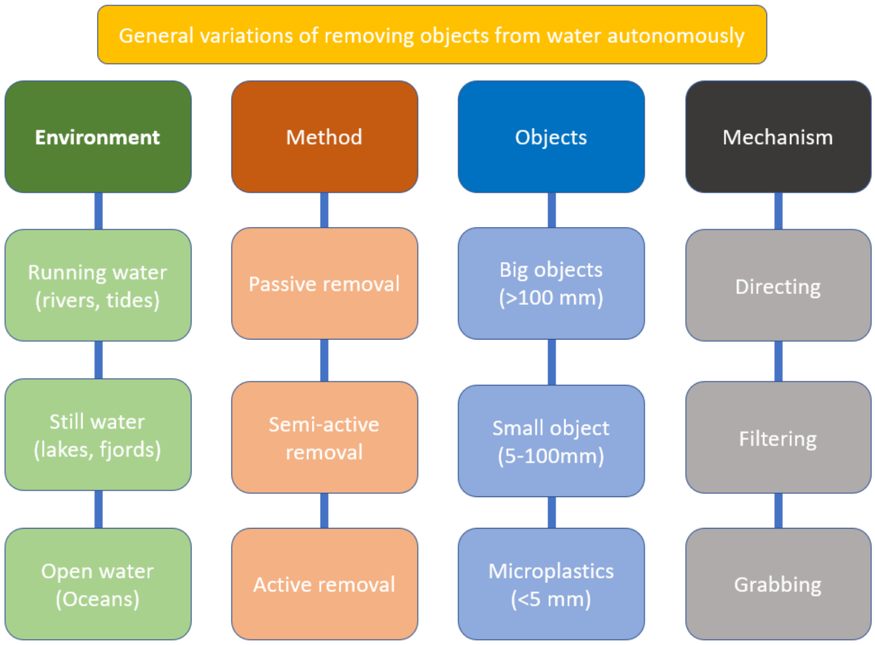


Figure 23: Some thoughts from brainstorming systematized into a matrix

From the brainstorming session, some central questions were raised and discussed:

- **What are the targeted objects? Where are they located?**
  The USV is a surface vessel, and our focus area is entirely on the surface segment. The data-vision approach is also only applicable to objects above the surface. Therefore not reasonable to target objects in the water column (between the bottom and the surface). It's discussed that any object not on the surface is either negatively or neutrally buoyant. Therefore focusing the design on targeting the water surface (2D-plane) solely seems sensible.

- **Will the objects act differently when collected?**
  So when the targeted object is in a positive buoyant state, will not the object also stay buoyant after being targeted and collected? It can probably be discussed that some objects will sink after being handled, but this probably only applies to a few exceptions. From this, we again resonate with the fact that the targeted area is entirely on the surface(2D plane).

- **What functions do a collective USV need?**
  So when a USV targets unknown objects in the 2D plane, what functions should the USV serve? An objective has been to develop a system that can perform all the mentioned tasks without human interaction. To accomplish these tasks, the navigation and control center will enter different "states," thereby also giving "commands" to the collective system. Integrating software and mechanicals to work together is essential. An actuator controlled by the control system will likely be needed to control these operations.

- **Can its function be divided into modes/states?**
From the preliminary work, a state diagram was developed. A new proposal is made based on the given value research and design mapping. It's been concluded that there are generally three main states.

  1. **Collective state**. The USV actively searches for objects (using data-vision) or follows a path plan to collect objects.
  2. **Transport state**. This state will apply when the USV does not target objects and wants to hold on to its objectives while moving. This can be for applications such as transport to disposal location, advanced maneuvers, transport to charging station, and transportation areas where collective-state are disabled.
  3. **Disposal state**. The mechanical system performs a maneuver that enables the USV to dispose of the collective waste.

  The fact that these states can be separated indicates what designs would be feasible or not.

- **How can the performance of the USV be measured** The USV should strive after a collective object as effectively as possible. Inspired by measurements used in existing technologies, its efficiency can be measured in terms of the covered area, which can be described through a simple formula:

$$Coveredarea = width * (time * speed)$$

8.2.1 Important findings

From this first brainstorming session, some highly relevant assumptions were made. These will be essential for decision taking in the initial conceptual development. Here is a summary of the most central assumptions:

- The targeted objects are only located in the 2D plane (water surface).
- It should not be necessary to target waste below the surface, and objects will keep their location on the surface after being collected.
- The USV will operate in 3 different states. Collective, transport, and disposal mode. The three states will demand different mechanical operations.

Figure 24: Visualization of a typical working environment, floating objects in focus

9 Stage 3 Conceptual work

Designers should explore and experiment with a wide range of concepts, designs, and geometries during the conceptualization process, by thinking "wide" can the designer anticipate slower early-phase progress but also decrease the possibility of mistakes later on. This corresponds to SBCE method and the designed PD approach. Furthermore, because designers are allowed to explore unique ideas and push the edges of what is feasible, this approach encourages creativity, collaboration, and innovation. The conceptual work is a creative and dynamic development process, which can be difficult to present chronologically. This work is partly systematized in the thesis so it's easier to follow. In reality, tools and techniques such as brainstorming sessions, sketches, paper prototypes, CAD modeling, and simulation, are all happening in parallel to various degrees. Throughout the conceptual work is the 3D model of the Otter used as a reference for development, further technical views of the Otter can be found in the appendix: 87.

9.1 Conceptual design techniques and tools

The process tries to follow the long set of values and ever-changing requirements already mentioned. From a very low focus on detail, but a high focus on function, where through each iteration, the focus on detail has slightly increased. A very general description shows the conceptual development with progressively fewer iterations and higher detail.

1. The first iteration was developed during the first brainstorming session. With a very high focus on overall function. This was done to expand our horizon of technical possibilities. This process is only based on the initial requirements. Ideas and concepts are mostly described through **simple sketches**.

2. The least feasible function models can be scrapped, while the rest is further detailed. The most feasible function models are detailed on paper, or digital illustration software(paint, one-note, etc.).

3. Feasible drawing will eventually reach its maturity on paper and is progressively drawn in **computer-aided design (CAD)** software. This is to further enhance our understanding of the concepts provided. Parallel to this the first iteration of prototypes is being developed. This is using simple materials to also further expand our understanding of the different concepts. SolidWorks is a CAD software that has been used to a large extent both for constructing and simulating prototypes.

4. Using detailed drawings and low-fidelity CAD models is another additional elimination performed, making room for the next version(v3). At this time **CAD-software and prototyping** approaches have equal priority. At this stage, the concept is eliminated down to a few concepts.

5. At the next stage, the process is moving over to the detailing stage. Identifying subsystems and starting to detail these is in focus. This includes acquiring materials and relevant parts that can be used for prototyping. At this stage, **3D-printing** is becoming a central tool for rapid prototyping. The Ultimaker 2+[52] is a 3D printer that was frequently used for prototyping.

6. When subsystems seem satisfying and both computations, measurements, and prototypes match the requirements, a working function model should be ready. This eventually leads to a process of **physical testing.** Both to further gather insight as well as a proof-of-concepts test.

9.2 Conceptual design

In an initial conceptual design phase, it is necessary to start with an open and creative mindset. This can be difficult, as it is important to also include concepts that may seem illogical, complex, and challenging. Some early-phase function model was drawn:

(a) Lifting

(b) Catching

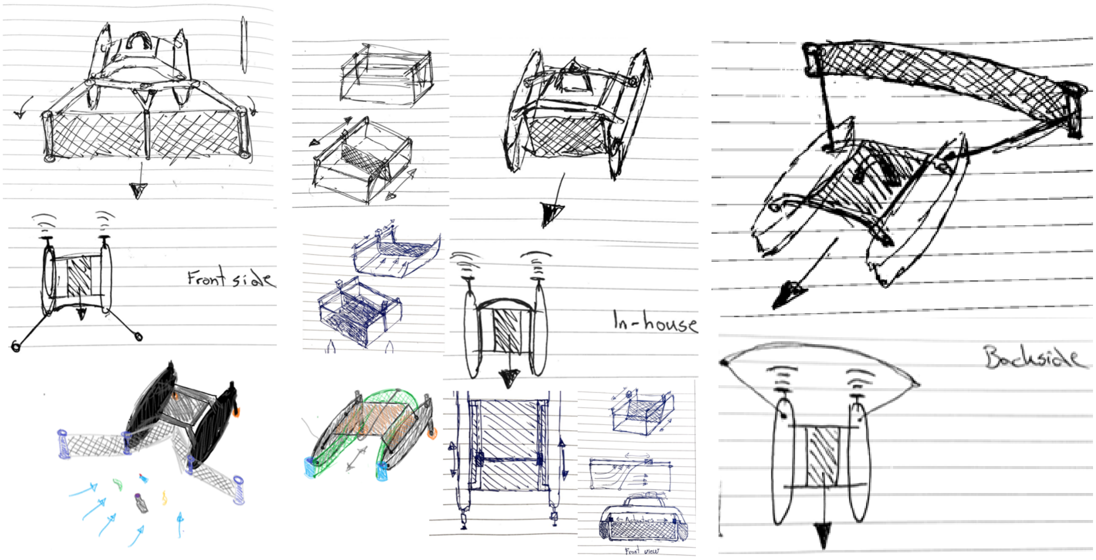
(c) Gripping

(d) Filtering

Figure 25: Overview of the first conceptual designs with described "collective-method"

As presented in 25 it was initially illustrated 4 main methods for collecting objects. From the brainstorming sessions, remember that the primary focus is on the 2D plane. Illustration (a) lifting and (c) gripping are methods that early was considered too complex for such task. Lifting/skimming water surface is sensible, but creates an issue when emptying the storage unit. It also limits the capacity. Gripping is only really sensible if the targeted objective is well-known. This is not the case and would face many technical issues. Illustration (b) catching and (d) filtering, both provide the feasibility to fulfill the project's need, especially in terms of the given states the USV will operate in. These function models are brought further into the conceptual process. Looking back at the literature study it can be seen that these methods resemble both the SMURF USV and the Jellyfish USV system.

For the next iteration of development, it was evaluated where to locate the collector system in relation to the USV. Three main alternatives were presented:



(a) Front-side (b) In-house (c) Back-side

Figure 26: Overview of system location

1. **Frontside**: This would resemble more of a snowplow or a thresher, with attachable equipment in front.
2. **In-house**: This concept is similar to aquadrone v1. Where the spacing between the pontoons is utilized as a collective and storing area.
3. **Back-side**: This concept is inspired by trawling methods used by fisheries. This can allow for a great collective area.

Primarily based on the performance requirements that are presented, the three geometric variations are evaluated. This evaluation is based on the performance feasibility of the concept, no tests have been carried out.

Location	**Front-side**	**In-house**	**Back-side**
Width			
Capacity			
Maneuverability			
Complexity			

Table 6: Assessment of collective location

It comes out relatively clear that a location on the back-side (c) would lead to many technical issues. As it would be unpractical in terms of reverse/rotation operations. The propulsion system would also be in conflict with this system. On the other side, both front-side and in-house have obvious strengths. Each of them values different performance requirements. A combination of the two systems is also considered feasible. It's concluded that (a) front-side and (b) in-house should be further researched.

9.2.1 New iteration conceptual work

From the previous elimination methods, it has been found that a front-side or in-house system is feasible. An earlier finding was also the process of filtering/catching in the 2D plane. This led to the next idea of a conceptual framework with a net/filter. The next iteration is therefore based on geometrical variations of such a system. To be able to iterate sensible variations it was looked back at the performance requirements. Efficiency, capacity, and maneuverability were factors that were considered highly relevant.

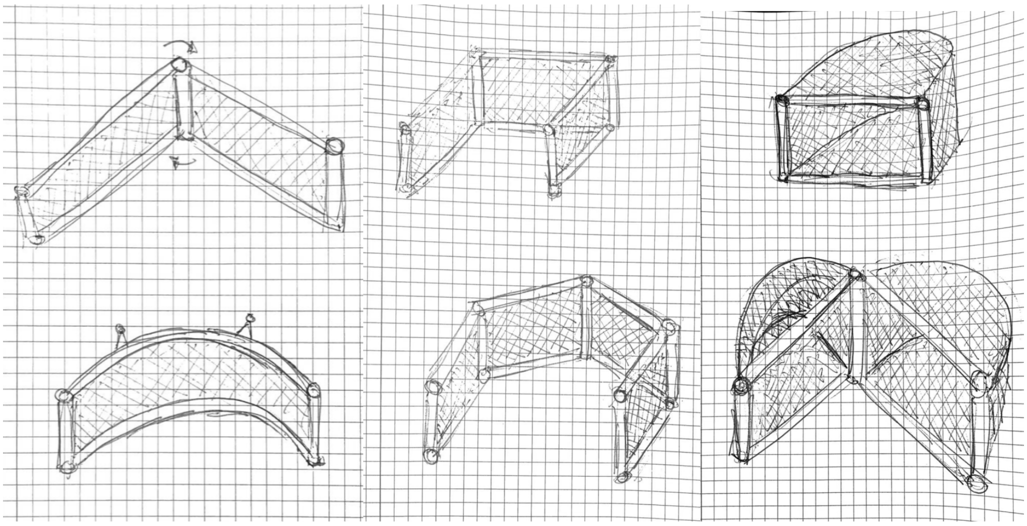


Figure 27: Iterations on geometrical design functions

Parallel to iterating conceptual drawings were also a small-scale (15cm in length) USV 3D printed. A set of filters/nets was also made. While this model serves no purpose as a functional prototype, it was a measure done to expand the insight within design geometric possibilities. In such a phase of the conceptual development, this was beneficial as it also made it more effective to discuss with other stakeholders (CCS and supervisor).

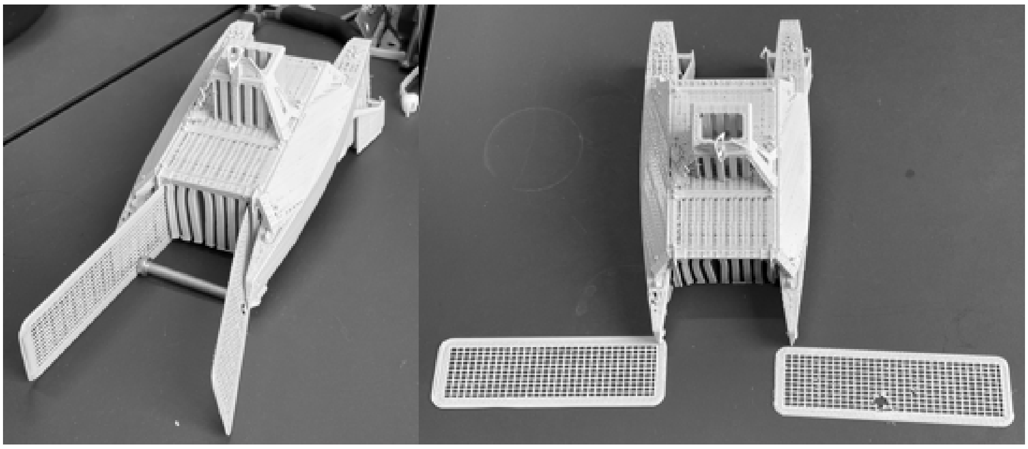


Figure 28: A 3D-printed model of the otter and conceptual collective elements

9.2.2 Parallel conceptual work in both 2D and 3D

Referring back to 8.2.1, the targeted objects are assumed to be on the surface (2D plane), and also stay there after handling. A new proposal in terms of geometrical conceptual designing was made, based on these assumptions. The collective system could be simplified into a 2D model, rather than a 3D model. If it's assumed that the system is designed perpendicular to the horizontal plane, it was considered possible to also perform conceptual iteration in the 2D plane. Another variable that can temporarily be overlooked would be the height of the system, as it would not affect the design from a 2D perspective.

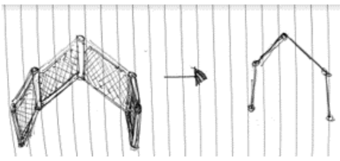
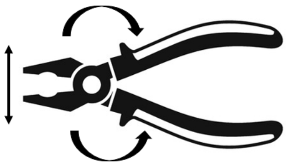
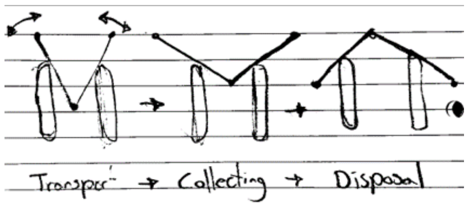


Figure 29: Simplifying the development



(a) Inspired by the motion of a plier, initial system dynamics was conceptualized



(b) Design geometry for different operational states

Figure 30: 2D conceptual drawings

Again looking back at the important findings found in 8.2.1, the system was designated three different working states. This being collective, transport, and disposal state. From the initial conceptual work, it was concluded that the system would benefit from being a dynamically defined system. Looking back at the aquadrone v1 system, the system was dependent on a push-back mechanism connected to an actuator. This push-back consisted of a metal plate that cause many technical challenges. A proposal of including this motion that would complete all the tasks in the same movement was proposed. Potential for this was observed through the connection of links and hinges, somewhat similar to how a plier is designed. A system like this could be able to satisfy the system described earlier. This conceptual work was further approached both using conceptual drawings and CAD software.

Figure 31: Early phase CAD modeling(while not visualized, the idea is to place some sort of net within the frame of the model)

Video-link to motion-visualization of early 3D design concept

9.3 Concept variations

Looking further into the concept of a 2D-dynamical linked system, it was considered necessary further detail the design to better interact with the raised requirements. Looking at the **??** figure, the straight links do not fully support initial requirements. This simplified system would not favor high capacity (system not utilizing the volume between pontoons) or being able to hold onto objects very well. A response to this was to add complexity using additional links in the frame, from this it was possible to iterate conceptual models with slight variations. From this session, 4 different models were iterated.

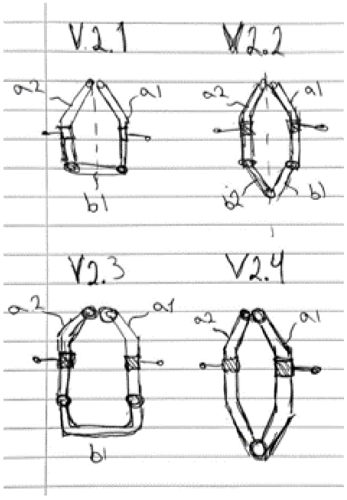


Figure 32: early phase conceptual variations

The iterations are based on the same mindset of having a dynamic system connected to hinges and sliders that would allow for an opening and locking mechanism. Initially, these variations were made to find geometric differences and to evaluate which of them would satisfy the requirements. The iterations are all made symmetrical, with links, sliders, and joints with the same purpose.

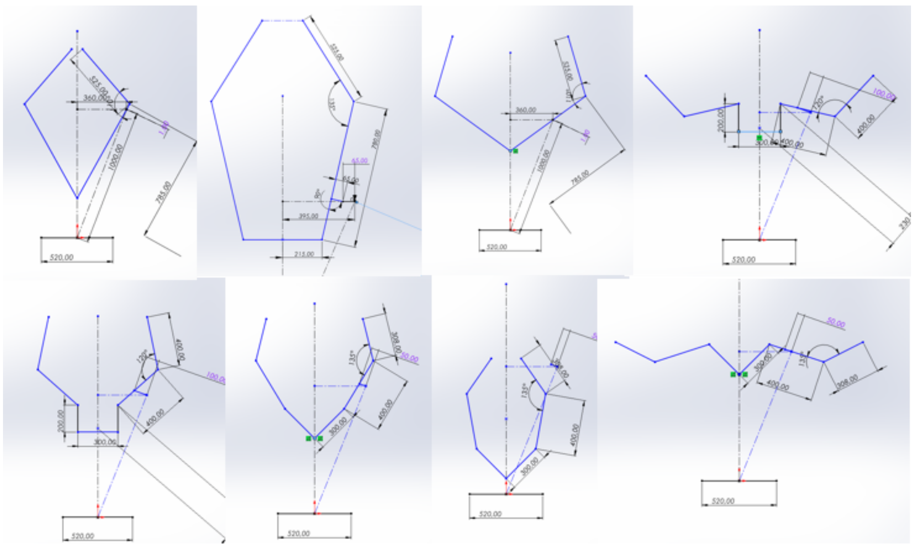


Figure 33: The four different concepts were experimentally tested with many different scale ratios

2.1 Consisting of three links, where two links on each side are given an angle to allow for capacity within the system. This system favors low complexity, wide width, and high capacity.

2.2 This iteration separates the mid-link from the previous iteration. This reduces capacity and increases complexity. At the same time, it allows for a much better disposal (push-out) mechanism.

2.3 A similar design as the 2.1 iteration, but with the mid-link transformed into a half-cut square. This allows for much higher capacity, but concerns for the disposal mechanism are raised.

2.4 This iteration is a simplified version of 2.2. With only two links, but with angles to allow for some storage. This design would benefit both disposal and complexity.

This approach ended up being a driving way of developing a feasible geometry. Many iterations and dimensions were provided and tested. When iterating and evaluating different designs, it was important to remember that this collective system is only a sub-system, that should be complementary to the USV system. From this, the pontoons can be separated from the USV system and used as a geometrical framework. This enables the possibility to design and draw geometries that would fit within the pontoons of the system. This was visualized digitally in SolidWorks, by doing some simplifications of the USV model. For all iterations provided the same USV pontoons were used as reference. This created a good framework for comparing the different types.

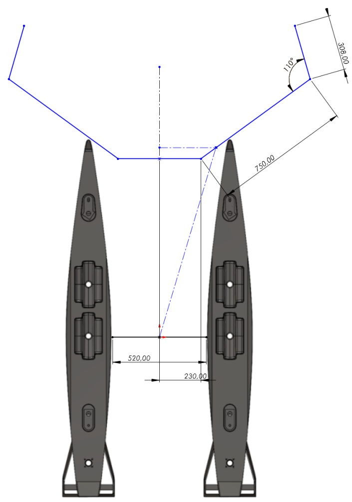


Figure 34: 2D CAD modeling, using USV as reference(dimensions not of relevance)

Video-link to motion-visualization of 2D-conceptual variations

Iteration:	V2.1	V2.2	V2.3	V2.4
Width				
Capacity				
Complexity				

Table 7: Evaluation of conceptual iterations based on performance requirements

After many iterations, and carefully analyzing the different designs, the 2.1 design was favored. This meant pursuing this geometric design, while also making it feasible to change design direction in-later stage development. An early estimation of the 2.1 design is illustrated in 34. This current concept only provides a superficial understanding of the dynamic system, to further understand the feasibility of this concept some dimensions must be detailed (dimensions provided in the illustration above were only temporary).

9.4 Dimensioning system

When the functional model and an understanding of the geometrical features are in place, the conceptual design can be dimensioned. The dimensional work is once again based on the requirements that have been set. A reason for dimensioning the collective system in an early stage is to be able to measure the system's performance as well as to confirm if the design is within the determined requirements. As mentioned under early requirements determination, the performance of the system will to a certain degree depend on the width capacity of the system, as well as the collective capacity. The width capacity can be measured in terms of length, the collective capacity can be measured as an areal or volume. To identify these values it was sensible to identify different variables related to the design. These computations are based on the system being symmetrical and two-dimensional.

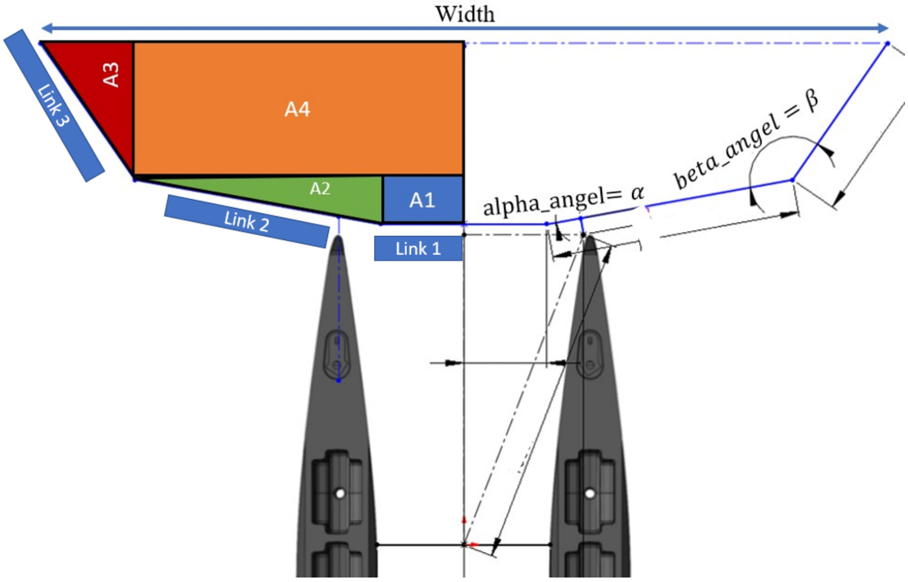


Figure 35: Visaulizing of the Area and Width of the collective system

To better get an understanding of the collective system's potential in terms of performance, it was made computational script. This script would make it possible to insert the length of each link as well as the relevant angles. From this, the script would be able to calculate both the width and area capacity at any given dimensional size in any position available for the system. Prior to this computation the set of variables must be specified:

1. **Link 1** = Length of link 1 (static parameter)
2. **Link 2** = Length of link 2 (static parameter)
3. **Link 3** = Length of link 3 (static parameter)
4. **alpha** = angle between link 1 and 2 (changing parameter)
5. **beta** = angle between link 2 and 3 (static parameter)

Width computation:

$$W_1 = l_1$$

$$W_2 = \sin(\text{radians}(\alpha - 90)) \cdot l_2$$

$$W_3 = -\cos(\text{radians}(\beta + \alpha - 180)) \cdot l_3.$$

$$W_{\text{total}} = \begin{cases} \text{if } W_{\text{total}} \geq 0: & 2\left(W_1 + W_2 + W_3\right), \\ \text{otherwise}: & 0, \end{cases}$$

Area computation:

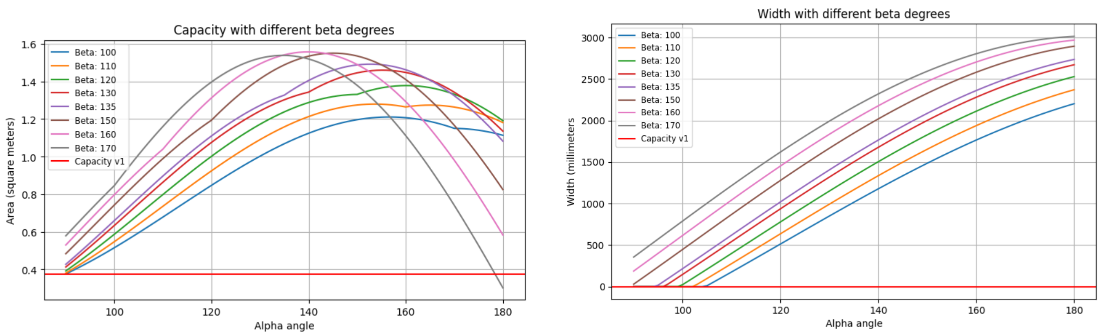
$$\alpha_1 = \alpha - 90$$
$$\beta_1 = 90 - \alpha_1$$
$$\alpha_{1r} = \text{radians}(\alpha_1)$$
$$\beta_{2r} = \text{radians}(\beta - \beta_1)$$
$$A_1 = l_1 \cdot (\cos(\alpha_{1r}) \cdot l_2)$$

$$A_2 = \frac{(\cos(\alpha_{1r}) \cdot l_2) \cdot (\sin(\alpha_{1r}) \cdot l_2)}{2}$$
$$A_3 = \left| \frac{(\cos(\beta_{2r}) \cdot l_3) \cdot (\sin(\beta_{2r}) \cdot l_3)}{2} \right|$$
$$A_4 = (l_1 + (\sin(\alpha_{1r}) \cdot l_2) - (\cos(\beta_{2r}) \cdot l_3)) \cdot (\sin(\beta_{2r}) \cdot l_3)$$
$$A = \frac{2}{10^6} (A_1 + A_2 + A_3 + A_4)$$

There are in total 5 variables, and counting in height of the collective arms and all parameters related to hinges/ sliders and connections, there are many more. In other words, it would be very complex to compute any optimized model using an optimization algorithm. There was rather performed a try-observe-learn approach. Which seemed to be sufficient at such a stage of product development. The initial dimension that provided the best performance while also providing good functionality was the following variables:

$$l_1 = 265, l_2 = 750, l_3 = 500, \alpha = 90 - 180°, \beta = 135°$$

$$\beta_{\text{row}} = \{100, 110, 120, 130, 135, 150, 160, 170\}, \alpha_{\text{row}} = \text{linspace}(90, 180, 91)$$



(a) Graph showing capacity in m2 using different beta-angles

(b) Graph showing different width ranges using different betas

Figure 36: Computation of capacity using Python

To plot the script it was necessary to determine some of the variables. The length of the links was set, while iterations on angles between the link(alpha and beta) were iterated to make a graph. Despite their apparent indistinctness, these graphs were used to determine the lengths of the prototype that was later made as well as evaluate performance.

9.5 Visualisation in CAD

When closing in on a more specific design, it's sensible to once again go back to the 3D environment to make a visualization of the model in comparison to the Otter. This makes it possible to design and construct a full-size collective system in the CAD-software. By simply adding height to the design, a 3D model of the collective system is visualized. This allowed for quickly determining additional conditions and variables such as system height, connection points, and location related to the USV. Based on the graphs provided in 36 and visual observations, the first constructional variables were determined. An important reason for choosing such a design approach was being able to later on changing variables if found necessary. The following parameters was initially given to the system:

1. **Link 1** = 400mm
2. **Link 2** = 750mm
3. **Link 3** = 350mm
4. **Link 4 (height)** = 300mm
5. **alpha** = 90-180°
6. **beta** = 135°

Figure 37: 3D visualisation of design concept

Video-link to motion-visualization of 2D conceptual variations

Even though a digital model of the system is defined in terms of geometry and dimension there are many subsystems/parts. This proposed digital model only focuses on the geometric dynamic of the system, as one can see the net/filter, connections, joints, etc. is not presented. This technical detailing will be provided in the next stage, covering prototyping and integration of the collective system.

10 Stage 4 - Detailing, prototyping, and integration

With a geometrical design defined, and the dynamical movement of the system defined, it still lacks a defined collective system. This particularly includes defining subsystems. To define these subsystems, a prototyping approach is utilized to a large extent. When initiating a prototyping process it's essential to evaluate feasible materials, in terms of their properties. For this assessment, four criteria are listed. Strength, workability, corrosiveness, and cost. These are a result of the requirements raised towards material and manufacturing in early-phase development.

Material	**Strength**	**Workability**	**corrosiveness**	**Cost**
Plastics				
Metal				
Wood				
Cardboard/Styrofoam				
Composites				
Glass/Ceramics				
Textile				

Table 8: Assessment of potential materials for prototyping

10.1 Identifying subsystems

Parallel to the conceptual work it was also systematized a set of subsystems that could be further developed. As identified in the previous chapter it was considered feasible to look further into a dynamical system, that by using a filter/net could perform the operations we want. The following list of subsystems is generated by analyzing the current conceptual design. Not all subsystems have been brought further into the development process. It's also not clear to what extent these subsystems will be refined.

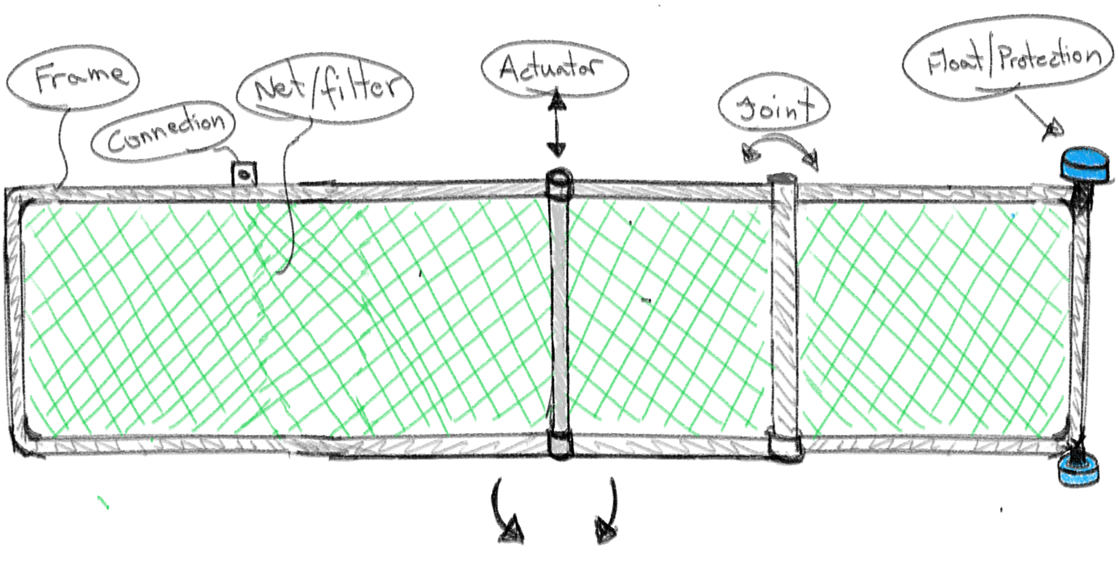


Figure 38: Early stage, subsystem identification

1. **Net/filter**
   The net/filter should filter out any targeted objects from the water, and keep them within the system until an emptying procedure is performed.

2. **Framework**
   The framework refers to the system that will keep all the other sub-systems together(also the one visualized in the previous CAD model). In comparison to Aquadrone v1 this would be the large aluminum box inside the Aquadrone.

3. **Joints/Hinges**
   With a focus on a dynamical system, it is reasonable to assume that it will be a set of joints included to make the system work properly in relation to each other.

4. **Floaters and protection**
   Due to factors such as stability, safety, durability etc. The system would likely need some form of buoyancy to maintain the stability of the system. The system must also tolerate light-medium collisions with objects or docks.

5. **Actuator**
   As the system is supposed to act depending on commands from the control system, an actuator is considered necessary to obtain control over the mechanical system.

6. **Sliding hinge**
   In addition to joints and it is also considered necessary to include a sliding mechanism. Meaning some of the framework would have to slide/move linearly independently in relation to the "rigid" USV. Looking at the visual video from the conceptual work, it's considered inevitable, for achieving the desired motion.

7. **Joining methods**
   There would be a need for connection between all other subsystems as well. This would likely vary in terms of function, dimensions, strength etc. Some being permanent others being possible to detach.

10.2 Subsystem detailing and prototyping

While the prototyping process was performed in a more dynamic manner, it is sensible to present the process for each subsystem individually. This is to maintain a better understanding of the process. The integration of the subsystems is presented in a later chapter. A spec-sheet was made to systemize the development, providing function description, origin of part, quantity, etc. This sheet is found in the appendix: 71. Considering the many subsystems, and relatively short timeline, where rapid prototyping was once again central to iterate until a usable design was present. Generally the approach for prototyping such subsystems where performed in the following manner:

1. Draw system on paper

2. Establish functions and dimensions

3. Design them in detail on paper or CAD

4. Create functional prototypes using accessible materials, parts, or additive manufacturing.

5. If the functional prototype is feasible, re-do from step: 2 or 3

6. Re-do process until requirements are satisfied.

10.2.1 Framework

Early in the conceptual generative process, the need for a modular framework was raised. The properties of the framework should be of a material that could easily be formed, constructed, and adjusted. Much like you would do with a Lego set. Other requirements such as strength, weight, and USV stability were also considered. Looking back at material assessment8, metal was eliminated due to its relatively time-consuming processing time. Cardboard or styrofoam materials are great for workability but would serve little purpose as a functional model due to low strength and weak water properties. A composite material would cover this, but issues with workability were decisive. The most sensible option was using Wood or plastics. Wood is excellent to work with, but also have concerns in terms of water resistance and fractures. Through a set of brainstorming sessions and research on accessible materials, it was found that tubular plastics provided surprisingly many of the desired features.

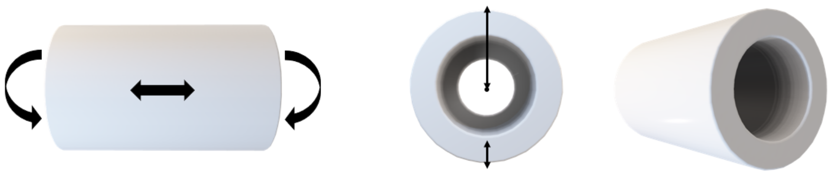
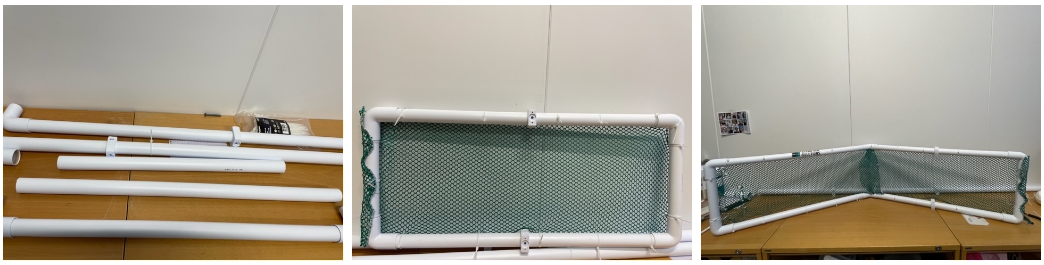


Figure 39: Tube-geomtry used a building block for prototyping

An early assumption is that the collective system will be exposed to primarily bending momentum and some compression forces. Tubes, with rotational symmetry, can provide the right properties in terms of both bending and compression. Having a homogeneous system also makes it easier to compute and estimate factors such as weight, buoyancy, etc. Additionally, it was assumed way less water drag from a tube, compared to a beam or metal profile. In a local hardware store, a modular tube set was found. This tube set was initially acquired to help with early stage-prototyping. However its properties were such a good fit, it was later also used for a functional prototype used for testing. Technical drawings of this tube are found in the appendix 81 and 72.



(a) Modular parts (b) First element assembly (c) Early-phase framework

Figure 40: Tube-set used for prototyping

Some of the observed strengths of using this as a prototype framework:

- High workability, modular, and easy to disconnect
- Sufficient strength
- Non-corrosive
- Low drag coefficient in the water
- Watertight construction (buoyant)

10.2.2 Net/filter system

It's concluded that using a meshed net/filter is unavoidable for this conceptual design. From preliminary work with the Aquadrone v1, it was obvious that the perforated plate serving as a filter had some serious limiting factors. Due to its design, its drag coefficient was disproportionately high. When considering such a net it's important to keep in mind the complexity behind such a process. The theory behind the fluid dynamics processes is highly complex and isn't either very logical to compute at this type of early-stage PD process. However, some relevant properties should be mentioned when evaluating this:

1. Its mesh size, is the size of openings within the filter that allows for water flow.
2. Wire/thread diameter, being a measurement of the thickness of the physical threads in a filter. This, together with mesh size are a great indication of the drag coefficient. At this stage, it's not considered sensible to compute this.
3. Durability. In terms of strength, flexibility, corrosive resistance, etc.

As we have little knowledge about the coefficient of resistance, this sets a considerable limiting factor for further calculations of forces on the system. To meet this problem, an empirical approach was chosen. It was decided that at least two different mesh sizes should be tested. Preferably one with very low drag and larger mesh sizes, and one with small mesh size but higher drag. For both versions it was desired to find a textile with minimal-sized mesh threads, to minimize drag. For the net with lower drag, the textile from a divers net was found to be a good match. Since its mesh design is made such that the diver can hold objects in the net, without causing too much drag. It was also reasonable due to its easy availability. Its mesh size was measured to be around 8mm openings.

The second net should provide a much smaller mesh sizing. A reasonable approach was to find a net that would push the boundaries of what was applicable to such a system(boundary testing). Possibly giving an indication of what capabilities a collective system could have. For this net, a construction net found at a hardware store seemed to fit the description. With a very thin mesh thread size and mesh openings of about 1.4 mm openings. A figure showing the two nets in comparison with the first-generation perforated plate. All three of them er shown on the same scale, showing the difference between them. Further description of the chosen net is found in appendix: 73.

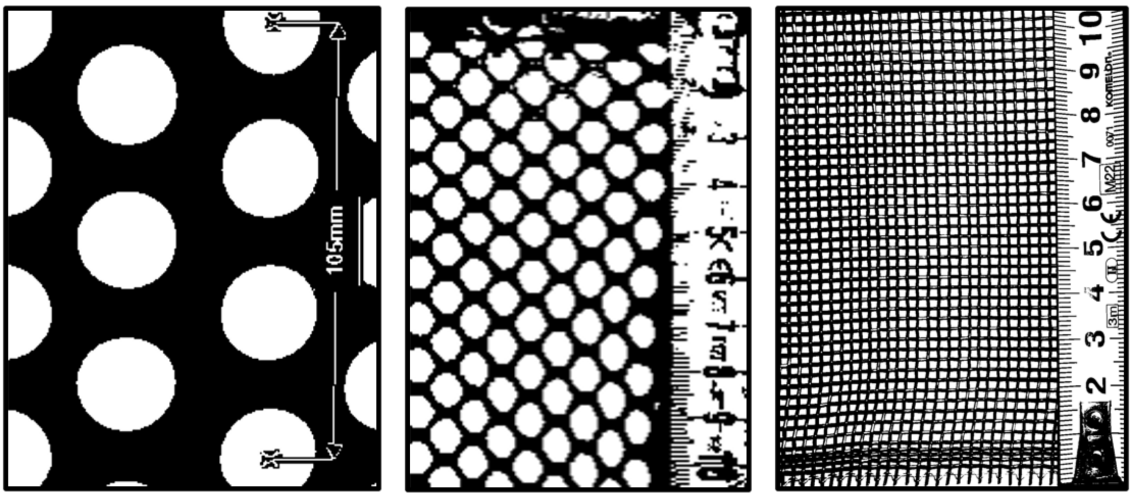
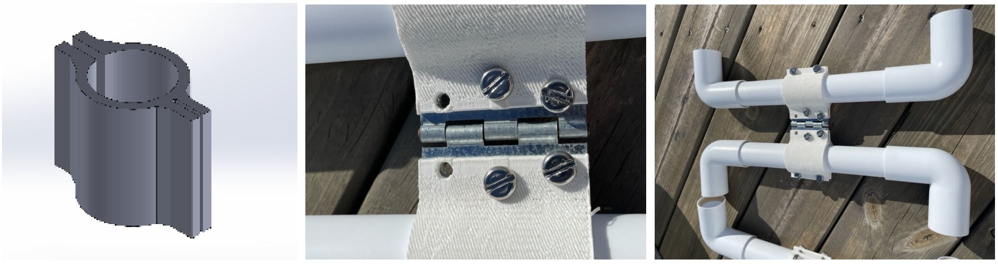


Figure 41: Mesh from Aquadrone v1 (left), big meshed-net(mid), small meshed-net (right)

10.2.3 Revolute joint system

Following the conceptual design toward a dynamical mechanical system, built on a tubular framework, the framework would likely be divided into links/parts. Between these links and the Otter, there would likely be a need for revolute joints. A revolute joint is simply a one-degree-of-freedom kinematic movement of two bodies. These are well described in the dimensional sub-caption. This could be developed in multiple ways, but to achieve the goal of rapid experience prototyping, some simple solutions were made. Hinges were bought from a local hardware store. These hinges had to be connected to the framework in some way. As for now, the design was focused on a framework of Ø-32mm tubes. To match this, a CAD model was made, and a hinge connection was 3D printed. The 3D-printed part was joined using nuts and bolts, connecting the hinge and framework together. Minimizing the spacing between these revolute joints was also important. While the first functional prototype was ideal, it did seem sufficient.



(a) Initial CAD-model (b) Hinge and 3D-print (c) Connected to tubes

Figure 42: Tube-to-tube connection

10.2.4 Sliding system

As visualized in the video links during conceptual work, the conceptualized design moves independently to the USV. This feature creates an issue, with the need for linear movement between the Otter and the arms. Visualization is made to address the sliding issue. This sliding movement adds a new level of complexity to the prototype. A very simple approach to deal with this was to 3D print a tubular part with connection capability. The part had an inner diameter slightly larger than the Ø32mm framework, the 3D-printed part had 1-2 mm clearance.

(a) Slider v1 and v2 (b) Wood plate connection (c) System to framework

Figure 43: Development of a sliding system

10.2.5 Net connections

An issue occurred due to the sliding mechanism. Initially, a temporary but easy approach using strips was made (Figure 75 c). This made it possible to connect the net to the framework quickly during prototype iterations. This worked sufficiently in the first place, however when the sliding system where introduced a conflict occurred. Since the system relies on moving/sliding along link 2, using strips/connection, revolting the framework would conflict with this function. As a response to this, a reversible fastening mechanism between the net and the framework was developed.

(a) Intial connection method (b) 3D print connection (c) 3D print in system

Figure 44: New method for attaching the net to frame. This allowed for moving the sliders along the tubes while also having a net connected

It was considered sensible to develop a modular method for connecting the net. This demanded more engineering than what might be included in a rapid prototyping process. At the same time, it also discovered the possibility of having a modular connection to the frame. Making it possible to connect/disconnect the net from the framework without wasting materials. It was also supported by other requirements such as sustainability, ease of use, maintenance, adaptability to other applications, etc. The approach for this was to use clamps to clamps to hold the net with a normally distributed force. These clamps would then be fixed at single points along the framework.

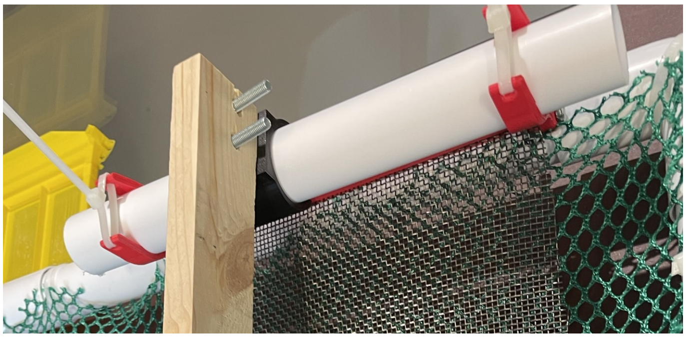


Figure 45: Visual of mechanism together with the sliding system

The attachment to the framework was dimensioned with a clearance that enabled the part to be pressed onto the framework manually and then attached by tightening around the framework. Since the sliding mechanism was designed with an opening on one side, which will prevent the net-contact system and the slider from colliding. This system was iterated many times before being considered feasible. While only applied for the segment with the slider, the system was designed to be used for the entire system. Further technical details are found in the appendix covering technical drawings: 85.

10.2.6 Adapter

Since this project is primarily being developed to fit the Otter, there is a need for a mechanism for connecting the Collective system to the Otter, therefore called an adapter. The Otter is not particularly engineered for easy attachment points in front. Most applications are usually attached to the topside cage of the Otter. However, focusing on a system located in the front section of the USV, it was necessary to design a specialized solution for this. The pontoons are made of welded polyethylene(PE) plastics, which are hollow to allow for buoyancy. Mechanical mounting into the Pontoons walls was therefore out of the question. There was a specialized part drawn, modeled, and 3D-printed. This was made to specially fit the nose of the pontoons, allowing for very easy mounting. The part was fixed in the lifting ear of the USV and the horizontal holes in the front nose.

(a) CAD model (b) Attached to the Otter pontoon (c) Attached to the collective system

Figure 46: CAD-file used for 3D-print

A set of holes was added to the part to allow for later-on height adjustment of the collective system. These holes were also specialized to fit a hinge that would work as the connection between the slider and the adapter.

10.2.7 Actuator

To be able to work according to the defined operation states, an actuator was needed to manipulate the system. The Aquadrone v1 had two linear actuators to perform its tasks. The conceptual work in stage 3 developed a system with emphasis on only one actuator. While there is a wide field of actuators available, it was clear from conceptual work that the needed movement would be linear. It was the initial objective of acquiring an actuator that could be used for testing the prototype. During the prototyping process, it was however concluded that it was not necessary to have an actuator for the first testing. While it would be beneficial, it would also rely on ordering a linear actuator within the right dimensions. It was agreed that it would be smarter to test the prototype, learn, and then, later on, decide on what dimension is needed.

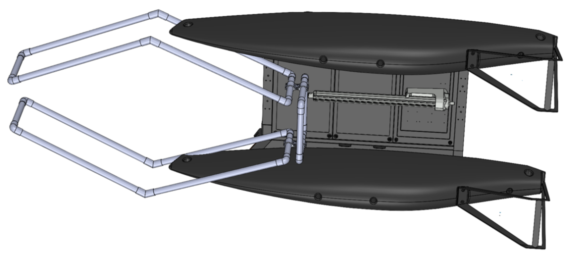


Figure 47: Proposal of locating a linear actuator

10.3 Final CAD model

Given that all subsystems were defined in SolidWorks, it was possible to create an assembly, to simulate the collective system prior to physical integration. This was a sensible measure to address potential issues and find the correct dimensions of subsystems. The net is not added in the SolidWorks model, as the software is not suited for soft materials.

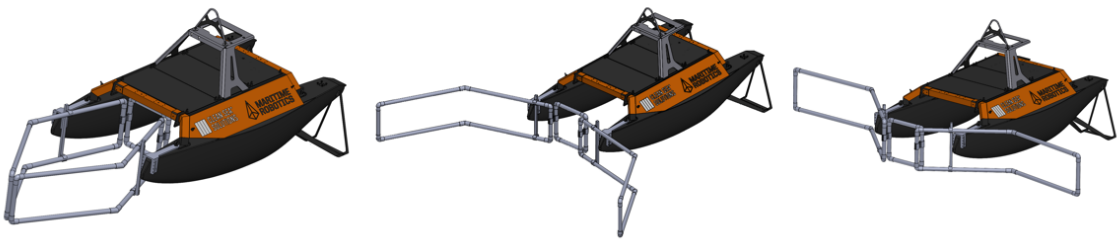
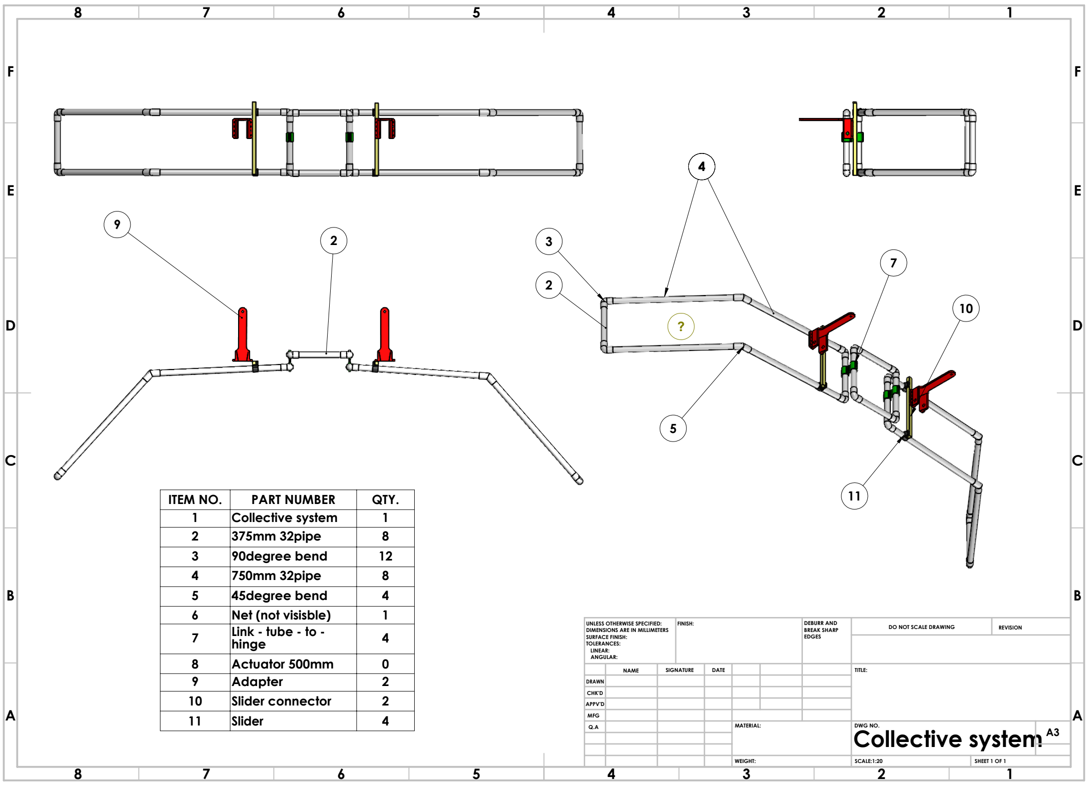


Figure 48: CAD model with the integrated subsystems, visualized in three states: Transport (left), collective(mid), disposal (right)

Video of final CAD prototype, explaining the different states



ITEM NO.	PART NUMBER	QTY.
1	Collective system	1
2	375mm 32pipe	8
3	90degree bend	12
4	750mm 32pipe	8
5	45degree bend	4
6	Net (not visisble)	1
7	Link - tube - to - hinge	4
8	Actuator 500mm	0
9	Adapter	2
10	Slider connector	2
11	Slider	4

Figure 49: Collective system with bill of materials(BOM)

10.4 Integrating subsystems

When all subsystems are defined and dimensioned the final functional prototype can be constructed. The different subsystems have been designed to fit each other. Many different assemblies were made (mostly with different tube sizes). Eventually, a first iteration of a functional collective system is made.

(a) Framework and net under construction

(b) All subsystems included

Figure 50: Building the prototype

It should be mentioned that this system is not defined in its current state, meaning the movement of the system is not clear from the construction. It can be assumed three connection points between the collective system and the USV. All points must be present to have a fully defined system. Two connections with linear sliding are located at the tip of the pontoons. In addition to this must an actuator be attached to the mid-frame. Without the connection to an actuator will it not be possible to keep the system in a static position, and the system will be under-defined. This under-defined issue can somewhat also be observed in the illustration below, where the system is slightly out of symmetry:

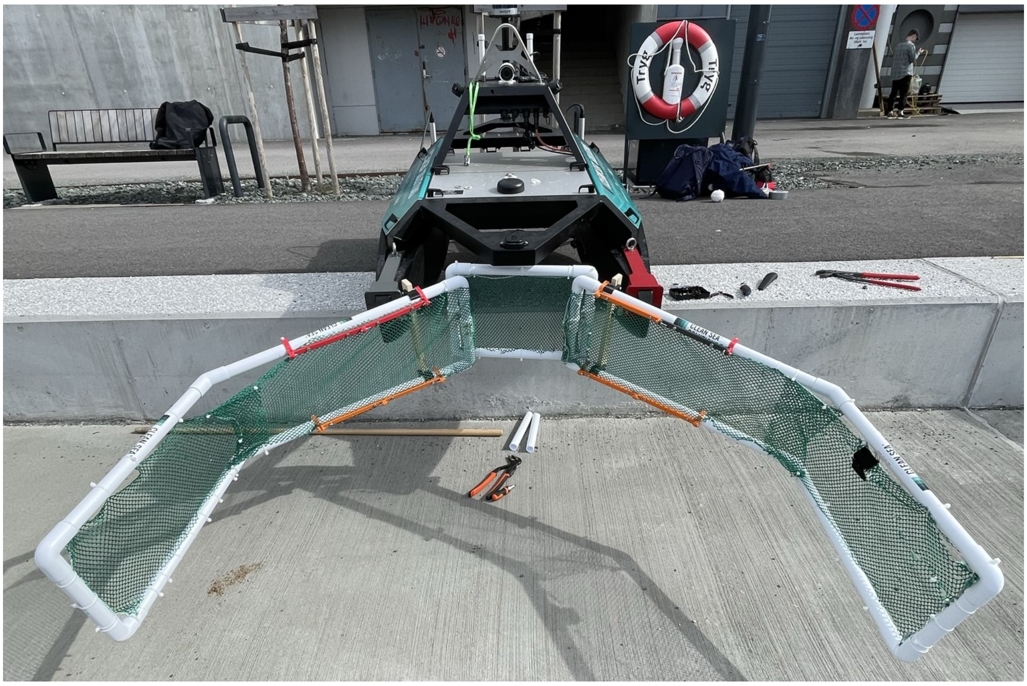


Figure 51: First iteration prototype attached to USV

11 Stage 5 - Testing and evaluating prototypes

At an early development stage, it was considered vital to perform a set of tests, simulating a realistic environment, as this would significantly strengthen the results. This is because it provides insight into the validity of findings, identifies challenges, tests user experience, performance evaluation, etc. Since Clean Sea Solutions have the Otter drone available, it was a good opportunity to perform a test in water with both the Otter and the collective system. A test like this would make it possible to simulate conditions very close to reality.

11.1 Test questions

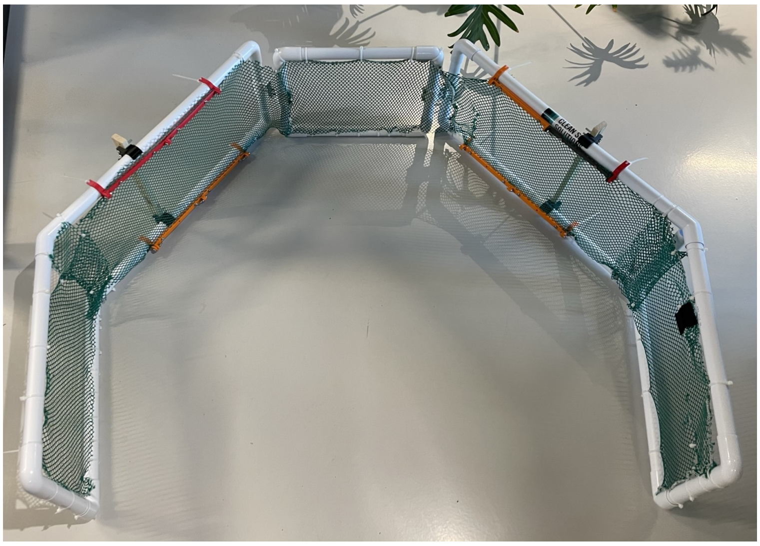
Before setting up a test plan, an evaluation was made to specify which research question could be answered from such a test. These were the questions raised prior to the test:

- How does the collective system affect the Otter's maneuverability and speed?
- Does the design of the collective system match the requirements that were initially set?
- Will there be a need to adjust the initial requirements?
- Are the different subsystems sufficiently durable and functional?
- How well can the Aquadrone operate in the different states?

11.2 Initial test plan

To answer the given questions as well as possible, an initial test plan was developed.

- Perform a baseline test, to be able to evaluate how well the collective system performs in comparison to its original state. This test, is also expected to have some errors. Conditions such as wind, waves, sensor reading, and sensor noise are just some of the sources of error that are difficult to minimize.
- Perform a similar test using the collective system, with different variables. Primarily with the system in different positions, by using different net meshes. Both variables will affect the water drag of the USV.
- Perform a set of maneuvers such as reverse throttling, rotation around its own axis, etc. In addition, perform such maneuvers when holding onto objects. This is important to verify the functionality of the system.
- As a final test, it was considered to run a test-to-failure test to address weak parts of the collective system.



(a) Setup for test day 1

(b) Setup for test day 2

Figure 52: Two different setups

As mentioned the Otter is operated through a onboard computer software, it allocates itself using GPS sensors. From this is also AIS data plotted. Through Maritime Robotics' own developed software, can a wide set of data be gathered from operations. In particular, is the AIS data of interest, as it shows how the path of the USV. By creating a standardized p2p route, and performing the route repeated times, one can compare the AIS data from different tests. In addition to AIS-data, is also speed and engine load possible to monitor during operation. The Aquadrone, which a planned to rely on data-vision, also has a camera of availability. It would be sensible to also record some of the operations from a USV point-of-view.

12 Test result

The following chapter presents the final results from testing, as well as the computed capacity of the tested system. It was first performed a reference test (**test 1.**), then followed up by the first test of the collective system(**test 2.A/2.B**), using a big meshed net. Test 3 was performed with minor upgrades and adjustments based on knowledge from the previous tests and with a smaller meshed net. Eventually a test-to-failure (**test 4.A**). The resulting performance, specific to the prototype in terms of capacity and width is presented in the graphs below. The dimensions are very close to the one presented when dimensioning system: 9.5.

12.0.1 Performance of test-setup

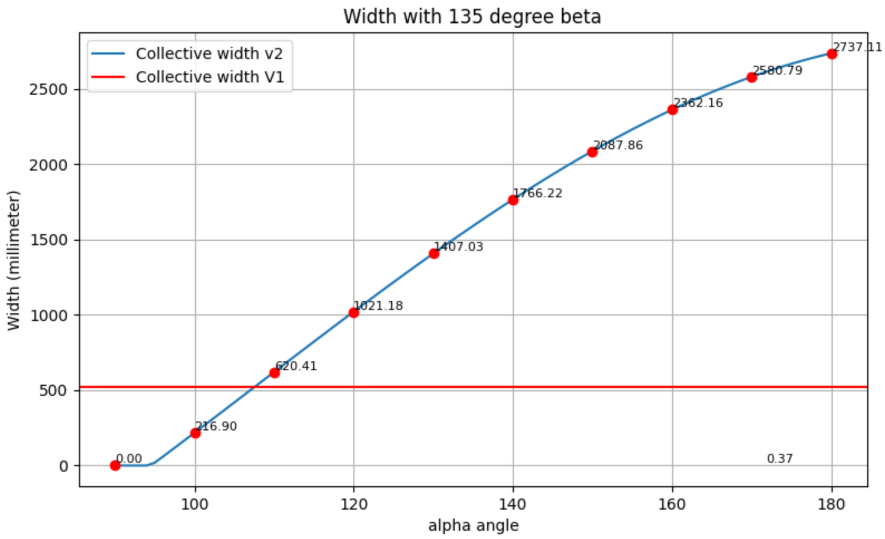


Figure 53: Width capacity of the collective system compared to the Aquadrone v1. The blue graph shows the nonlinear changes in width during operation

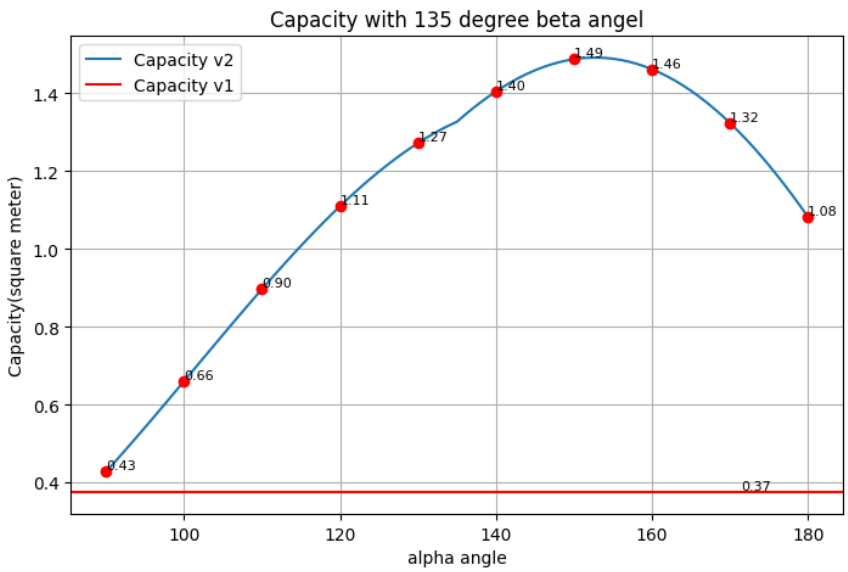
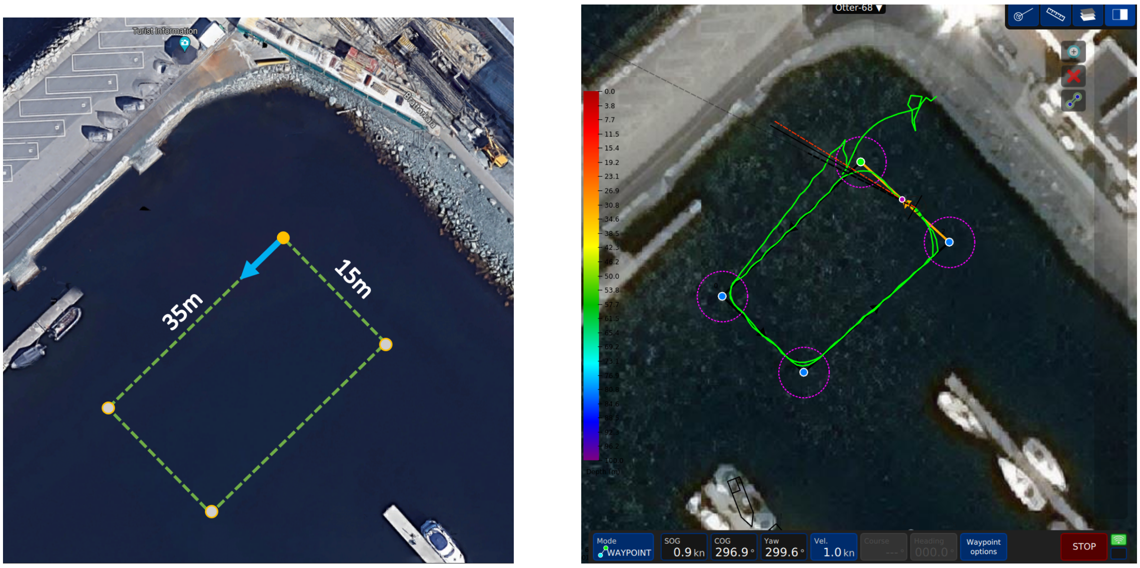


Figure 54: Collective Capacity of the collective system compared to the Aquadrone v1. The blue graph shows the nonlinear changes in areal within the system

12.1 Test 1 - Reference test



(a) Planned test route, forming a rectangle

(b) Baseline test

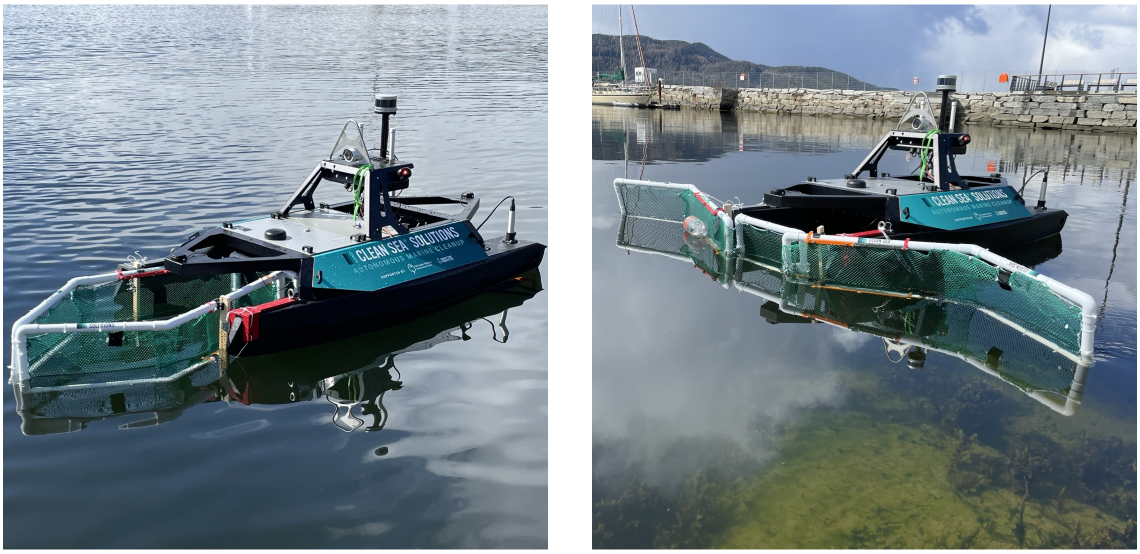
Figure 55: Reference test without any collective system attached

For the illustration above, the green line is AIS plotting, meaning the actual navigation of the USV within a timeframe. The color scale on the left can be rejected, as this is only a depth measure. Blue dots are points the USV must reach, similar to the point-to-point navigation explained. It is surprisingly difficult to reach a specified coordination point, therefore is the pink circle introduced, which is the radius where the point is considered to have been reached so that the USV can navigate to the next point. For the testing, this radius was set to approximately 2 meters.

Test no.	1
Set-up	The Otter in its original form, without any mechanical systems attached.
Actions	Deploy Otter
Test hypothesis	We assume that errors will occur when plotting GPS-coordinates. We therefore want to track these, to better validate the later tests.
Orientation in water	Good, slightly pitched backwards (negative rotation).
Navigation	Close to a perfect square, but the systematical errors from the control system and environment can be easily spotted. The route was completed twice as seen in the figure. The deviation observed on top origin from launching and test-setup(this can also be discarded).
Technical Set-up and issues	Unproblematic, the Otter are capable of navigation from pre-set commands. This gives green light for further testing of the collective system. Speed was limited to **1.5kn**, with avg. speed between 1-1.5 kn.
Comment	Good reference test, also proves that there are some underlying systematic errors that should be subtracted from test results.

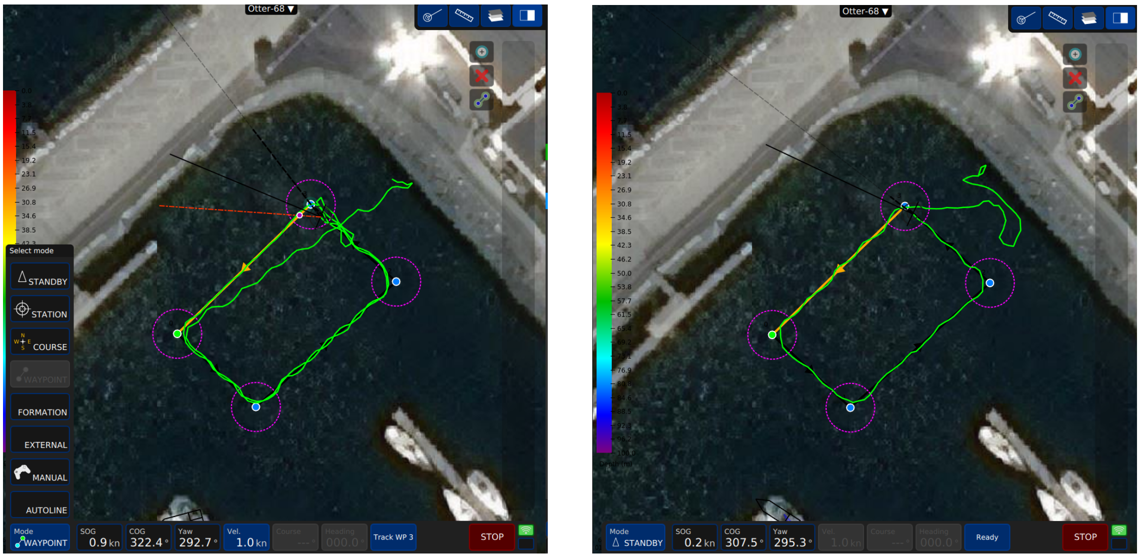
Table 9: Notes from reference test

12.2 Test 2.A and test 2.B



(a) Closed position (b) Open position

Figure 56: Test using big mesh net (8mm mesh opening)



(a) Closed position (b) Open position

Figure 57: Test using big mesh net (8mm mesh opening)

Video-link to test 2.A and 2.B

Test no.	2.A
Set-up	Collective system with 8mm mesh attached in closed-position **(transport-state)**
Actions	Attach first functional prototype of collective-system, due to the missing actuator, the system is undefined. This was fixed using a rope between the mid-frame and the Otter. The collective system was unproblematic to attach. Some slight adjustments had to be done with the revolute joints to make the system fit.
Test hypothesis	Considering a big meshed net and operating in a transport state, this setup should provide the lowest water drag (low drag coefficient and area).
Orientation in water (still)	Very satisfying orientation. Close to horizontal, with possibly a few degrees backward tilt.
Navigation	Point to point was performed twice in a row. It can be observed that the USV tends to overshoot more now. Therefore, ends up moving as a pending graph.
Technical Set-up and issues	Unproblematic, but with tendencies of overshooting, this overshooting was similar for both completions of the route. Speed was limited to **1kn** with an estimated average of around 0.9 kn.
Comment	Good test. Satisfying orientation and stability, as well as net height in water (about 5-10 cm submerged). The issue with overshooting was expected, but slightly more than originally anticipated. The system had no issues holding onto a floating object during operations.

Test no.	2.B
Set-up	8mm mesh attached open-position **(collective-state)**
Actions	Open the collective arms and defined it in open position
Test hypothesis	For the next test, the collective arms were opened to a maximum position of roughly 2.5 meters in width. This width should drastically increase the water drag, and one would potentially see more overshooting.
Orientation in water (still)	Orientation still good. Better than in the closed position, likely since the buoyancy of the frame is moved closer to the center of the USV.
Navigation	The overshooting was still present, but not significantly worsened. With fewer bends, but somewhat greater deviations from the original route.
Technical Set-up and issues	The resulting forces on the submerged links 1 and 2 were significant. The collective system was slightly bent inwards in the lower part (submerged), creating some misshaping of the whole structure. This misshaping was estimated to be from the tubular framework rotating within the joint, meaning the joints rotated when torsion was applied to the tubes. Additionally, weaknesses in the joints were observed, between links 1 and 2, and in the hinge between the Otter adapter and the slider. To solve this, an additional hinge was added for more strength between the adapter and slider. Due to higher drag impact, and concern about breaking off hinges and connections, speed was held around **0.8kn**.
Comment	Orientation and stability are still not an issue. The issue with drag was more present, but not at a crucial point. A water bottle was collected, and the system performed a full completion of the route in ”collective state” without losing the object.

Table 10: Notes from Test 2.A/B

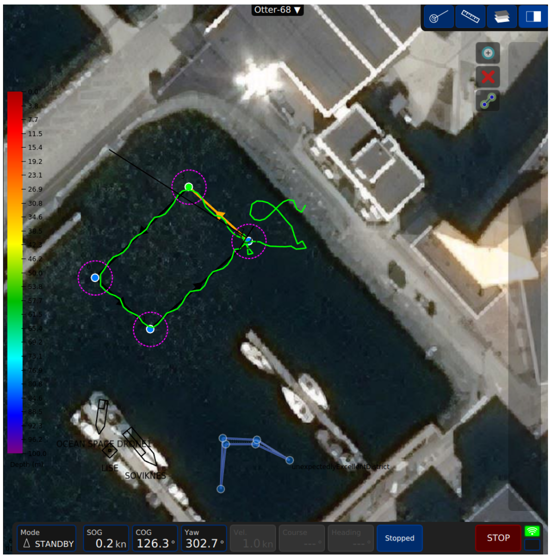
12.3 Test 3.A and test 3.B

For the next testing, some slight adjustment was done. An additional hinge was added between the slider and the adapter, as this link was not sufficiently strong in the previous test. In addition, was superglue applied in all joints of the framework to avoid bending of the framework(as experienced in previous test). In addition, was also the low meshed net applied.

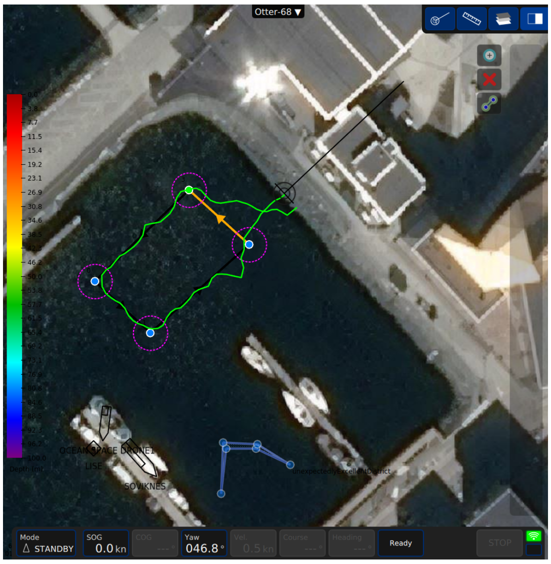
(a) Closed position

(b) Open position

Figure 58: Test using big mesh net (8mm mesh opening)



(a) Transport-state



(b) Collective-state

Figure 59: Test using small mesh net(1,5mm mesh opening)

Video-link to test 3

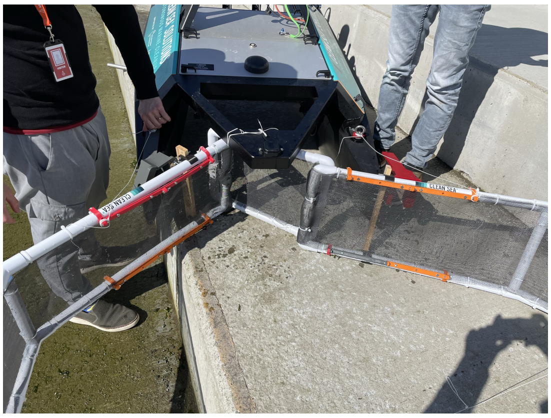
Test no.	3.A
Set-up	1.5 mm mesh attached closed-position (**transport-state**)
Actions	Attach modified collective system in closed-position
Test hypothesis	With the small meshed net, it was expected to observe more overshooting and issues with structural strength.
Orientation in water	Same as test 2.A
Navigation	The route was only completed once, and as expected the route was followed with increased overshooting issues as seen in plots. Now with significant deviation, however, the USV still managed to operate continuously by itself.
Technical Set-up and issues	When pushing the throttle of the USV, the collective arms experience the same issue. This is likely caused by the increased water drag from the new net. The manual operation was however fairly unproblematic. Speed was regulated to around **0.7kn**. The collective system seemed to have a problem handling operation speed above this, while the propulsion system was capable of higher speed.
Comment	Satisfying test, The minor adjustments seemed to have a variating effect. This was solved by reducing speed.

Test no.	3.B
Set-up	1.5 mm mesh attached open-position (collective-state)
Actions	Open the collective arms and locking in open position
Test hypothesis	This test is considered the boundary test of the system, with smallest mesh and maximized width, meaning highest water drag. It is expected to see a drastic reduction in performance.
Orientation in water (still)	Same as test 2.B
Navigation	The effects of using small mesh was clearly inflicting the navigation. The Otter overshoots more than any other test, while also the speed was adjusted to avoid breaking the system. From the AIS it can also be since an extreme deviation from the original route, which would've not been acceptable.
Technical Set-up and issues	Speed was approximately around avg **0.6kn**. It was also necessary to tighten the arms with ropes to withstand the forces applied by the water drag(seen in the video). It also seemed like some objects were pulled underneath the system, also meaning some of the water was pushed underneath instead of flowing through the net. This would be a strong contradiction to the working of the system.
Comment	It seemed like a benchmark was reached, and the system was pushed beyond its capabilities. It was also a concern that the net actually pushed the water down and around the net and not through.

Table 11: Notes from test 3.A/3.B

12.4 Test 4

(a) High speed, resulting downwards pointing system



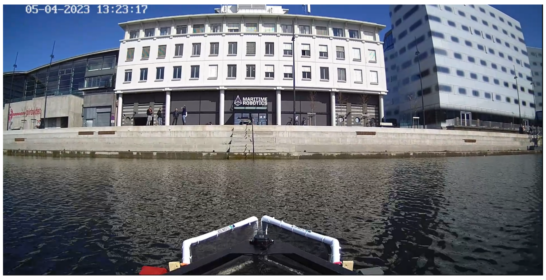
(b) Broken adapter after unsuccessful USV retrieving

Figure 60: Some issues from testing

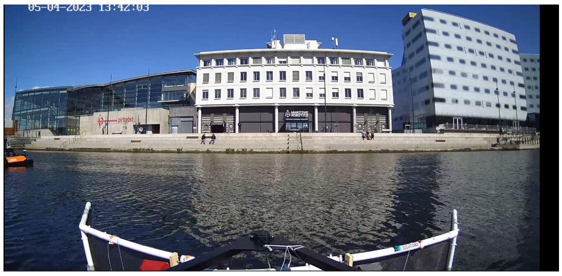
Test no.	4.A
Set-up	1.5 mm mesh attached, arms in open position
Actions	Nothing, same set-up as test 3.B
Test hypothesis	As the previous test was tested using throttle limitations, it was considered a more destructive approach. Since the prototype had served its purpose, the model in itself would not be used in a later project. It was expected that 3D-printed parts might break, or the framework twist into a crooked position.
Orientation in water (moving)	Due to high throttle and increased drag, the net sunk downwards and pitched the Otter forward.
Navigation	During this testing it came out clear that the system was not designed for high-speed navigation. For this test the navigation where done manually. It was no problem controlling the drone in terms of navigation capability.
Technical Set-up and issues	The collective system did however experience too much water drag and was twisted permanently. It did however not break under maximum throttle, but rather dig itself down in the water as shown in the figure above.
Comment	When retrieving the Otter after testing, there were some practical challenges with lifting the Otter since the tide had sunk below a certain point. This led to the Otter being dragged over some large rocks, with the collective system being the lowest part of the Otter. Naturally, the arms broke off, as the adapters didn't stand the momentum from the Otter's weight. The test generally proved the weakness of many subsystems.

Table 12: Notes from test 4

12.4.1 Other observed results



(a) **Video-link to point-of-view of test 3.A**



(b) **Video-link to point-of-view of test 3.B**

Figure 61: Collective system observed from the camera that is used for navigation

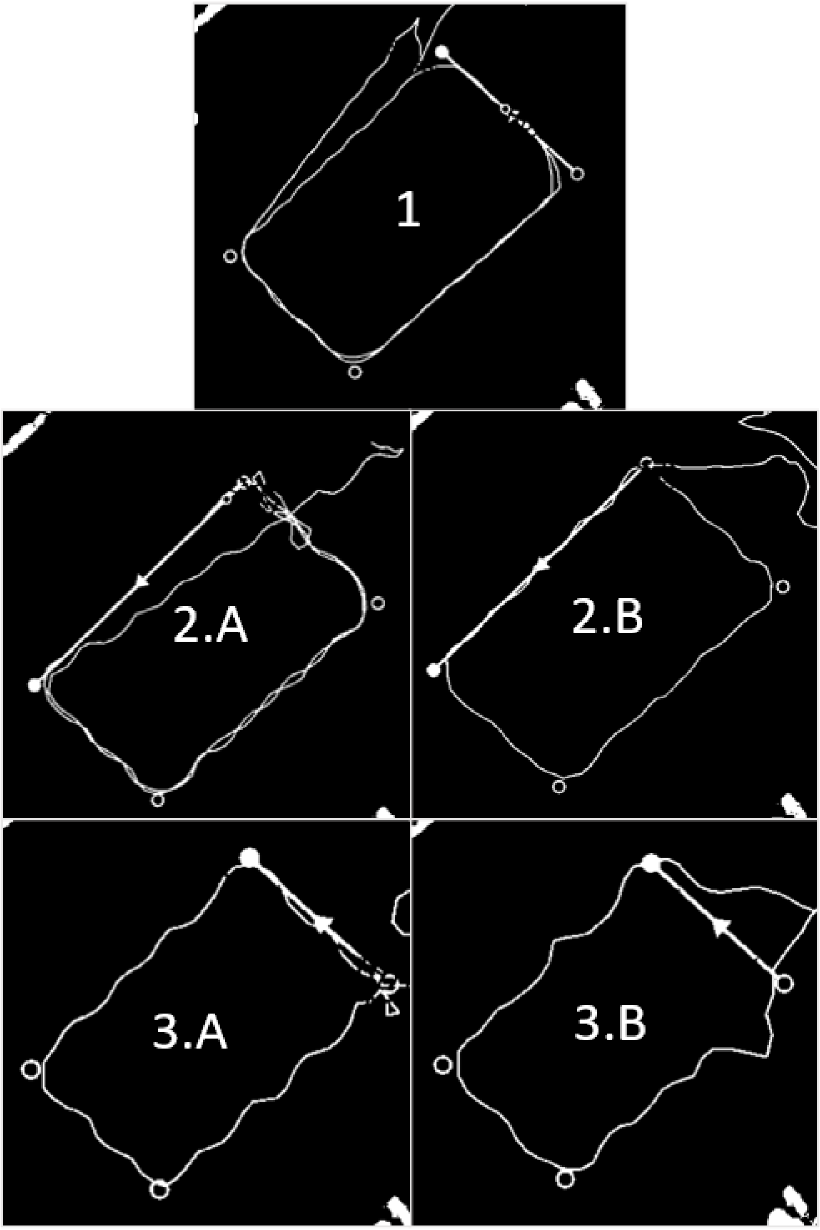
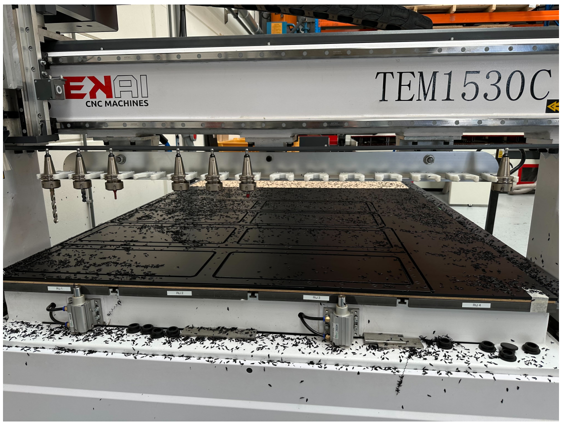


Figure 62: Comparison of AIS plotting, graphically manipulated to amplify the pathline

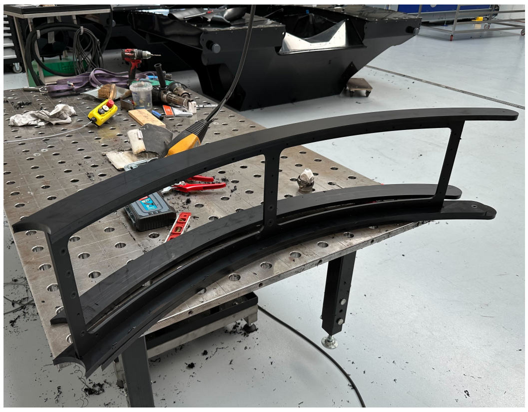
12.5 Update on testing and results by Clean Sea Solutions

Disclaimer: the following content is partly but not exclusively the result of the described thesis. Furthermore, the development has been done under the auspices of Clean Sea Solutions and the author has only contributed with recommendations on the development. The author takes no credit for the development and work presented in this section.

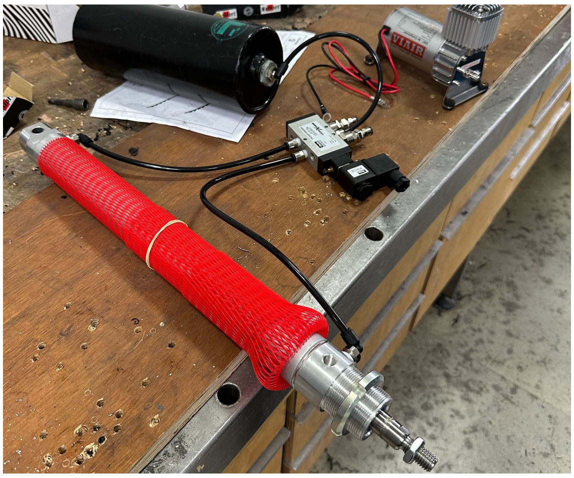
During the testing of the system, two participants from Clean Sea Solutions were present to observe. While there were some issues with the testing, it was said that the geometry of the system seemed promising and that it was desirable to continue the development of the system. As a result, in a short time after the testing, Clean Sea Solution initialized a development process of the proposed geometry. This process is briefly summarized and documented as the author believes it can generate interesting insight into the entirety of the project. Clean Sea SOlutions iterated a new CAD model of the collective system. Very much like the one developed in this thesis. A new, much more robust, and fully working version of the collective system was designed and manufactured. This was done in a workshop in Rotterdam, Netherlands, in collaboration with a company called HeKaTec[53], which specializes in PE-processing.



(a) CNC PE manufacturing



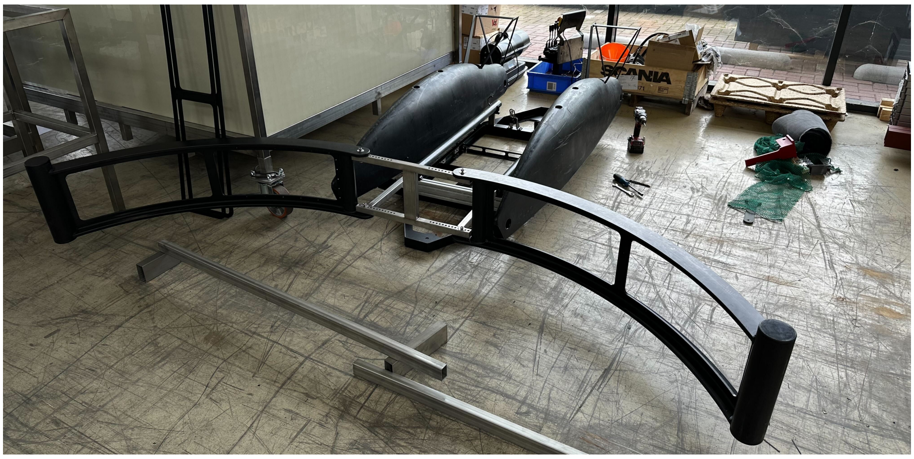
(b) Plastic welded collective-arm



(c) Pneumatic linear actuator applied

Figure 63: Manufacturing of the next generation collective system

As seen in 63, parts of the framework was manufactured from PE plates using CNC machining. These parts were then plastic welded togheter. The collective arms were connected to the midframe, which now was in metal. It can be noticed that all subsystems are still presented, even though they are all changed to various degrees.



(a) Open position

(b) Closed position

Figure 64: Collective system mounted to the USV

Test of new iteration of the collective system (UPDATED: 25.05.2023)

A fully working system is manufactured, and in addition, in contrast to this case study, an actuator is also added. This completes the collective system, in terms of now being defined. The control system of the actuator still needs to be integrated into the navigational software, however, this is not yet developed. There are also made some changes in terms of the buoyancy systems and net connections. The system is also now entirely located in front since the mid-frame does not move between the USV anymore. However, it is not a part of the project to evaluate this new design work.

PART V

DISCUSSION

The discussion chapter will proceed in chronological order, beginning with an evaluation of the research approach. This initial section will encompass the chosen product development method and its application throughout the project. Subsequently, the case study will be discussed in detail, incorporating all its stages, prototype design, and test results. Any issues or challenges that emerged from the development and testing will be discussed as part of this analysis. Eventually, will an evaluation of the findings be presented.

Prior to the case study, a list of research questions was raised. It's concluded that these research questions are best reviewed and answered in different segments of the case study. Relevant observations and circumstances that are considered important are mentioned. Looking back at the initial research questions:

1. *Explore how physical product development methods can be evaluated, designed, and applied based on a specific case study.*
2. *Identifying the current state of autonomous waste collection methods and evaluating their effectiveness.*
3. *Identify key functionalities for developing a waste collection system in relation to a USV.*
4. *Identify requirements that can be used to measure such a system in terms of its efficiency.*
5. *Research the potential of a USV system design that is more optimized for its application.*

12.6 Evaluation of research approach

The first research question was described as:

RQ 1: Explore how physical product development methods can be evaluated, designed, and applied based on a specific case study.

The thesis framework, which combined elements of SBCE and the stage-gate model, proved effective in guiding the product development process. However, there were also challenges related to strictly following this method. One issue that was observed was the relatively sequential method and the lack of agility and flexibility when moving through a set of stages. It should be emphasized that the case study in reality was much more dynamic. Process phases and associated techniques have to a great extent been performed in parallel as shown in the figure below.

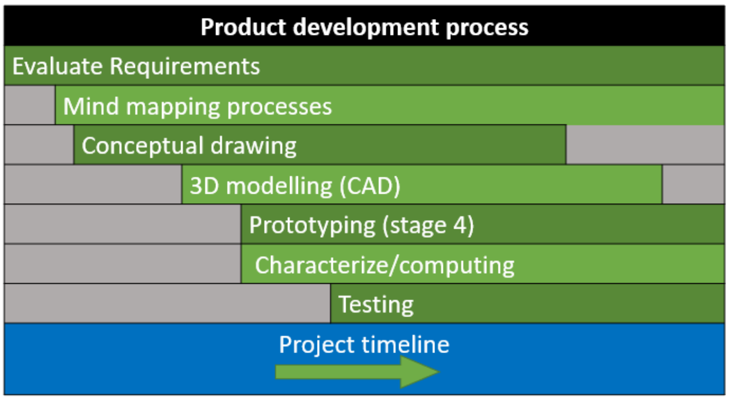


Figure 65: Estimated timeline for different techniques and tools during PD

From the method part, a framework for the case study was presented. It included dividing the case study into five stages of development, very much like a stage-gate model. In reality, the work was more dynamic and parallel, still, the five stages stand as the framework.

The method chapter also included an assessment of the case study's characteristics, identified as the key determinants in selecting the final approach. The characteristic of the study made it somewhat logical to pursue a prototype-driven research approach. While other academic studies might lean toward simulation analysis, this approach was not deemed suitable here. Early comprehension of the project suggested the inclusion of real-life prototype testing to gain maximum experience and insight.

Throughout the study, weekly meetings were arranged with a supervisor from the university and a technical supervisor from Clean Sea Solutions. It was concluded that physical prototyping was a sensible approach. This was important for the validation of the project. In retrospect, it comes out clear that the combination of digital and physical conceptual work also are influenced by personal preferences. One thought suggests that real-life conditions encompass numerous variables that simulations may fail to represent accurately, making real-life testing an effective tool for rapidly testing parameters in potentially complex and time-consuming conditions. Of course, simulations have their merits in certain contexts where real-life testing would be too costly, dangerous, or inaccurate. From the conceptual work, it is clear that dynamical simulations (in SolidWorks) have been a major part of the development, specifically to test dimensions and geometries in relation to the USV. In a case study with more participants, a longer timeline, or limited testing resources, incorporating more advanced analysis simulations would likely be a sensible choice.

12.7 Research approach limitations

Most PD processes make it mandatory to include a team in development processes, this is because teams/groups have an advantage in completing complex tasks. For this particular study there was only one participant, this also likely had an impact on the final outcome. Design thinking can become very one-sided when one participant is the "ruler" of all decisions. Eliminations of conceptual iterations have to a large amount be based on subjective views. The conditions of the case study also had implications on the research approach, where many simplifications were done, especially in early phase development. In an ideal SBCE approach should customer value be assessed and included in early development. However, there was no "customer" contact in this issue, other than Clean Sea Solutions.

12.8 Suitability of research approach

Looking back at the method chapter, two conditions were described in relation to the research approach:

- *The combination of stage-gate and SBCE should be able to handle a short timeline and few participants better than a "traditional" approach)*

  Given the final outcome, one might conclude that the approach satisfied this condition. An early goal was to develop a prototype that could be used to answer the task description. This deadline was met, even though the prototype was rather simple.

- *By prioritizing physical prototyping and testing over theoretical simulations, should the development achieve more insight(empirical approach over theoretical)*

  While this might be arguable, there is an expression that the insight gathered from testing was more comprehensive compared to what a "theoretical" approach could've achieved. To validate this, two similar case studies with two different approaches had to be completed. Since this is not possible it's difficult to say if the result would of any significant difference.

13 Evaluation of Case study

The evaluation of the case study will be performed stage by stage, with a final discussion on the outcome at the end of the chapter. The research questions are included in the process stage that was deemed fitting.

13.1 Stage 1 Preliminary work and litterateur study (case-specific)

Information and knowledge from Clean Sea were collected through case-focused meetings. While Clean Sea provided this information from their perspective as a company stakeholder, dialog with Maritime Robotics was also important, being the technical provider of the USV. It was noticed that CSS and MR are different stakeholders and that different views on the project characterized the dialog with them. In addition to having a dialog with relevant stakeholders, was also a case-specific study performed, primarily looking into similar relevant projects.

RQ 2: Identifying the current state of autonomous waste collection methods and evaluating their effectiveness.

It was found that most waste management projects are conducted and driven by the science community. This also applied to the USV waste management project, which was more thoroughly presented. A common finding was that these systems operate after a path-planning algorithm, with a collective mechanism that pushes water through the system due to the movement powered by the propulsion system. All systems' autonomy is limited because it needs human interactions to dispose of their collected waste. In addition, the collective width and collection storage are relatively limited in size. The issues and challenges observed from other projects seemed to be very similar to the current status of the Aquadrone v1, with none sticking out as a better solution. Some conclusions were made to answer the first research question. Similar USV systems (including aquadrone v1) are subjected to poor performance due to two driving factors:

1. Low Autonomy level, both caused by lack of right software and complementary mechanical system.

2. Low efficiency due to dimensional constraints, causing narrow collection capacity and small storage bins, demanding rapid disposals.

It is questioned why these similar projects are not sufficiently developed. Technology related to autonomy is proven to be available, so missing technology gaps should be a sufficient reason. One thought is that these projects have little commercialization potential, thereby limiting investments in such projects. Development projects must often be driven by the potential of capitalizing from the result. How to capitalize from such waste management projects is currently unclear.

13.2 Stage 2 - Mapping design space

Based on the problem description, preliminary work, and insight from the literature study, it was possible to describe a set of requirements for the project. These requirements were used to map the design space for further development. This process was also performed in close collaboration with CCS.

RQ 3, Identify key functionalities for developing a waste collection system in relation to a USV
RQ 4: Identify requirements that can be used to measure such a system in terms of its efficiency

The mapping included five categories of requirements, but in retrospect, it can be seen that it was mostly the performance and functionality requirements that were used during development decisions. This is probably due to the phase of this development. As mentioned in the literature study, the point of view will also affect design thinking. For the following PD process developed by CCS (post-project), it can be seen that material, manufacturing, and cost requirements were much more central. This also implies that some of these requirements served their right in later processing, even though not used for this project.

13.3 Stage 3 - Conceptual work

The conceptual development stage was the most extensive period in the project's timeline. Developing numerous iterations from very low-fidelity to high-fidelity prototypes was surprisingly time-consuming. The approach followed the Set-based approach, where all solutions were evaluated. In retrospect, it's obvious that having a detailed model of the USV was beneficial for providing a feasible design. It was possible to evaluate and simulate prototypes in early-stage using CAD before any physical building. The conceptual process (stage 3) and the physical prototyping (stage 4) were two individual processes that, to some extent occurred parallel. Some prototyping materials, such as the tubular framework, were also used in the conceptual drawings. It can perhaps be assumed that these two processes should have taken place separately from each other. It's an impression that the acquired materials influenced the iterative design process. Ideally, it should've been the opposite way so the design iterations continued undisturbed.

RQ 5: Research the potential of a USV system design that is more optimized for its application.

The three operational states (collection, transport, and disposal) can be said to have been crucial for the development pathway. In addition to this, it was assumed that the system should only focus on floating objects on the surface, also allowing for simplifaction of the development process. Firstly was, a 2D conceptual model identified. When this was considered geometrically feasible, a computation script was made. This was used to optimize the dimensions of the concept. The optimal dimension was based on the requirements. One may argue that this was a specification-driven prototype rather than prototype-driven specifications. The computation that was made allowed for easy and quick adaptions to different dimensions and where considered a sensible method for validating the design. When the dimensions from computations and the visual from dynamical simulation correlated with the requirements, a proposed design was made. In retrospect this way of working utilized dynamic simulation in Solidworks a lot more the initially estimated.

13.4 Stage 4 - Detailing, prototyping, and integration

Conceptual work in CAD effectively replicated simple functional prototypes, enabling us to transition directly to higher-fidelity prototypes. Tubular materials were essential in this stage due to their properties and efficiency in design iterations, saving both time and cost. While this approach allowed for testing geometries, several subsystems were lacking. These subsystems, designed concurrently in CAD, were unique and not easily sourced locally, thus prompting to 3D-print them. A broad array of parts were 3D printed, with many subsystems undergoing numerous improvements. Some of these designs were time-consuming and provided minimal project insight in hindsight, suggesting some processes could have been eliminated. However, these subsystems were crucial to the functional prototype's completion, implying a simplified version would have been necessary if some sites were skipped. An actuator, identified as necessary in the early prototyping phase, was also desired for inclusion in the testing phase. However, through a number of limitations, this objective was not reached. acquisition time, installation, and integration into the navigational software made it a time-consuming process to include this important subsystem. In a discussion with CCS, it was concluded that the acquisition of an actuator could be postponed. While it would be interesting to integrate, it also was no hard constraint to the project. The testing did not depend on the system being able to change between the different phases on its own, but rather proving that each phase was possible to operate on its own. In addition, it was also not unlikely that changes would have to be made to the dimensions of the system after testing. A rushed determination of the specifications of an actuator was therefore equally important to avoid. Now, looking back, it can be seen that CSS included a linear actuator during their next development iteration. This also justifies the decision of postponing this system.

13.5 Stage 5 -Testing and evaluating prototypes

Initially, some tests were performed at the office to ensure the prototype's working. However, it was quickly concluded that the only really sensible testing was using the USV in real-life conditions. Two factors somewhat restricted the amount of testing. The first was the limited timeline, and the second was a limited window where the USV where available for testing. A central approach for the testing was boundary testing, where factors such as width, speed, and filter size were tested incrementally. Thereby indicating the applicable range of these factors. The testing phase of the product development process was carefully planned and executed in real-life conditions to assess the functionality and efficiency of the collective system for the USV. The test plan was developed to gather as much useful insight as possible, however, there were also some issues limiting the quality of the testing. AIS-data was retrieved from testing, but ideally should also propulsion power and speed have been tracked. Issues with the software made it difficult to retrieve this. Speed was only possible to monitor live, an estimate on the avg. speed was therefore provided. There is great uncertainty related to this described speed. It should also be noted that the speed was adjusted during the testing. The speed applied for test 2.A was just not feasible in test 3.B due to the increase in water drag. This is a big source of error in the testing. The plot 62 comparing the overshooting provides a good indication of the performance of the result. However, in retrospect, the validity is uncertain due to the variable speeds. Prior to the testing, a set of test questions were established. These questions are now subsequently evaluated.

13.5.1 Evaluation of test questions

- **How does the collective system affect the Otter's maneuverability and speed?**

  The system will significantly affect the maneuverability of the USV. While manual control made it relatively easy to maneuver, the built-in control system needed to be more suitable for the proposed system. Overshooting in navigation primarily results from the control system needing to accurately reflect the dynamics of the USV with the added collective system. The control system was initially designed for a streamlined USV without any additional attachments. Therefore would the addition of any system alter the hydrodynamic profile of the USV. This leads to more significant water drag, which the current control system does not account for, resulting in overshooting as the USV tries to maintain the intended navigation path. To rectify this, the control system of the USV needs to be updated to incorporate these new dynamic properties. This involves tuning the control parameters to match the new hydrodynamic characteristics. Maritime Robotics agreed that this was a fixable issue but relied on a fair bit of engineering. Therefore this should be fixed when a final design is provided to reduce rework. By optimizing the control system to reflect the USV's new dynamics better, navigation accuracy can be improved and overshooting minimized. The propulsion system for the USV is more than sufficient in terms of strength, meaning it is not a limiting factor.

Figure 66: Visualized water-line along the hull proves a very stable position in the water(horizontal)

Since the framework is built using tubes, the system's volume is greater than its weight, meaning the collective system is buoyant. This stableness was also very visible during stationary position and operation. Regarding operation speed, it is evident that this would be a trade-off between efficiency and power usage. As brought up in the value research, the water drag equation provides a squared gain in drag force when speed is adjusted, but the experience drag force is linear when the area is increased. The trade-off between areal, speed, and drag coefficient (determined by the design of the system and speed), is something of high relevance. However, a Computational fluid dynamics (CFD) analysis would be performed to determine this central water drag coefficient. A CFD analysis was considered at one stage, but this was discarded, given the conditions of the PD. Being in a very early-design phase, such a study's result didn't seem enlightening. In retrospect, this type of analysis could have been interesting to include. This trade-off would be something of further detailing.

- **Does the design of the system match the requirements that were initially set?**

  The proposed design is a result of the requirements that were established. However, some trade-offs were made. The design is strongly inspired by favoring low complexity. From early on, it was clear that using only one actuator would be preferred. In addition, is the resulting subsystems relatively simple to further engineer. The modular method has also been followed, especially with the framework and net being separate systems. This modular attachment system allows for easily adapting the net to desired applications. Performance wise proves the system to be significantly better compared to the Aquadrone v1. From testing, it was seen that some trade-offs had been made with the performance, especially in terms of maneuverability and speed(mentioned in the previous question). Regarding material properties and manufacturing, the prototype used for testing was insufficient. On the other hand, the new iteration prototype by CSS was completely different in terms of material and manufacturing properties. This indicates that all requirements were indeed of relevance but in a later stage(out of this project scope).

- **Will there be a need for adjusting the initial requirements?**

  Looking at the initial requirements and the results from testing, it is considered necessary to make a trade-off between some of the requirements. Waste size ability was mentioned as a factor, referring to the mesh size of the net. An initial object was to use a net with a mesh below 5 mm, as this would also collect smaller objects, such as small plastic fragments. From testing, it is evident that too small mesh would not benefit the system. Speed, maneuverability, and power usage would be highly affected by this. Once again, a trade-off must be made. Based on testing, including meshes opening below 5 mm does not seem sensible. This would, of course, depend on the properties of the filter(thickness, flexibility). One thing to note is that the net is a topic that is frequently mentioned throughout the discussion, rightly so, because of its major affection for the rest of the system. It is advised to devote extensive resources to finding a proper net, and not the simple textile used for this project. Other factors, such as cost, time, and material, seem to hold for now.

- **Are the different subsystems sufficiently durable and functional?**

  During testing, weaknesses were found in all subsystems. This was also somewhat expected, as the system used for testing was a prototype and not a complete product. The framework, in particular, was not sufficiently strong to endure the applied force when operating at high speed. Not breaking the framework but bending the plastics so that it loosed some of its capabilities. Much of the same issues applied to the joint and hinges. The weakest subsystem was likely the slider, which was not sufficiently developed for such operations. Making the "top-slider" and "bottom-slider" move parallel proved to be difficult, resulting in the system "get-stuck." Since the adjusting of the arms where done manually and not with an actuator, was this issue manageable? That would, however, not be the case for a linear actuator. The first big meshed net was working well. It did have some esthetical issues, but the net proved its functionality. For the small-meshed net however, it seemed like the resulting drag was too great a strain, both in terms of the collective system and the USV. Another issue with the small-meshed net where an indication of the water flow moving underneath rather than through (see figure on next page).

This indication was made by the surprising result that the big-meshed net actually collected more fragments compared to the small-meshed, which was relatively empty. While some of this may be a cause of the system being out of position, it might also be due to the low water drag coefficient in the net. This could be further investigated using simulations or doing additional testing with better and more optimized nets. Orientating the frame or net so that objects naturally does not flow underneath is also an option that should be easy to implement.

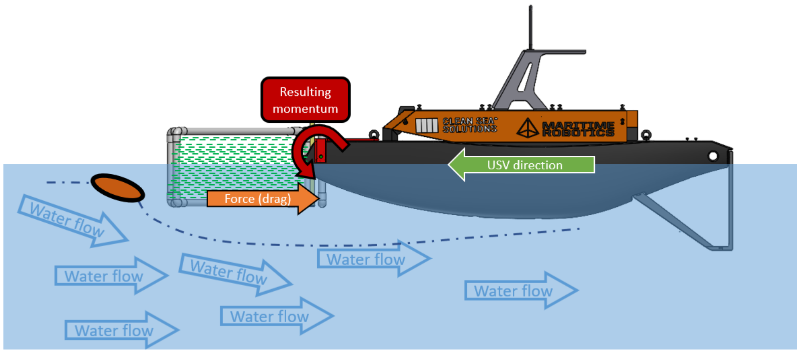


Figure 67: Illustration of hypothetical issues with too small mesh and high speed

- **How well can the Aquadrone operate in the different states?**

  During the testing, floating objects were also placed out. During both transport and collective state, the USV had no issues with holding objects. This proves and justifies the chosen geometrical design of the collective arms. Even when doing 90-degree turns, the object kept within the arms in the open position. The 45-degree angle in the framework facilitates the operations. One limitation of not having an integrated actuator was that no testing of a disposal operation where performed. While a "close-to-reality" test where completed by operating in an open position and trying to dispose of objects at a given location, this seemed doable.

13.6 Evaluation of final system design

The system proved its right, especially in terms of operations. Overall the provided design seems to be a sufficient proof-of-concept test. As mentioned, one major challenge for the autonomous operation was overshooting navigation. For most autonomous operations, these conditions were worse than what could be tolerated. It's agreed that the problem lies in the control system, which is specially adapted to the hull design of the Otter, and that adding elements that inflict on the water drag of the system would conflict with this adapted system. However, this is only an engineering task that Maritime Robotics could deal with when a final product is made.

The final design is an outcome of the requirements that were set. The provided design bases its operation on three developed operational states. It also showed that expanding the collection width of a USV is feasible and will greatly improve efficiency. Looking back at the computed capacity it can be seen a relatively low capacity at "closed-state". An early objective of the development was to utilize the area between the pontoons. This was only partly achieved, as the system do not fully retract between the pontoons during transport-state. In addition, it can be seen from the computation that the capacity changes quite dramatically depending on the state of the arms. At maximum capacity, the new system has four times the capacity of the first generation, but at the lowest, it's close to the same(in closed position). So when the system has such weak capability in the transport state (close position), one might argue that the system is not significantly better than its predecessor. Having a changing area might affect how objects handle within the system. One concern is that a fully-loaded system will start to lose objects since they are pushed underneath the system. It is clear that a more robust prototype, with an actuator integrated would be needed to declare these uncertainties. The lack of a more fitting implemented system can be said to limit the final result of the development process.

In addition to a subjective influence on the project, have also other stakeholders (primarily Clean Sea Solutions) had their influence on the project. Clean Sea uttered a wish for a design proposal that rather would be limited in terms of complexity in favor of having a higher TRL on the proposed product. In terms of academic research, one might argue that rushed decisions pushed by stakeholders are not a good approach. It's believed that the project found a middle way through its focus on developing the best potential design for the given case. Given the state of the Aquadrone v1, it is difficult to give an estimation of the TRL prior to this project. If focusing solely on the subsystem, would maybe a TRL 4 (validated technology) be a fitting level. The current status is on the other hand lifted many levels. Both a proof-of-concept and a full-scale prototype are tested under realistic conditions. From this, it's clear that the system is now closer to a 7(full-scale prototype tested under real conditions) [6].

Given the further development provided by Clean Sea Solutions, the TRL might even be increased to a TRL of 8.Only a short month after the first testing had CSS built a new iteration. It's obvious that the design has had its influence on this external development process, also proving the benefit of doing the testing. For the next iteration, CSS focused on developing a model that would work in the long term. This was done by using thicker dimensioned PE plastic, welding, and stronger dimensions slider, midframe, hinges, etc. Clear similarities in design geometry and dimensions between the two prototypes can undoubtedly be observed.

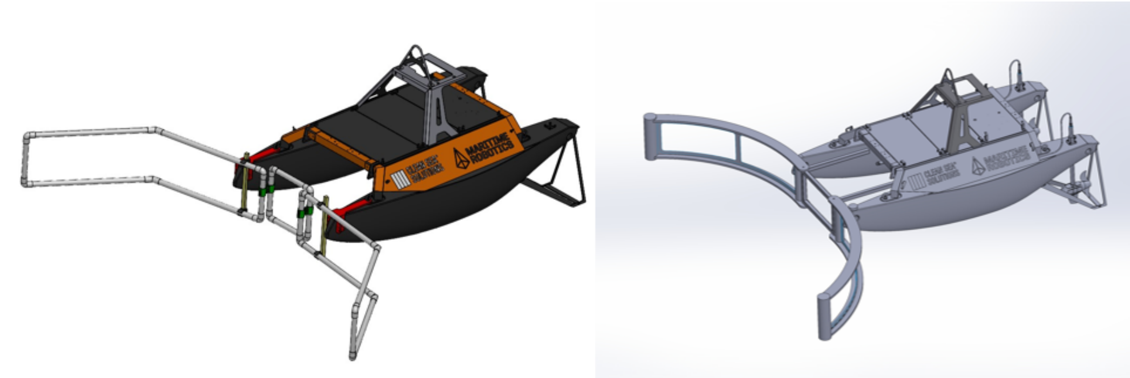


Figure 68: Some obvious similarities can be spotted between the designs, first functional prototype(left), further engineered by CSS (right)

Looking at the similarities between the two iterations, one might argue that it was unnecessary to develop all the subsystems during this project. Most of the subsystems, such as the sliding mechanism, mid-frame, and revolute joints, have been completely renewed. A counterargument is that this project actually defined these subsystems through research. Meaning this project facilitated the work that now is further engineered by CSS. Regardless of this, further detailing of the design will still be required to ensure the requirements set for the project.

14 Contribution and implications of study

Based on the nature of the study and the final outcome its sensible to conclude that strategies from both SBCE and stage-gates models can be combined to benefit case studies that are constrained in terms of time and workforce. Combining this approach with modern prototyping approaches such as additive manufacturing and CAD tools allows for a practical exploration of a product development process while addressing real-world issues. The approach shows that real-life development, prototyping, and testing in some PD cases can be superior to the newer techniques concerning simulation in software. The approach also proves that modern tools can be utilized to obtain lean values, such as limiting rework and maximizing the value of the final outcome. It is not inconceivable that this method could have been feasible in similar physical PD case studies.

This case study concludes with a final geometrical design that can be considered to be an innovative solution, without corresponding similarities to other projects. While the system without a doubt still is affected by many weaknesses, the proposed design offers guidance on a geometric solution that favors low complexity with desired mechanical capabilities. It further suggests appropriate dimensions and details affecting different subsystems. Even though not fully developed, it offers insight into viable designs. This project's contributions primarily include an innovative waste collection solution using Unmanned Surface Vessels (USVs), addressing current technological gaps, and proposing ways to enhance efficiency. The impact of these contributions can hopefully be used to improve waste management and environmental sustainability.

The development has defined a new proposal of operation, that divides the operation into; Collection, transport, and disposal. All of which are states that the USV can change between. This allows for more agile and optimized operations that should benefit the USV way of working. The design provided has capacity in terms of storage and collective width many times the previous version and similar projects. The proposed design facilitates further development of the autonomous system. This capability of collection and disposal in one motion is one of the decisive features that distinguishes the concept from similar projects. While also providing this, it also keeps complexity low.

Although it is complicated to evaluate the project based on a TRL scale, one can give an estimate based on the start-end point. By focusing only on waste collective systems, it is not inconceivable that the TRL has been raised several levels. Given Clean Sea Solutions' further development based on this design, it's evident that the conceptual design has significantly contributed to technological advancements.

PART VI

CONCLUSION

15 Conclusion of report

This thesis, centered on the development of a mechanical subsystem for a given USV, provides a recommendation for a geometrical design. Although the conceptual proposal may appear straightforward at first glance, the implementation of the study reveals complexity and significance that exceed initial impressions.

The PD method involved a hybrid approach that fused elements from Set-Based Concurrent Engineering and the traditional stage-gate model. In particular, the unique nature of the study revealed the complexities involved in formulating a fitting PD approach. The methodology of the study encompassed both qualitative and quantitative data collection, with an emphasis on real-world testing. Given the numerous unpredictable requirements and variables, a decision was made to both include digital and physical prototyping. This led to a more practical approach of rapid prototyping, mock-up building, and real-life testing. It's evident that this approach has substantially advanced the outcome of the product development process.

The insights obtained from this case study suggest that the conceptual proposal is an innovative geometric design that uniquely provides a method for waste collection using USVs. The result introduces a new solution with the potential for increasing efficiency and effectiveness in waste management. While there are areas for further refinement, the design's potential is underscored by its versatility and simplicity, maintaining low complexity while meeting the technical requirements. The provided design has proven to be more efficient and agile than similar projects. The dynamical system provides different operational states that allow for more flexible operations, as well as facilitates further autonomous operations. For the successful deployment of such a system, advancements are required in areas like collision avoidance, path-planning algorithms, and other operational-sensitive systems.

The findings of this thesis have far-reaching implications beyond the immediate scope of product development and waste management. The research contributes to broader insights into technical solutions for environmental challenges. Further, it acts as a springboard for future advancements in the field of autonomous systems and product development. As we move forward with technological advancement, the knowledge and solutions derived from this project will hopefully continue to hold significant value. This project could serve as a platform for further studies, technological advancements, and innovative solutions in environmental sustainability and product development processes.

16 Further work

As stated in the methodology chapter in figure 15, this case study is only covering a part of the development of an autonomous collection USV. Looking only at the mechanical waste-collective system, there still are processes that must be completed before the project has reached a sufficient TRL. As mentioned, the thesis concludes with a design geometry that can sufficiently cover the raised requirements. The end product, however, is not ready to be implemented for real-life applications yet. A list of technology gaps must be filled before a fully-working collective system is operational. Despite the fact that CSS has started "further work", it was considered useful to propose further development of the project. As one can see, CSS has already started development on several of these points.

- Decide on a new framework material (or the same but bigger dimensions), preferably plastics or metal. Design the connection of the framework in a way that it benefits the joining of the framework. Metal or plastic welding is advised.
- Design and detail more durable subsystems that are better suited for the application. This applies especially to the slider, hinges, joints, connection between the system and USV, etc.
- Provide a sufficient linear actuator, with feedback control. This actuator must be implemented into the navigation and operation software.

Proposal of further application areas of proposed design

As stated in the introduction, assessing other potential applications for this system was a desirable goal. While not yet addressed, this consideration certainly influenced the development process. Advocating for a modular design that allows easy changes to the net/filter was crucial for catering to various applications. Several application ideas have emerged throughout the project. The following is presented merely as inspiration for potential project development and to increase the substantial impacts:

- Chemical spill control
- Waste monitoring
- Search and rescue operations
- Biomass gathering (kelp and algae)

In any case, it will be exciting to see which way Clean Sea Solutions chooses to take this project in the future.

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Appendix

A Python scripts for computation

File - C:\Users\mathi\PycharmProjects\Master_Thesis\Collective capacity.py

```
import numpy as np
import matplotlib.pyplot as plt
# Aquadrone v1 collective capacity
Width = 524
length = 715
area_v1 = (Width*length)/10**6
#v2.1 Area computation
#Links
link_1 = 250
link_2 = 750
link_3 = 500
def area(alpha,beta,link_1,link_2,link_3):
    alpha_1 = alpha - 90
    beta_1 = 90 - alpha_1
    alpha_1r = np.radians(alpha_1)
    beta_2r = np.radians(beta - beta_1)
    A1 = link_1 * (np.cos(alpha_1r) * link_2)
    A2 = ((np.cos(alpha_1r) * link_2) * (np.sin(alpha_1r) * link_2)) / 2
    A3 = np.absolute(((np.cos(beta_2r) * link_3) * (np.sin(beta_2r) * link_3)) / 2)
    A4 = (link_1 + (np.sin(alpha_1r) * link_2) - (np.cos(beta_2r) * link_3)) * (np.sin(beta_2r) * link_3)
    A = (A1+A2+A3+A4)*2
    A = A/10**6
    return A
beta_row =  np.array([100,110,120,130,135,150,160,170])
alpha_row = x = np.linspace(90, 180, 91)
lists = [[] for i in range(len(alpha_row))]
areal = np.array([])
volume_list = np.array([])
for i in range(len(alpha_row)):
    volume_list = np.append(volume_list, area(alpha_row[i], 135, link_1, link_2, link_3))
    for j in range(len(beta_row)):
        areal = np.append(areal,area(alpha_row[i], beta_row[j],link_1,link_2,link_3))
    lists[i] = areal
    areal = np.array([])
plt.plot(alpha_row, volume_list, label="Capacity v2")
plt.axhline(y = area_v1, color = 'r', linestyle = '-', label="Capacity v1")
plt.ylabel('Capacity(square meter)')
plt.xlabel("alpha angle")
for i in range(0, len(alpha_row), 10):
    plt.plot(alpha_row[i], volume_list[i], 'ro')
    plt.text(alpha_row[i], volume_list[i], f'{volume_list[i]:.2f}',
             fontsize=8, verticalalignment='bottom', horizontalalignment='left')
plt.text(plt.xlim()[1] * 0.95, area_v1, f'{area_v1:.2f}', fontsize=8,verticalalignment='bottom',
horizontalalignment='right')
plt.title("Capacity with 135 degree beta angel")
plt.legend()
plt.grid()
plt.show()
for beta_value in beta_row:
    volume_list_beta = np.array([area(alpha_value, beta_value, link_1, link_2, link_3) for alpha_value in
alpha_row])
    plt.plot(alpha_row, volume_list_beta, label=f'Beta: {beta_value}')
plt.axhline(y = area_v1, color = 'r', linestyle = '-', label="Capacity v1")
plt.ylabel('Area (square meters)')
plt.xlabel("Alpha angle")
plt.title("Capacity with different beta degrees")
plt.legend(loc='upper left', fontsize='small')
plt.grid()
plt.show()
```

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Figure 69: Area capacity computation

File - C:\Users\mathi\PycharmProjects\Master_Thesis\Width capacity.py

```python
import numpy as np
import matplotlib.pyplot as plt
# Aquadrone v1 collective capacity
Width = 524

#v2.1 Area computation
#Links
link_1 = 265
link_2 = 750
link_3 = 500

def area(alpha,beta,link_1,link_2,link_3):
    Width_1 = link_1
    Width_2  = np.sin(np.radians(alpha-90))*link_2
    Width_3 = -np.cos(np.radians(beta+alpha - 180)) * link_3
    Total_width = (Width_1 + Width_2 + Width_3)*2
    if Total_width < 0:
        Total_width=0
    return Total_width

beta_row =  np.array([100,110,120,130,135,150,160,170])
alpha_row = x = np.linspace(90, 180, 91)
volume_list = np.array([])

for i in range(len(alpha_row)):
    volume_list = np.append(volume_list, area(alpha_row[i], 135, link_1, link_2, link_3))


plt.plot(alpha_row, volume_list, label="Width v2")
plt.axhline(y = Width, color = 'r', linestyle = '-', label="Width v1")
plt.ylabel('Width (millimeter)')
plt.xlabel("alpha angle")
for i in range(0, len(alpha_row), 10):
    plt.plot(alpha_row[i], volume_list[i], 'ro')
    plt.text(alpha_row[i], volume_list[i], f'{volume_list[i]:.2f}',
             fontsize=8, verticalalignment='bottom', horizontalalignment='left')
# Display Y-value for the Area V1 Line
plt.text(plt.xlim()[1] * 0.95, Width, f'{Width:.2f}', fontsize=8,
         verticalalignment='bottom', horizontalalignment='right')
plt.legend()
plt.grid()
plt.title("Width with 135 degree beta")
plt.show()

for beta_value in beta_row:
    volume_list_beta = np.array([area(alpha_value, beta_value, link_1, link_2, link_3) for alpha_value in alpha_row])
    plt.plot(alpha_row, volume_list_beta, label=f'Beta: {beta_value}')
plt.axhline(y = Width, color = 'r', linestyle = '-', label="Width v1")
plt.ylabel('Width (millimeters')
plt.xlabel("Alpha angle")
plt.title("Width with different beta degrees")

# Add legend and grid
plt.legend(loc='upper left', fontsize='small')
plt.grid()

plt.show()
```

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Figure 70: width capacity computation

B Subsystem list for final prototype

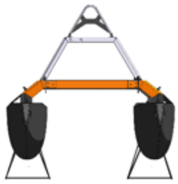
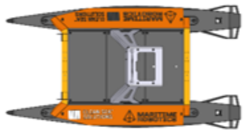
Part. No	1.A - USV
Name	The Otter
Function	Existing system covering both prupolsion, controll system and navigation.
Source?	Maritime Robotics
LINK	https://www.maritimerobotics.com/
Design process	Pre-made
Quantity	1 stk
Illustrations	  
Description	Assumed a standarized dimensioned Otter
Sufficent?	

Figure 71: The USV

Part. No	3.A	3.B
Name	Frame	Frame joints
Function	To hold the filter in the right position a frame must be connected to the filter/net.	The frame will contain corners and angels. How is these connected?
Source?	Biltema	Biltema
LINK	https://www.biltema.no/bygg/vvs/rorinstallasjoner/avlopsror/pp-ror-32-mm-2000051669	https://www.biltema.no/bygg/vvs/rorinstallasjoner/avlopsror/bend-med-gummitetning-90-2-muffer-2000018594 https://www.biltema.no/bygg/vvs/rorinstallasjoner/avlopsror/bend-med-gummitetning-45-2-muffer-2000051541
Design process?	Cut to right size	
Quantity	>8m	16stk
Illustrations	 	 
Description	Tube Ø32 mm, up to 2000mm in length (more than sufficent). Not extremely strong.	90/45 deegree 32mm tube
Sufficent?		

Figure 72: The framework

Part. No	2.A/2.B
Name	Net/filter
Function	To remove waste from water, a filter net is pushed through the water. Water goes through and waste stays trapped in the fitler.
Source	Divershop/Biltema
LINK	https://www.dykkershop.no/produkt/fangstnett-mesh-gronn-xl-m-d-ring/ https://www.biltema.no/bygg/vvs/ventilasjon/ventilasjonsventiler/insektnett-2000031340
Design process	
Quantity	3m * 0.5 m * 2
Illustrations	
Description	2.A Diving net 8 mm mesh sewed plastic 2.B Construction 1.5mm mesh (PE-plastic threads)
Sufficent?	

Figure 73: Net

Part. No	6.A	6.B
Name	Revolute joint-Frame	Revolute hinge
Function	Joint between link 1 and 2 (both sides), as well as for the actuator	Actual hinge between the two links. Same hinge use for the actuator.
Source?	3D-Print	Biltema
LINK		https://www.biltema.no/bygg/hengsler/loftehengsler/loftehengsler-hoyre-50-mm-2-stk-2000051967
Design process		
Quantity		4
Illustrations		
Description	Goes around the 32mm tube which can be tightened using screws. On the other side an opening where a hinge can be mounted (6.B)	An revolute hinge providing rotation around one axis. Galvanized but not suited for long term appliaction. Questionable durability and strength. Also had some slack, later on creating a unstable system.
Sufficent?	Works well, tight and solid	No

Figure 74: Joint

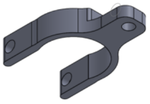
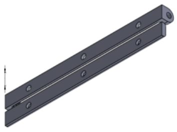
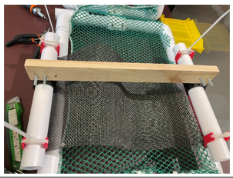
Part. No	5.A	5.B
Name	Filter-to-frame connection detacable	Filter/frame connection detacable
Function	A demand for a detachable connection between filter and frame. As well as a conneciton that do not circumize the frame-tube. A mandatory design to make the slider work. Also test possibilties of modular net design.	A evenly distributed tightened plate to hold the net. This was made to make the slider work without conflicting with the net connection.
Source?	3D-Print	3D-Print
LINK		
Design process?		
Quantity	4 stk	Missing a few lengths. 2 of 8 pieces.
Illustrations	  	 
Description	A easy to attach an deatch component that can be tightened to lock both for sliding and rotating. Good desing but too weak(see picture of broken part).	200 mm long connections. Ideally should be 400mm+. Limitations of 3D printer only 200mm.
Sufficent?		Should be longer.

Figure 75: Net connection

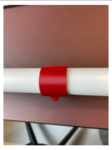
Part. No	7.A	7.B
Name	Slider	Slider-to-slider connection
Function	Along link 2 there is a need for a slider. Slider along 32 mm tube.	The two sliders must be connected so they can move parallell. A pin/rod is connected between the two sliders. 320mm long.
Source	3D-print	Wood
LINK		
Design process		
Quantity		
Illustrations	  	 
Description	Tube that goes outside of the frametube. With a small clearance to make it slide. The brack connection is to weak. Must iterrate a new one. New model har thicker walls, more strength. Large opening in fron to avvoid collision with 5.B2. Also added bracket to connect 8.A. Issues with slider getting stuck when not percetly perpendicular.	Connector would be 400 mm, 3D printing is therefore discluded. In a need of a strong, customable and light part, wood is considered as a V1 model. Holes are drilled to allow for height adjustment
Sufficent?	Only temporary	Only temporary

Figure 76: Slider

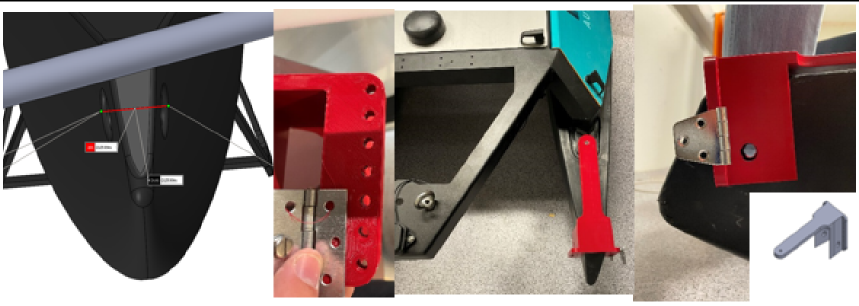
Part. No	8.A Adapter between collective system and Otter
Name	Otter adapter
Function	To connect the collective system to the Otter an specialized connector must be made to avoid drilling any holes in the pontoons
Source?	3D-print
LINK	
Design process?	
Quantity	2
Illustrations	
Description	A 3D modell is made. First iteration had holes for the hinges misplaced. Second model is fixed. The model fits good. With adaptable height adjustments. Part is also only fixed in two positions. Making it easy to connect and disconnect the system. Concerns about strength in part.
Sufficent?	

Figure 77: Adapter between systems

Part. No	11.A - Joining method	11.B - Joining method
Name	Bolts and nuts	Plastic strips
Function	All above mentioned connection must fastened and tighten using an effective an reversible mechanism.	To connect the filter to the frame. Should be easy to connect and deconnect
Source?	Biltema	Biltema
LINK	https://www.biltema.no/bygg/festeelementer/bolter/skrue--og-muttersett-125-deler-2000051316	https://www.biltema.no/bil---mc/elektrisk-anlegg/strips/strips-36x140-hvite-2000046010
Design process?		
Quantity	Enough	Enough
Illustrations		
Description	From function description, theres is obvious that using bolts and nuts is a applicable method for covering the function demand. Nuts and bolts M6-M8. Not sufficently corrosive restiante	Strips 150-mm
Sufficent?	Only tempoary solution	Only tempoary solution

Figure 78: Joining method

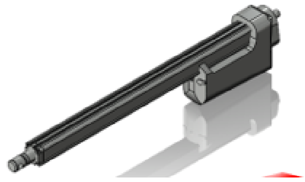
Part. No	12.A - Actuator
Name	Linear actuator
Function	To provide sufficent fucntional requirments, the system must be actuated using an actuator. Can be pneumatic, hydraulic or electric.
Source?	Order from LINAK
LINK	https://www.linak.no/produkter/lineaere-aktuatorer/
Design process	
Quantity	0 out of 1
Illustrations	
Description	A linear actuator seems to be most feasible for such a application area. Estimated stroke length: 400-600mm. Feedback control. 12 volt, power supply. Force: Unknown
Sufficent?	

Figure 79: Actuator

C Mechanical drawings - subsystems

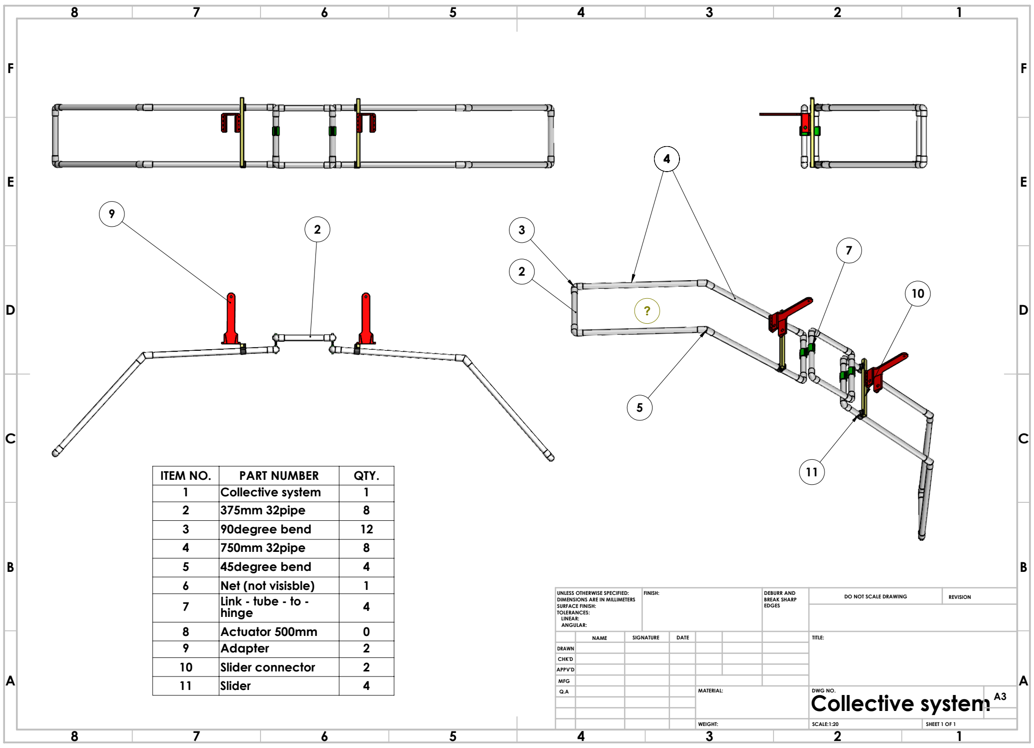


Figure 80: Collective system with BOM

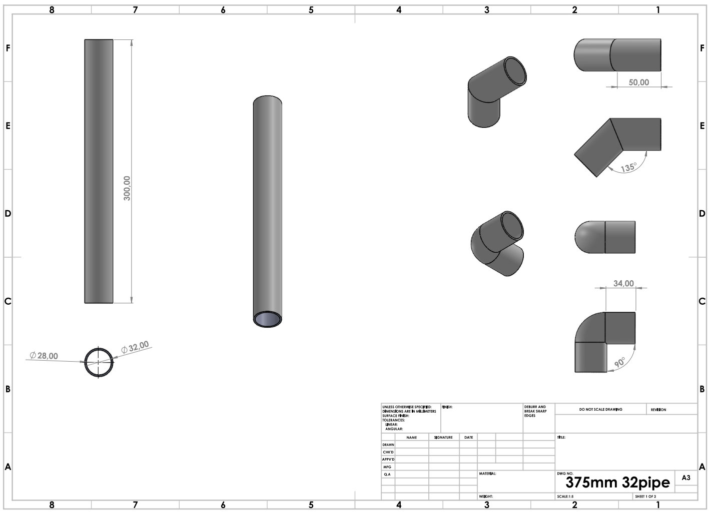


Figure 81: Tubes and joints used for framework

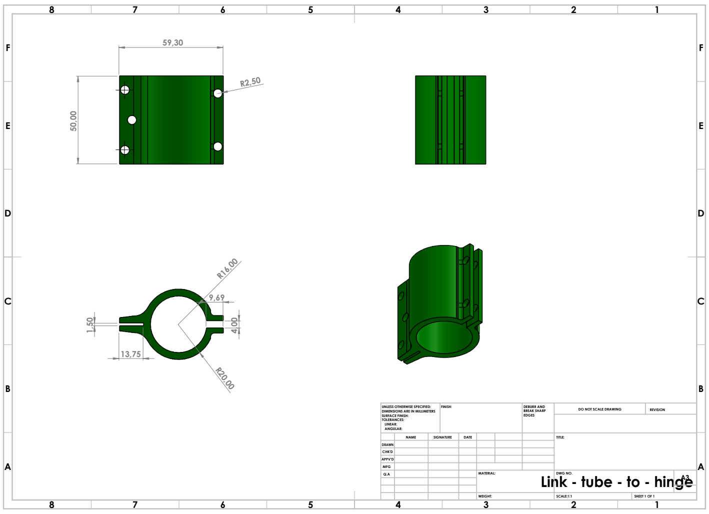


Figure 82: Link-tube

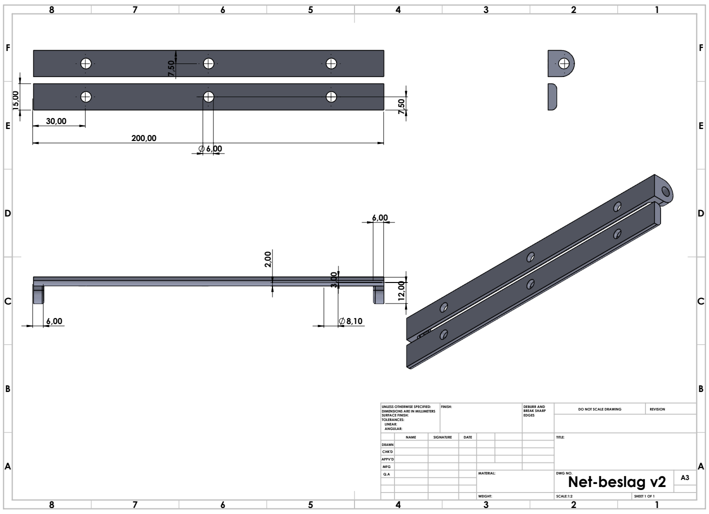


Figure 83: Net-holder

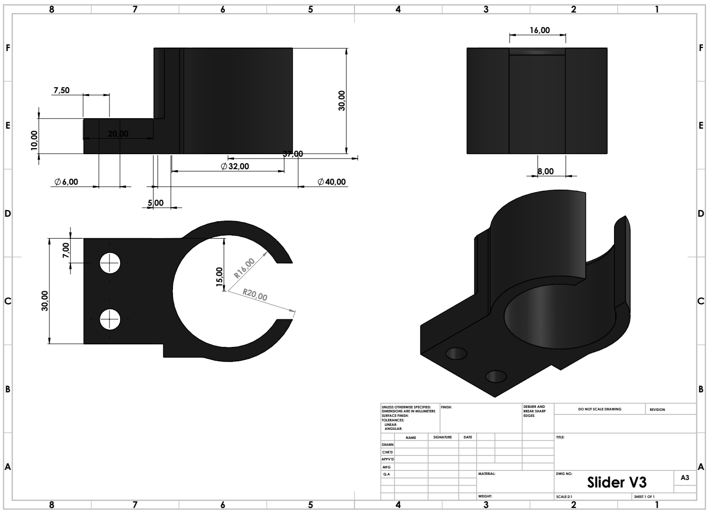


Figure 84: Slider

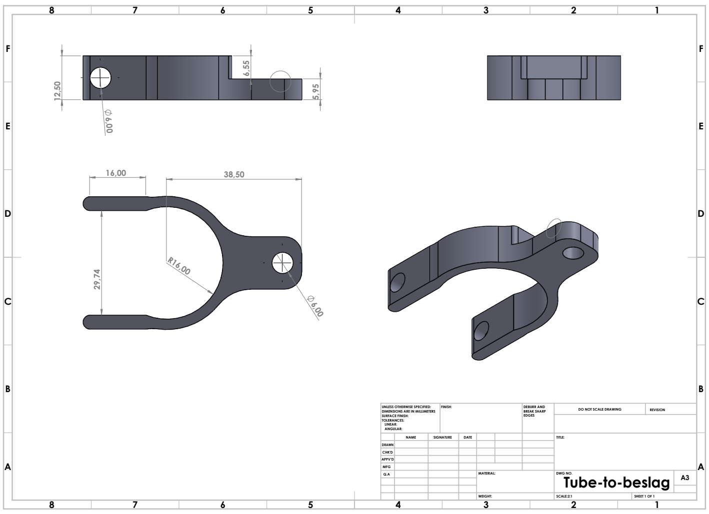


Figure 85: Connection between hinge and tube

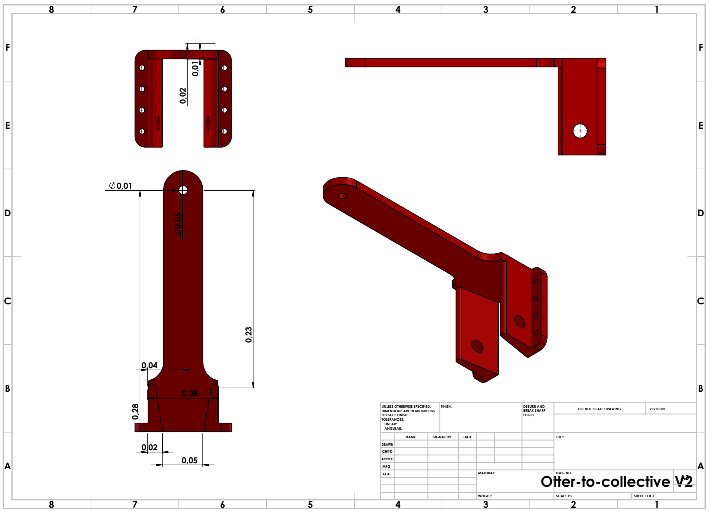


Figure 86: Connection between the Otter and collective system

D The Otter technical drawings

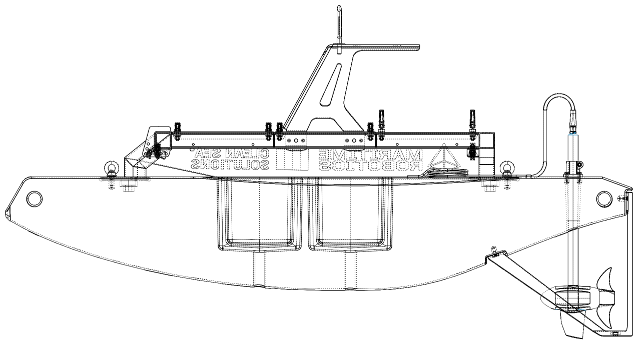


Figure 87: The Otter - see through

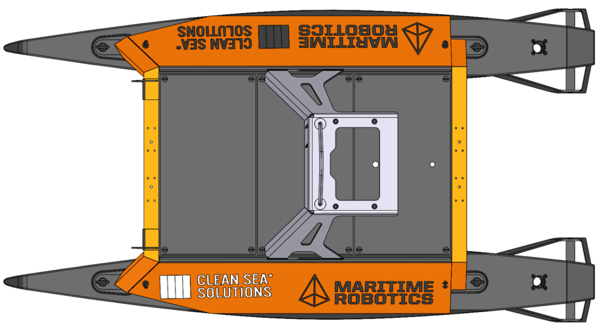


Figure 88: The Otter top-view

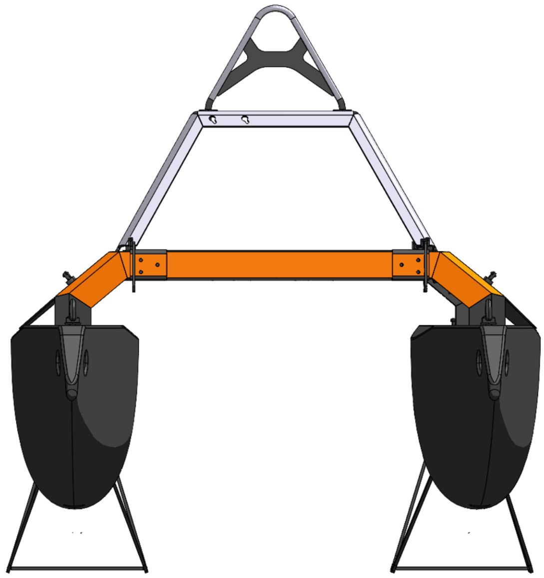


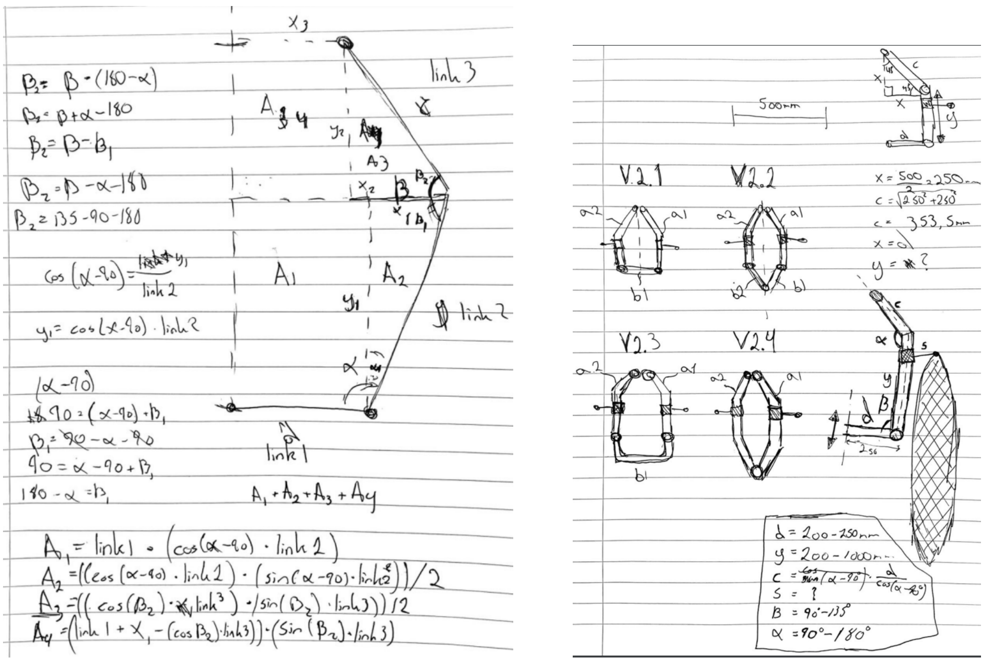
Figure 89: The Otter front-view

Figure 90: The otter 3D-view

E Testplan

Test no.	1	2.A	2.B	3.A	3.B	4.A
Set-up	1. Without any parts mounted	8mm mesh attached **closed-postion**	8mm mesh attached **open-position**	1.5 mm mesh attached **closed-postion**	1.5 mm mesh attached **open-postion**	1.5 mm mesh attached **open-postion**
Action (adaptation to otter)	Nothing	Attach Collective system	Open the collective arms and locking in open position	Connect the smaler net.	Open the collective arms and locking in open position	
Test hypothesis	There is a need for a baseline test to document any underlying errors that will be present, independent of the collective syste.	The collective system was unproblematic to attach. The right measurments was done. However there was some miscalculations on the width link 1. Which made it impossible to slide in the right area along link 2. This was solved by rotating the hinges between link1 and link 2.	For the next test the collective arms was opened to a maximum position of about 2.5 meter in width. There was some stability issues that where solved with some ropes.	As mentioned some adaptation was done, due to experience from last test. The tubes where glued, additonal hinges for more strength. The new net was also connected more consise and accurate.	Open the arms.TH	Test the strength of the system. High speed and advanced operations
Orientation in water (still)	Good, a little backwards tilted	Very satisfing orientation. Closed\ to horizontal. With possibly a few degrees backwards tilt.	Orientation still good. Better than in the closed positon, likely since the buoancy in the frame is moved closer to center of buoancy.	Same as test 2.A	Same as test 2.B	Same as test 2.B
Navigation	Close to perfect square. Cut corners to smoothen out route. Some errors, which can be considered due to environmental and control system errors (out of our ocntrol) .	Point to point was perfomed twice in a row, with GPS tracker. It can be observed that the USV tend to overshoot more now. Therefore ends up moving as pending sinus graph.	It was expected a lot of drag in this test scenario. Which it also was. The collective system was bent inwards in the lower part(submerged). Creating some misshaping of the whole structure. At the same time, was the GPS pattern not in particuler worse.	As expected to route was followed with additional overshooting issues as seen in plots.	As expected to route was followed with additional overshooting issues as seen in plots.	The resulting forces on the collective arems where too much for the systen. Causing the arms to shoot downwards, bendning the system.
Comment	Good reference test, also proves that there are some underlying errors which should be subtracted from test results.	Good test. Satisfiying orientation and stability, as well as net height in water (about 5-10 cm submerged) . The issue with overshooting was expected, and did not occur more than feared.	Satisfing test. Orientation and stability is still not any issue. The issue witrh drag have however apperead to a greater extent. Weaknesses in the construction have appeared. Particulary in the joint between linke 1 and 2, and in the hinge between the Otteradapter and the slider. To solve this an additional hinge was added for more strength between adapter and slider.	Completely different result when scaling down to a small meshed net. The observed forces where significantly higher	Same as 3.A, but now even a bigger concern. . Had to regulate throttle to not destroy the system.	Speeding up the USV showed the weakness of the tubular framework Not sufficent.
Techincal Set-up and issues	Unproblematic.	Unproblematic, but with tendecies of overshooting, du to delay in system.	Turn was doable, but the inertia of the arms in the water created what seemed to be a high momentum in the links between 1 and 2.	Okei setup, but the applied forces had it's toll on the system.	Easy to observe the weakness. Now it was also easy to obsverve the issues of not having a defined system .	Rotating tubes, causing the system to bend out of place. Clearly a weak point in the joints.

Figure 91: Initial test-plan and first observations during testing



(a) Front-side construction (b) Conceptual brainstorming

Figure 92: Conceptual brainstorming

F Conceptual drawing

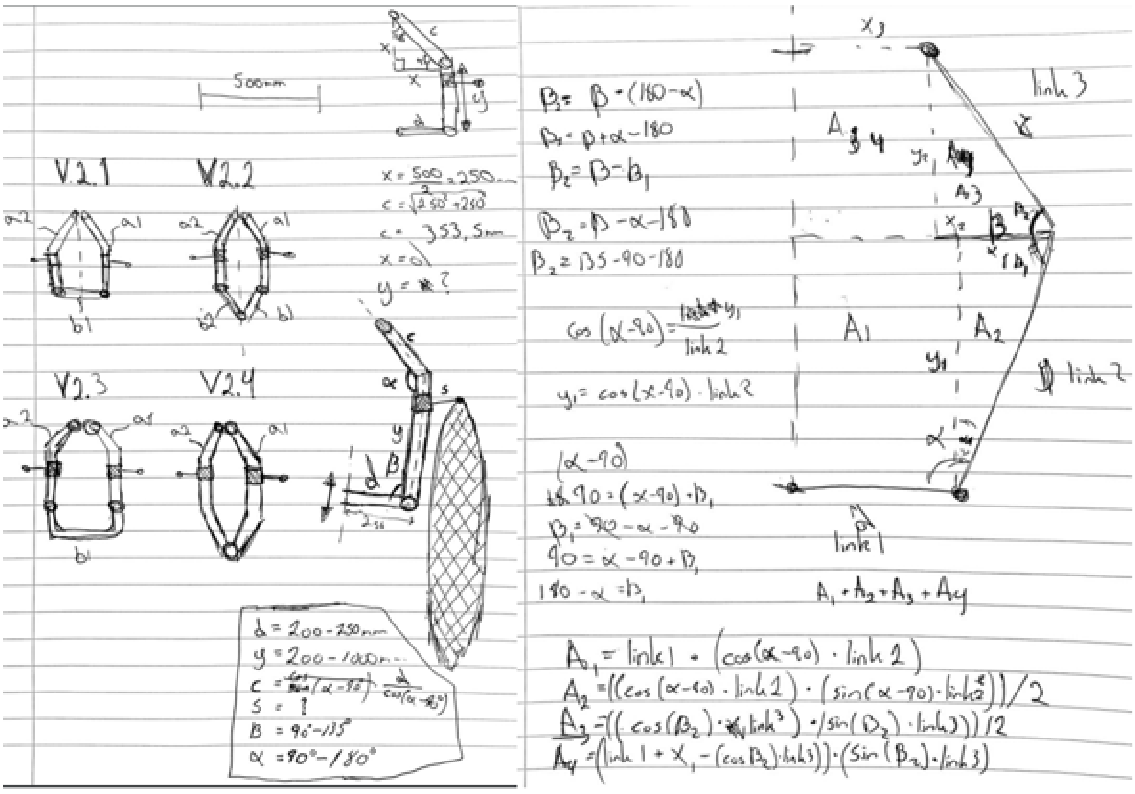
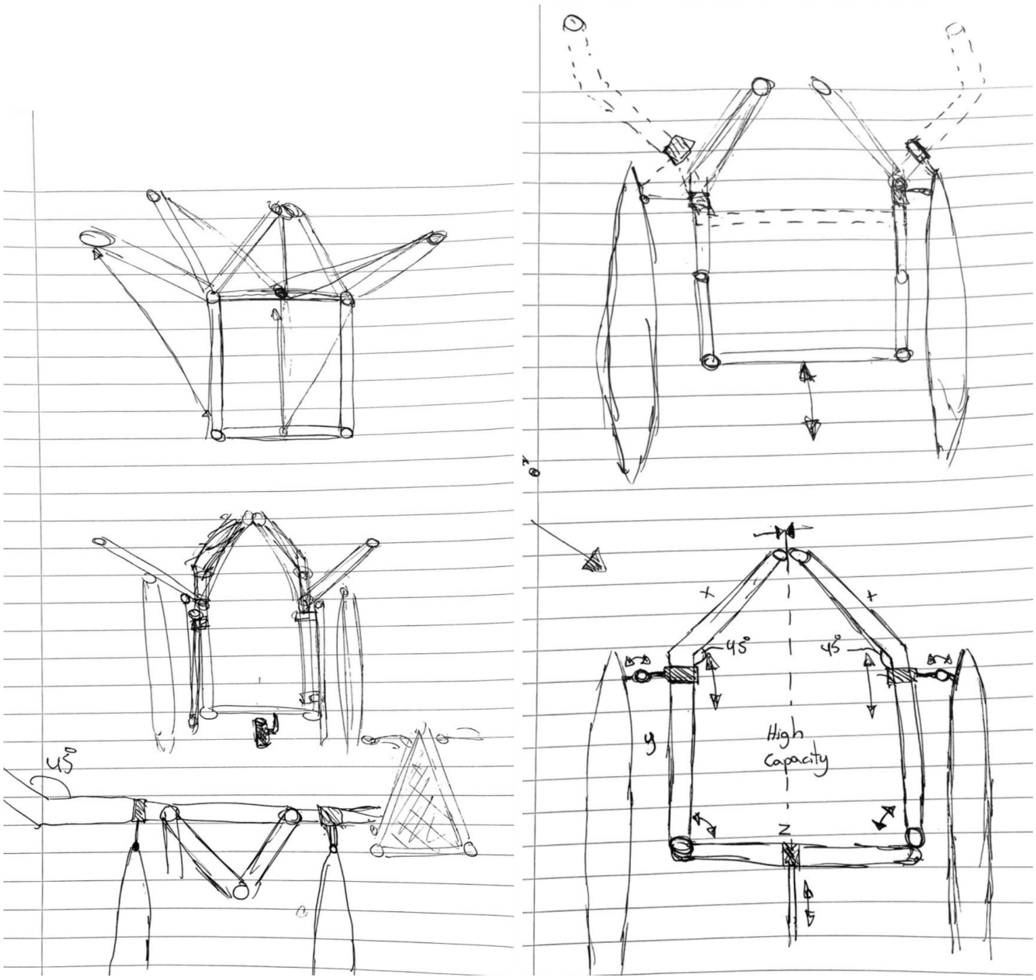


Figure 94: Early phase performance computing



(a) Front-side construction (b) Conceptual brainstorming

Figure 93: Conceptual brainstorming

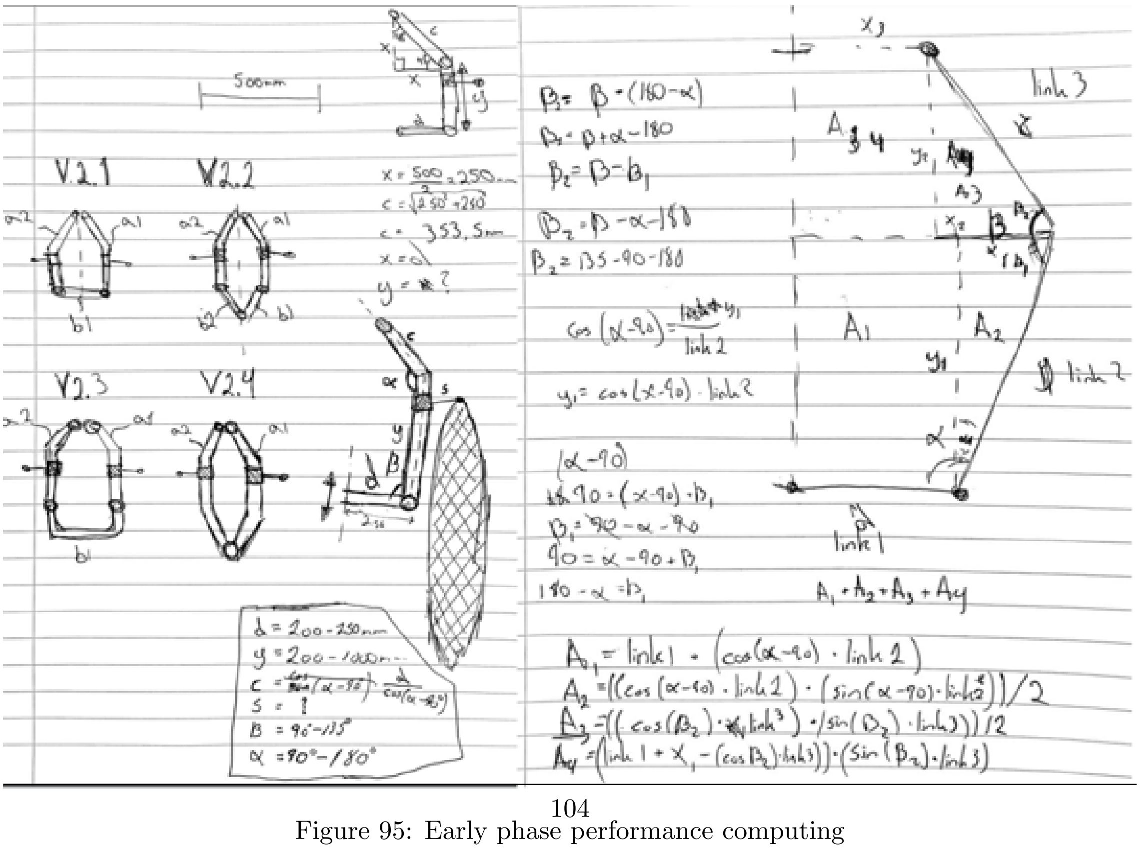


Figure 95: Early phase performance computing

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