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MMA4002 - Automated Manufacturing

Design of a product for automatic manufacturing

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Date

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1 Introduction

1.1 Background

In recent years, advancements in automated manufacturing and 3D printing have unlocked new possibilities for creating specialized equipment for diverse applications. One such application is underwater sample collection, where the need for durable, customizable, and pressure-resistant containers is essential for gathering samples such as seabed sediments, water, minerals, corals, and other marine organisms. This project focuses on the design and automated production of 3D-printed containers and bracket, specifically engineered for undersea sample collection. Our goal is to develop containers that can meet the diverse and stringent requirements of marine research and industrial sampling operations, offering a flexible and modular solution tailored to customer needs.

1.2 Objective

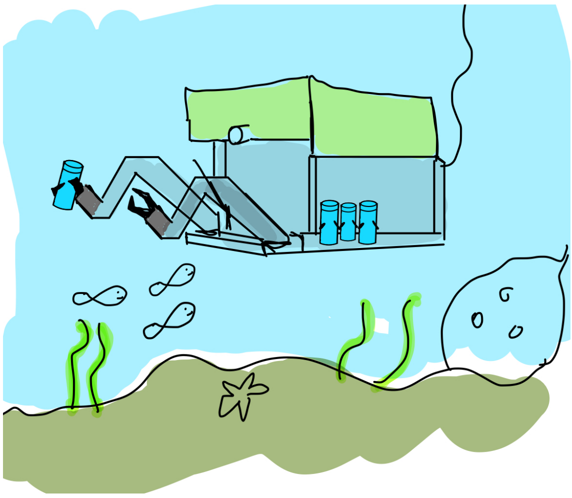


Figure 1: Concept drawing of underwater sampling using ROV

The primary objective of this project is to design a 3D-printed container system that can be automatically manufactured and assembled for use in undersea sample collection as illustrated in Figure 1. This system will address various environmental and operational challenges, such as high-pressure conditions at different ocean depths, material durability, and underwater turbulence. The design will allow customers to specify the container size, intended sampling purpose, and other preferences, such as lid and clip variants, which will be translated into automated 3D printing and robotic assembly.

Key design elements include:

1. **Pressure Resistance**: Containers will be designed to withstand varying pressure levels, depending on the sampling depth.
2. **Customization**: The container system will be adaptable, offering different sizes, cross sections and lid options, with universal clip sizes for ease of use.
3. **Bracket and Mount Design**: A bracket will be integrated to allow secure attachment of the containers during sampling. During the project, three different clip variants will be evaluated to determine the optimal clip for a finished product.

Key Challenges

1. **Material Selection**: One of the most critical aspects of the design process is selecting materials that can withstand the harsh undersea environment. This includes resisting corrosion, pressure variations, and underwater currents, while also maintaining the integrity of the seal for reliable sample collection.
2. **Pressure Resistance and Seal Integrity**: The design must ensure that the containers can endure the increasing water pressure at various depths, and the sealing mechanisms (lid and clip variants) must prevent water leakage while maintaining ease of operation for divers or robotic manipulators.
3. **Ease of Operation**: The containers should be user-friendly, particularly for automated handling or for use in challenging environments where human interaction is minimal.
4. **Customization and Manufacturing**: A key feature of the project is the ability to customize container size, cross-section, and functionality, and to integrate these customizable designs into an automated manufacturing workflow.
5. **Automation and Lean Manufacturing**: Using collaborative robots for the assembly process ensures efficient, accurate production and lean engineering principles to minimize waste, enhance product quality, and streamline the production process. Additionally, an automated assembly process serves as validation that the product is sufficiently simple to handle, with regards to challenge nr 3.

1.3 Proposed Workflow

The manufacturing workflow for this project is built around a streamlined, fully automated process that leverages 3D printing and robotic assembly. The steps involved in this process include:

1. **Design Phase**: The project begins with a comprehensive design phase, where containers are conceptualized with the customer's specifications in mind. This phase includes initial sketches, computer-aided design (CAD) modeling, and simulation of the container's structural and pressure-bearing properties.
2. **Material Selection**: Based on environmental requirements such as underwater pressure and corrosion resistance, materials suitable for 3D printing are selected. Candidate materials include high-strength polymers and composite materials that can endure deep-sea conditions.
3. **Pressure Testing**: Once the design is finalized, calculations for pressure resistance are made based on the container's cross-section and material properties. These calculations help recommend safe operating depths for different container sizes and shapes.
4. **3D Model Prototyping**: A 3D model of the container is created and adjusted according to the depth, size, and application requirements. During this stage, the lid and clip designs are also prototyped to ensure easy operation and strong seal integrity.
5. **Prototyping and Optimization**: Physical prototypes are produced using 3D printing, allowing for real-world testing. Based on the results of these tests, the design may be optimized for strength, ease of use, and manufacturability.
6. **3D Printing**: The final design is sent to the 3D printer, which produces the containers based on the customer's specifications. The printing process will be closely monitored to ensure the quality and consistency of each component.
7. **Automated Assembly**: Collaborative robots (cobots) will be used to assemble the printed components, including attaching lids, clips, and brackets.
8. **Quality Control and Testing**: Each container will undergo rigorous quality checks, such as seal integrity validation, to ensure they meet the required standards for undersea use.
9. **Packaging and Delivery**: Once the containers pass all quality control stages, they will be packaged and prepared for delivery. The automated system will ensure that the customer's specifications are met, from size and design to packaging.

1.4 Envisioned final product

The final product for production and assembly will consist of the following:

- Bracket with three different clip variants
- Small container with unique clip, lid mechanic and wall thickness
- Medium container with unique clip, lid mechanic and wall thickness
- Bigger container with unique clip, lid mechanic and wall thickness

2 Theory

2.1 Industry 4.0

Industry 4.0 is characterized by the advanced digital techologies added into production systems. ([1]) The core concept of Industry 4.0 is automating and improving manufacturing processes. This is done by adding and integrating SMART factories using simulation, Internet of Things (IoT), cloud computing etc. The foundation of technologies of Industry 4.0 are depicted in Figure 2.

By introducing these technologies to automated manufacturing, aspects such as flexibility, efficiency and customization have improved drastically. By interfacing a SMART factory and making the machines communicate, optimizing production has become easier than ever.

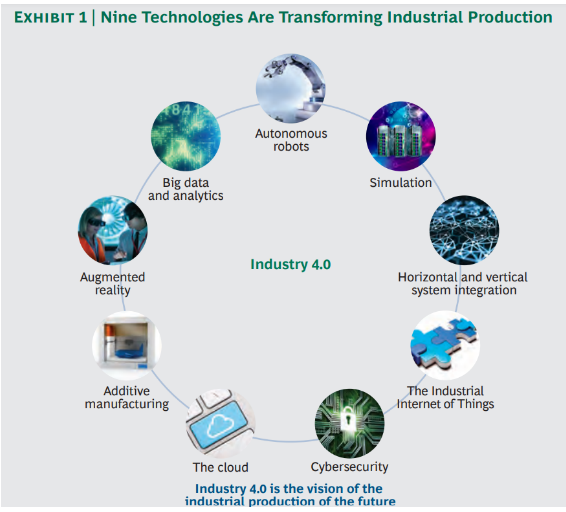


Figure 2: The foundational techonologies for Industry 4.0 (Source: [1])

2.1.1 Autonomous Robots

Robots have been used to tackle complex tasks in manufacturing for a long time, yet they are constantly evolving ([1]). By becoming more autonomous, flexible and cooperative, eventually they will be able to interact with each other and with humans. This will cut costs and offer more possibilities in regards to automated manufacturing. In ManuLab there are collaborative robots that can be useful in for example transportation and assembly of products.

2.1.2 Additive Manufacturing

Additive manufacturing such as 3D-printing is becoming more widespread in manufacturing organizations ([1]). They are mostly being used to prototype and produce individual components or small batches of products. Additive Manufacturing builds object from digital designs and offers a high degree of flexibility. and swift prototyping with less waste.

2.1.3 Simulation

Simulation is an essential tool in Industry 4.0, allowing manufacturers to digitally model products, processes, and systems before physical production ([1]). Simulation is primarily used to test and optimize designs, ensuring that the product performs as expected under different conditions.

2.1.4 Industrial Internet of Things

IIoT is widely used in manufacturing to monitor machine performance, track production progress, and ensure quality control ([1]). With IIoT, devices such as 3D printers and robots communicate with each other, allowing for automated workflows and predictive maintenance. This connectivity improves overall efficiency, reduces downtime, and provides greater control over the manufacturing process.

2.2 Industry 5.0

Industry 5.0 implements the foundations of Industry 4.0 in a collaborative environment that allows for humans to work alongside the robots in the manufacturing process ([3]). There are three core elements of Industry 5.0; **Human-centricity, sustainability and resilience**.

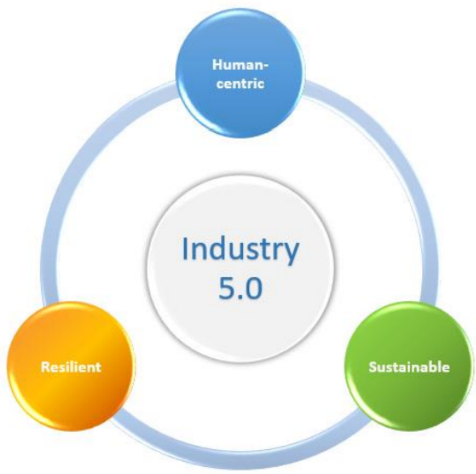


Figure 3: Illustration of main concepts of Industry 5.0. Source: ([3])

1. **Human-centricity** is the biggest difference between industry 4.0 and 5.0. The purpose is to utilize and enhance the skills of the workers. In industry 4.0, the workers are asked to adapt to the technology, while in industry 5.0 the technology is made to adapt to the workers needs.

2. Due to the ever-growing environmental struggles, the need for a **sustainable** industry is paramount. A circular process that re-uses, reproduces and recycles natural resources would end up reducing both waste and environmental impact.

3. **Resilience** refers to the need for industries to withstand disruptions. Recent episodes such as Covid-19 has highlighted the vulnerability of global supply chains. Industry 5.0 aims to balance the framework of these by improving synergies between advanced technologies and humans.

2.3 Lean Manufacturing

Lean is an approach used in manufacturing to minimize waste while maintaining quality. The principle of lean manufacturing was originally developed by Toyota in the mid 1900s. The primary goal for lean manufacturing is to create more value for customers with less resources.
The implementation of Lean is put in place by the four Ps, which are the foundation of the "Toyota way" ([5]):

1. **Philosophy**
   By implementing Lean manufacturing, you prioritize long-term over short-term success. Decision-making should reflect this and should be done with sustainable improvement in mind for the business, employees, customers and also society.
2. **Process**
   By designing a good process flow, you optimize your results. This is being done by:
   - Continous flow of materials and information
   - Eliminating waste (non-essential activities)
   - Implementing standards ensures efficiency and consistency
   - Quality checks prevents defects from reaching customer
3. **People and Partners**
   Lean Manufacturing is reliant on progress. Employees and processes should respect and challenge each other, and thus be under continous improvement (Kaizen). By implementing such incremental improvements in all phases of the organization, you ensure a sustainable future for your business.
4. **Problem Solving**
   By cultivating a learning culture where employees learn from their mistakes, you foster an environment of continuous improvement. This in combination with root cause analysis where you address the cause of a problem before making decisions and learning from them is a vital part of a lean organization. Techniques like "5 whys" and "Genchi Genbutsu" are central here.

By implementing these four Ps, you adapt to a Lean mindset which optimizes organizational and sustainable growth for businesses.

2.4 Design for Automated Assembly (DFAA)

Design for Automated Assembly is a practice of designing products in a way that optimizes assembly by automated machines or robots. By simplifying the assembly process while maintaining the quality and functionality of the product, you optimize this practice. Key principles to be implemented in DFAA: ([2], [6])

Table 1: Key principles in DFAA

Reduce Number of Parts	Unique Parts	Base Object	Design Base Object	Assembly Directions
Parallel Operations	Chain of Tolerances	Disassembly	Packaging	Sum

By following the DFAA principles, digital designs are optimized for automated assembly. This reduces both assembly time and cost of production.

2.5 Product Architecture

"Product architecture is the scheme by which the function of a product is allocated to physical components", [10]
There are four main types of product architecture;

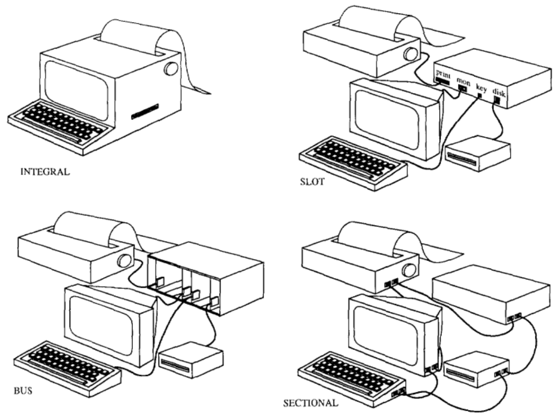


Figure 4: Four personal computer architectures, Source: ([10])

- **Integral Architecture** features an integrated system that is designed to perform at high performance but with limited flexibility.
- **Slot Architecture** has dedicated slots or spaces for products. An example of this is a desktop PC
- **Bus Architecture** features a common connection (bus) where all modules can easily be added, removed or replaced. An example of this is USB peripherals
- **Sectional Architecture** modules can be attached in multiple configurations, providing a great amount of flexibility. An example of this is LEGO blocks which can be used to create unique structures.

Modular architecture promote easier assembly and customization while integral architectures promote higher performance.
A well thought out product architecture is crucial to facilitate easier production.

3 Design

3.1 Concept

The concept is an underwater sampling container illustrated in Figure (5). The containers are designed with automated manufacturing and assembly in mind. Compared to other concepts, this solution offers several advantages; it is scalable, easy to handle, relatively cheap and adaptable. Additionally, it features a robot-friendly bracket and mount design, ensuring a smooth and efficient operation. The use of cost-efficient material and automated manufacturing makes the concept a more affordable alternative to other sampling containers.

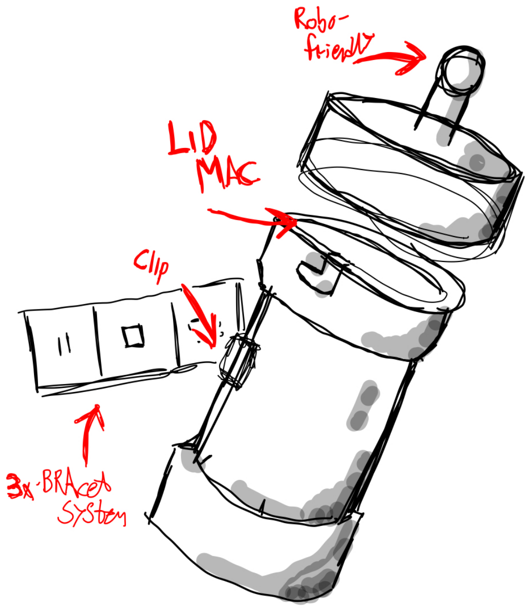


Figure 5: Concept sketch of underwater sampling container (right) and bracket design (left)

The sampling container consist of a top lid that is designed with a top handle with a twist opening mechanism and a sealing. This makes the lid easy to operate and properly sealed when closed. The container body that can be delivered in various sizes with the option for three bracket systems, and the ability to operate in different depths based on customer need.

3.2 Material

3.2.1 Choosing the material

In selecting the appropriate material for the underwater sampling containers, several factors were considered, including ease of printing, cost, availability, and performance under underwater conditions. The following materials are evaluated and given in Table 2.
([7],[8], [9], [11])

Table 2: Comparison of 3D Printing Materials: Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG), and Nylon

Material	Properties	Advantages	Disadvantages
PLA	Biodegradable, easy to print, moderate tensile strength, smooth finish	Eco-friendly, user-friendly, cost-effective, easily available	Low heat resistance, less durable, absorbs moisture
ABS	High impact resistance, higher heat resistance, matte finish	Strong and durable, good heat resistance, easy post-processing	Requires heated bed, emits fumes, non-biodegradable
PETG	High strength, flexible, chemical resistant	Durable, easy to print, resistant to chemicals	Can produce stringing, more expensive, adhesion issues
Nylon	Very high tensile strength, flexible, excellent wear resistance	Ideal for functional parts, durable, chemical resistant	Requires high printing temperatures, absorbs moisture, expensive

PLA was chosen for prototyping due to its ease of printing, cost-effectiveness, and adequate strength for moderate underwater applications. The availability of PLA also makes it a practical choice for development stages. **However**, PETG may be considered for the actual product due to its higher strength, durability, and better chemical resistance, making it more suitable for long-term use in underwater environments. Detailed information on the properties of PETG is included in the appendix.

3.2.2 Pressure and Depth Considerations

The pressure exerted on the container at various depths is calculated using the formula:

$$P = \rho \cdot g \cdot h \tag{1}$$

where P is the pressure, ρ is the density of water (approximately $1000\,\mathrm{kg/m^3}$), g is the acceleration due to gravity (approximately $9.81\,\mathrm{m/s^2}$), and h is the depth in meters.

3.2.3 Wall Thickness Calculation

To determine the appropriate wall thickness for the containers, we use the following equation:

$$t = \frac{P \cdot r}{\sigma} \tag{2}$$

where t is the wall thickness, P is the pressure, r is the radius of the container, and σ is the allowable stress of the material. For PLA, the allowable stress (σ) is typically around $60\,\mathrm{MPa}$, while for PETG the allowable stress is typically around 50 MPa ([11]).

Comparison between minimum wall thickness in PLA and PETG.

Table 3: Miminum thickness of PLA under various pressure

Radius [mm]	Wall thickness [mm]	Max Depth (Pressure)
20	1.1	Up to 33 meters (3.3 bar)
25	2.1	Up to 50 meters (5 bar)
30	3.75	Up to 75 meters (7.5 bar)

Table 4: Minimum thickness of PETG under various pressure

Radius [mm]	Wall thickness [mm]	Max Depth (Pressure)
20	1.3	Up to 33 meters (3.3 bar)
25	2.5	Up to 50 meters (5 bar)
30	4.5	Up to 75 meters (7.5 bar)

4 Prototyping

4.1 Initial design

At the start of the prototyping, Decided the group to submit three distinct concepts for consideration. These designs provided three solutions for the lid. Since the lids will endure frequent handling. Developing a lid concept that is robot-friendly and capable of withstanding prolonged handling.

Out of the three concepts submitted, the team decided to use a lid mechanism featuring a simple twist-locking mechanism. Illustrated in Figure 6 and 7. This lid concept incorporates an engraved groove to ensure proper sealing, with the addition specifically designed to accommodate an O-ring.

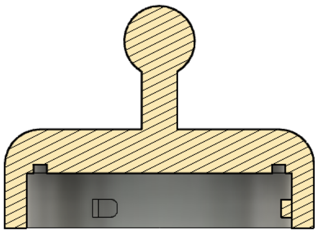
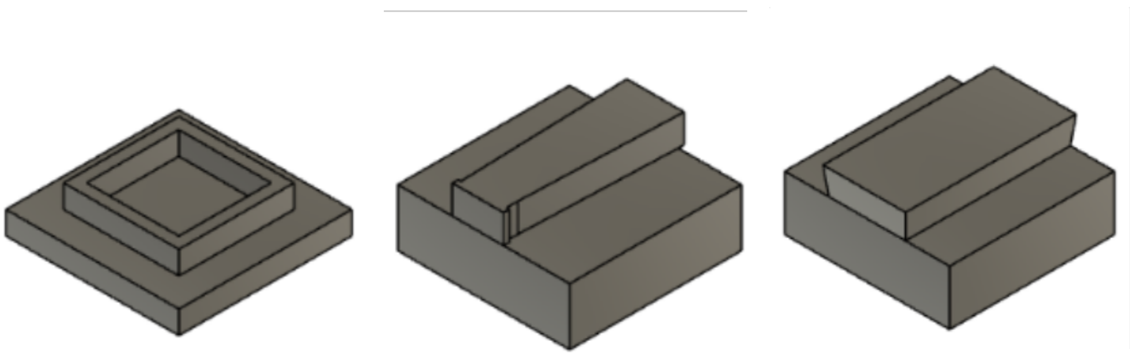


Figure 6: Container lid

Figure 7: Container

For the bracket and mounting system, three alternative designs were developed to meet the specifications of simplicity, robustness, and robot compatibility. Figure 8 presents the initial bracket designs:

Figure 8 and 9 illustrates the three initial clip and bracket designs. The first clip features a magnetic clip mechanism, were magnets are mounted both to the container and mount. The second and third clip would utilize a sliding clip mechanism to secure the container in place when mounted.



(a) Clip that would use a magnet (b) clip that be a slightly incline (c) Clip design 3 would be a wide slide clip

Figure 8: Presents the initial design for the three clips

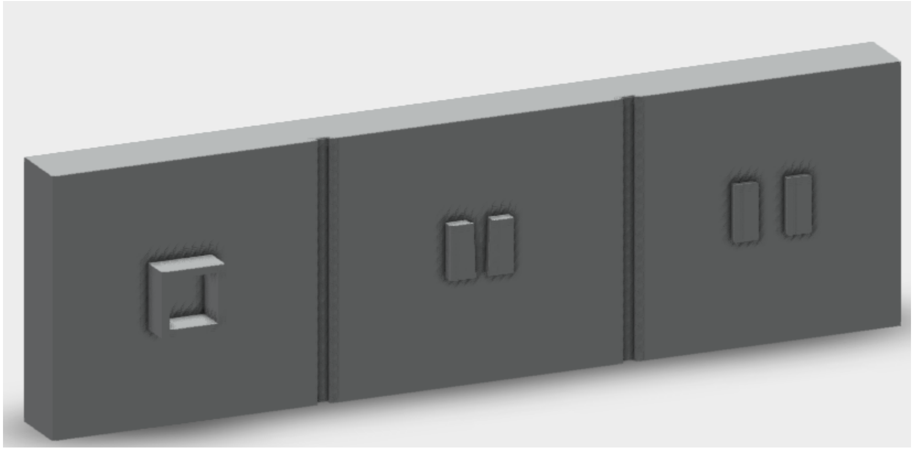


Figure 9: Presents the Initial bracket design

4.1.1 DFAA of Initial Design

An initial evaluation of the DFAA methodology of the initial design was performed. The evaluation is done with a grading of 1 as a baseline. Design implementations that improve automated assembly increase the score, up to a maximum score of 9. [2].

The DFAA2 index of the design is estimated and presented in Table 6

Table 5: Calculations of DFAA2 index of our initial prototype

Reduce number of parts	Unique parts	Base object	Design base object	Assembly directions
3	1	1	3	1

Parallel operations	Chain of tolerances	Disassembly	Packaging	Sum
3	9	3	1	23

The indices in the table above are used to estimate the DFAA2 index as follows

$$DFAA = \left(\frac{\text{sum}}{81}\right) \times 100 = 28.4 \tag{3}$$

Key aspects of the initial DFAA:

The **number of parts** used utilized in the product are quite few. However, considering the size of the product, this was deemed insufficient to warrant a grading of 9. As all clip solutions are unique, the number of **unique parts** is very high. As only half of the parts are directly connected to the **base object**, this received a low grade.

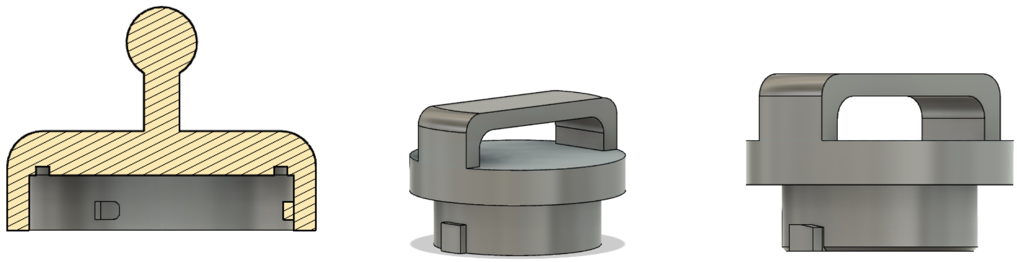
The design of the base object, on the other hand, opens up the use of a fixed mounting jig, enabling automated assembly. However, the designs reliance on unique solutions results in low grade of the **assembly directions**. The number of **parallel operations** is substantial during the 3D-printing of the product, but there are no parallel operations during the assembly, as only one robot arm is utilized.

The tolerance accumulation due to **chain of tolerances** is limited, due to only one clip between bracket and containers. The simplicity of the design ideas contributes to a higher grade for the **disassembly**, at the same time, will the different solution slightly more complex for automation. Lastly, a solution for **packaging** is yet to be determined.

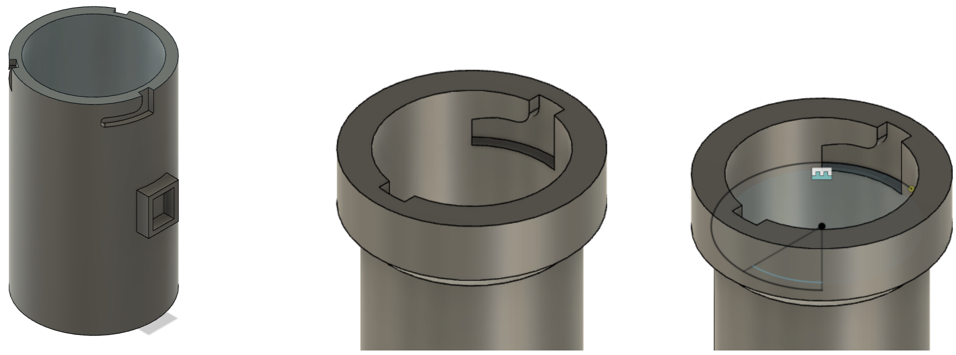
4.2 Further design improvements

4.2.1 Design improvements for the Lid mechanism

The initial draft, focused on meeting functional requirements. These basic concept have since been refined through iterative improvements, driven by experiences and insight gained from prototyping and testing.



(a) First twist concept v1.1 (b) Second twist concept v1.2 (c) Final Twist concept v1.3



(d) First container concept v1.1 (e) Second container concept v1.2 (f) Final container concept v1.3

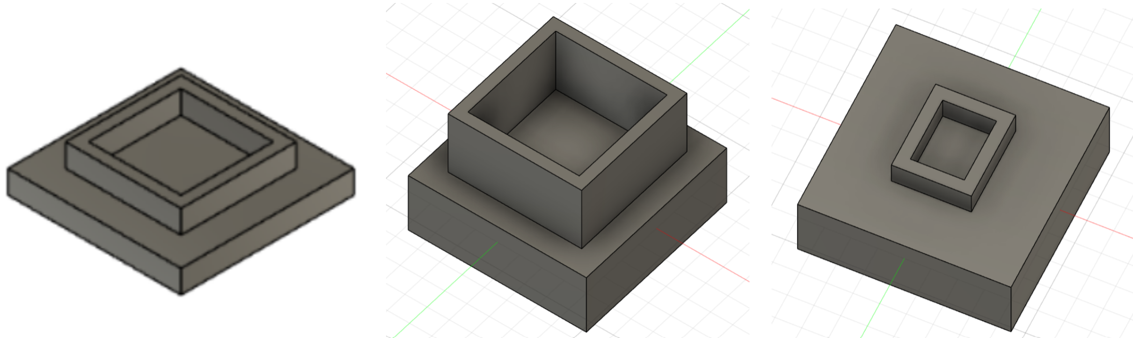
Figure 10: Illustration of design improvements from initial concepts to the final design for both the lid and container.

Version 1.1 illustrated in Figure 10a. During the initial prototyping phase the group started prototyping, and realized it was rather difficult to achieve solutions 1 and 2, as previous attempts did not yield any positive results. As such, the group resorted to the twist concept and modeled three twist concept solutions as shown above towards achieving a perfect fit that would allow for the lid to be closed and opened easily. In the first concept, the container had a locking mechanism on the outside of the container.

Version 1.2: In this solution, the containers locking mechanism was placed on the inside to allow for the lid to fit perfectly. This worked, however, the lid could not be removed once kept in place as it required too much force to fit. The only way to remove the lid once closed would be a total destruction of the lid.

Version 1.3: Adaptations were made to both the lid and container. Increasing the size of the cut in the container as well as decreasing the size and angle of the knob on the lid mechanism. This resulted in a seamless fit.

4.2.2 Design improvements for Clip 1 (Magnet)



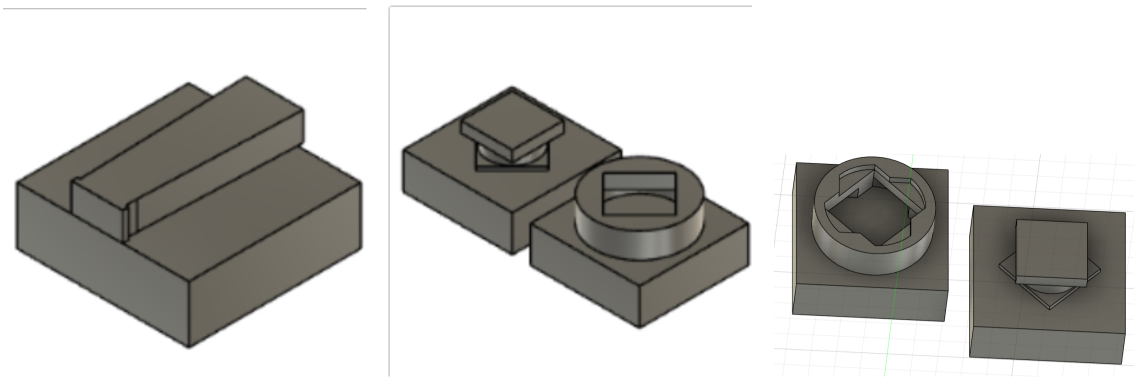
(a) Clip 1 v1.1 (b) Clip 1 v1.2 (c) Clip 1 v1.3

Figure 11: Figures portraying the progress of designing the magnet clip

The magnet clip is the easiest to design and put into practice, as all that is needed is a hull to fit a magnet.

- **Version 1.1** of the magnet clip is mainly used to portray that a magnet is supposed to be used for this particular clip, and the dimensions aren't fitted to any particular magnet size.
- **Version 1.2** is made to fit a particular magnet, but after consideration, the decision was made to use a different magnet. This decision was made due to two concerns, magnet strength and mounting direction. A square magnet would give the sampling container four different angles to mount to the bracket, which could result in the container being offset by 90 degrees. The square magnet was also deemed too powerful for the intended use, with a strength of 10kg.
- **Version 1.3** of the clip features a smaller rectangular magnet hull which ensures that the sample containers are mounted correctly and with a suitable strength of 3.5kg. This strength makes the clip easily manageable for both human- and robot arms while not failing easily.

4.2.3 Design improvements for Clip 2 (Twist)



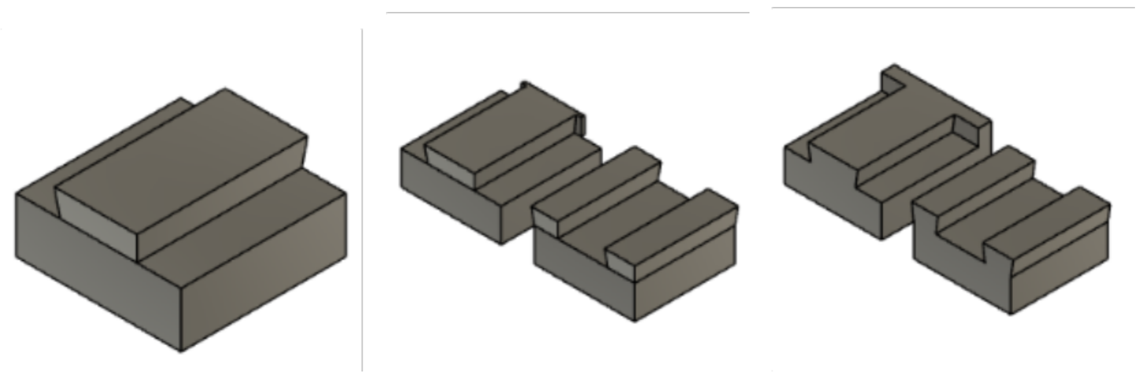
(a) Clip 2 v1.1 (b) Clip 2 v2.2 (c) Clip 2 v2.2

Figure 12: Figures portraying the progress of designing the clip using twist mechanism

The twist clip is the most complex of the clip solutions, and tenfold of different clips were made while prototyping fine tuning margins to make an accetable fit. The concept of the twist lock is to insert the male end of the clip into the female end, and after twisting, it will be locked securely in place.

- **Version 1.1** was a sliding clip, but this was abandoned due to a better sliding solution in clip 3, and a wish for a proof of concept solution featuring a twist solution.
- **Version 2.2** of the clip faced two main struggles. The female end of the clip had a fully circular hull at the bottom, allowing the male clip to rotate 360 degrees, which is highly undesireable. To prevent this, a small (1 mm) extra square extrusion was made on the male clip (45 degrees offset), which was designed to fit into the square, thus preventing any more rotation. This extra extrusion prevented the male clip from fitting fully in the female clip, rendering the clip version useless.
- **Version 1.3** solves both of the issues in v1.2, effectively making rotation more than 45 degrees impossible. By rotating the "entrance square" of the female clip 45 degrees and cutting 1 mm into the clip and rotating the square 45 degrees in the other direction and the extruding down into the circular hull, the clips now match perfectly and are secured with a tight fit.

4.2.4 Design improvements for Clip 3 (Slide)

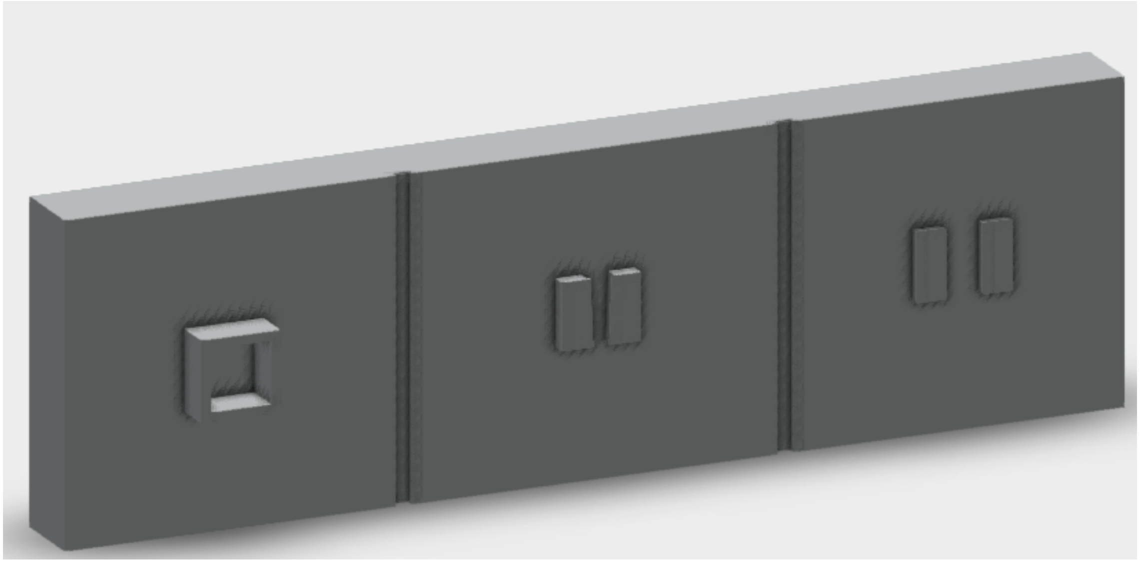


(a) Clip 3 v1.1 (b) Clip 3 v1.2 (c) Clip 3 v1.3

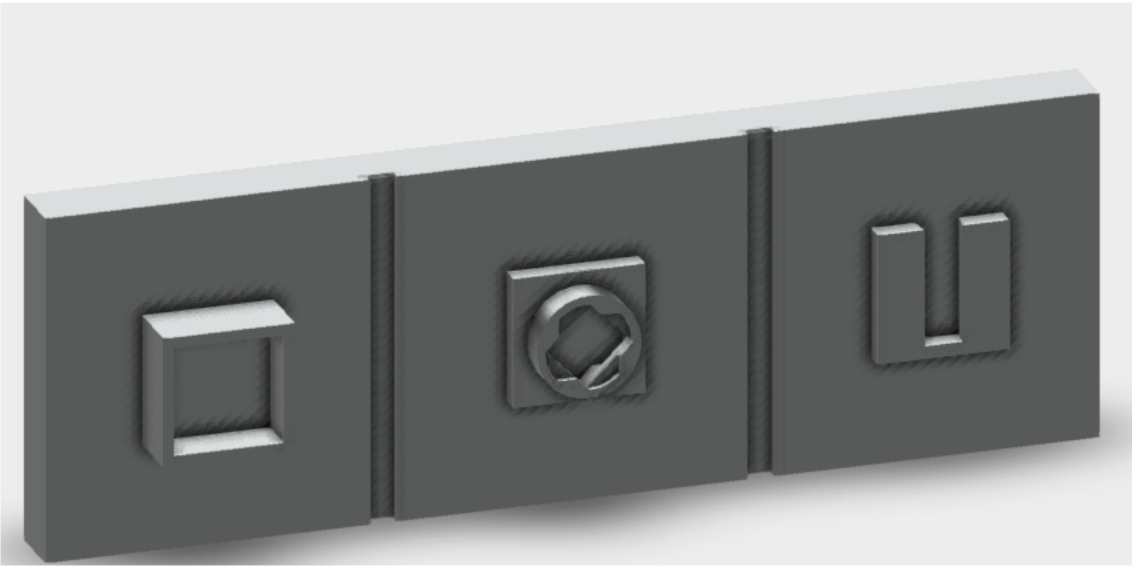
Figure 13: Figures portraying the progress of designing the clip using sliding mechanism

- **Version 1.1** is secured by having the clip at an angle. This version has no defined end, and thus the sliding mechanism would simply slide straight though the bottom.
- **Version 1.2** was made to solve the problem of v1.1 in a subtle manner, by only having a slight indent at the bottom to prevent the sliders from sliding all the way though. After considering the durability of the design, this design was also scrapped.
- **Version 1.3** features a durable solution to the issues faced in the earlier clips. In addition to this, the angle of the clip is also slightly increased to secure even safer grip between the clips.

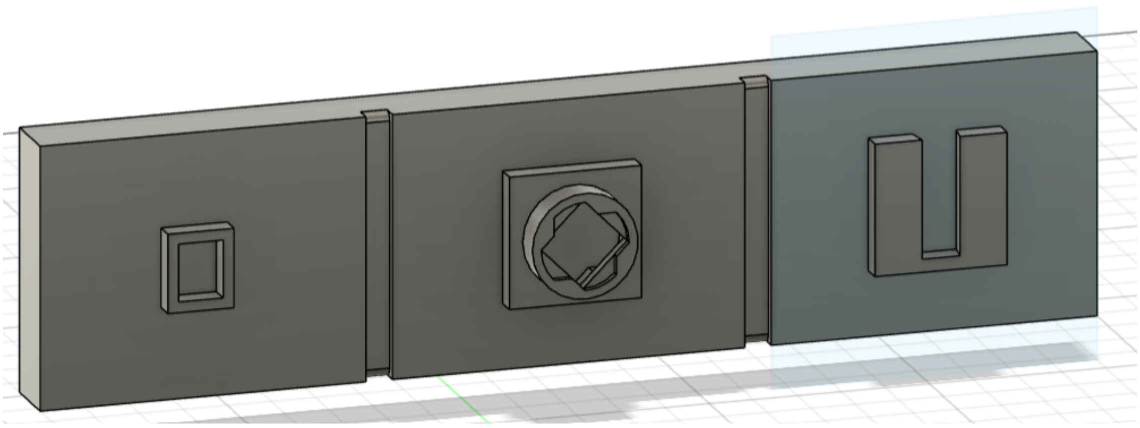
4.2.5 Designing Main bracket



(a) Main Bracket v1.1



(b) Main Bracket v1.2



(c) Main Bracket v1.3

Figure 14: Main Bracket Versions 1.1, 1.2, and 1.3

- **Version 1.1** features all clip solutions v1.1. These are fitted onto a bracket with dimensions 30mm x 120mm x 400mm. In addition to the clips, there are also thin cuts into the bracket. These are made to fit cable ties to mount the bracket to an ROV or divers belt.
- **Version 1.2** reduces the dimension of the bracket to make 3D-printing easier. The new bracket design has the following dimension 15mm x 80mm x 240mm. Additionaly, the clip versions are updated, along with a fillet on the edge where the cable tie is tightened to prevent unwanted damage to the cable tie.
- **Version 1.3** presents the final version of the main bracket. The dimensions of the final version is 15mm x 60mm x 240mm. Other than this, the only update is the addition of v1.3 of clip solutions.

4.2.6 Scrapped ideas

During the development of the project, several concepts for the lid and bracket has been tested, but has failed to prove its function and been scrapped.

One solution, illustrated in Figures 15 and 16, involves a circular lid that is designed to be pressed into the container by an arm. This solution eliminates the need for any joints, as the lid is intended to be sealed once closed. Designed for press-fit sealing, this concept was abandoned due to material flexibility issues and high tolerance requirements.

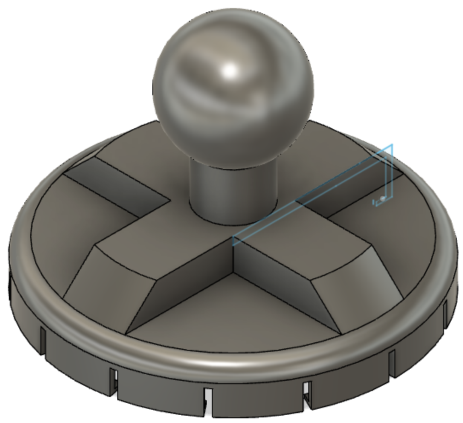


Figure 15: Container lid

Figure 16: Container

Second locking mechanism illustrated in Figure 17 and 18, would use thread's and a sealing. the threads would offer a proper seal wild being easy to open and close. Although promising for sealing, this design faced challenges with thread durability and print quality, making it unsuitable for the intended application.

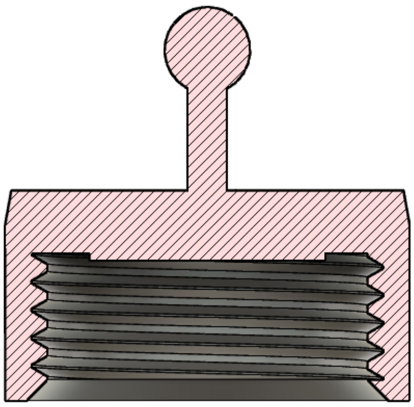


Figure 17: Container lid

Figure 18: Container

5 Final Product

5.1 Products

The final product, presented in Figure 19, represents the culmination of extensive design and prototyping efforts to develop a modular, automated solution for underwater sampling. The system consists of three key components:

- **Lid**: Features a twist mechanism and an O-ring for secure closure and sealing, preventing spillage and contamination.
- **Container Body**: Serves as the primary storage unit for samples, with thick walls to withstand underwater pressure and maintain sample integrity during transportation and analysis.
- **Main Bracket**: Interfaces with robotic arms and supports modular clip solutions (magnet, twist, or slide) for flexibility in underwater operations.

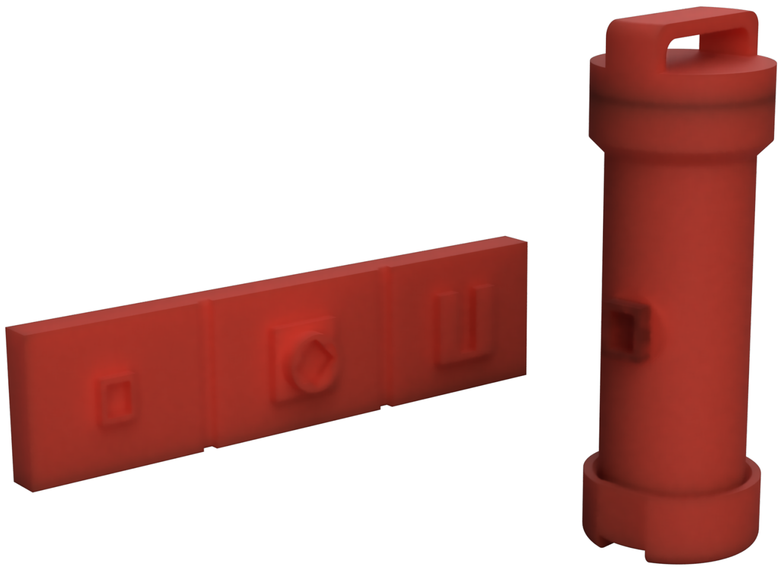


Figure 19: Rendered design of the underwater sampling container (right) and and mount design (left)

5.2 Product family (Product architecture)

Figure 20 illustrate the product family for the final product. The container consists of three modular components, each component in the product has a designated function for the container.

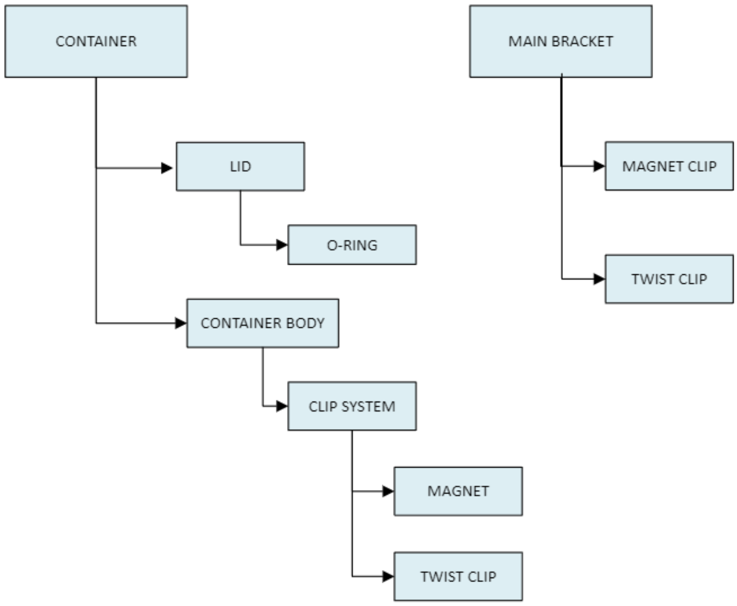


Figure 20: Product family of container system and main bracket

The container consists of a lid with a twisting mechanism. The lid is equipped with an O-ring that provides a secure seal solution.

The body is the main component of the container. Its main function is to store a sample as mentioned in 1.1. The container is connected to the main bracket via different clip solutions, either twist or magnet.

The container is designed to be handled by a robotic arm, making the bracket system a crucial part of the project. The system can be delivered with different clip solutions that are compatible with robotic arms.

5.3 Assembly

A wooden framework jig was constructed using a laser cutter to facilitate the assembly. This framework ensures a secure platform at all stages of the assembly line. The automated assembly process is separated in distinct steps.

1. Mobile robot fetches 3D-printed components
2. Robot places container onto jig
3. Robot places container with magnet hull facing up in a laying down position
4. Magnet is placed in hull
5. Robot moves container upright
6. Robot Assembles lid onto container
7. Robot places container onto main bracket

The assembly process is documented in a separate video to be delivered with the report.

To program the robots, their own respective collaborative programs were used. The program *TMFlow* illustrated in Figure 21 was used to program the assembly robot while the program *Mobile planner* was used to program the mobile robot.

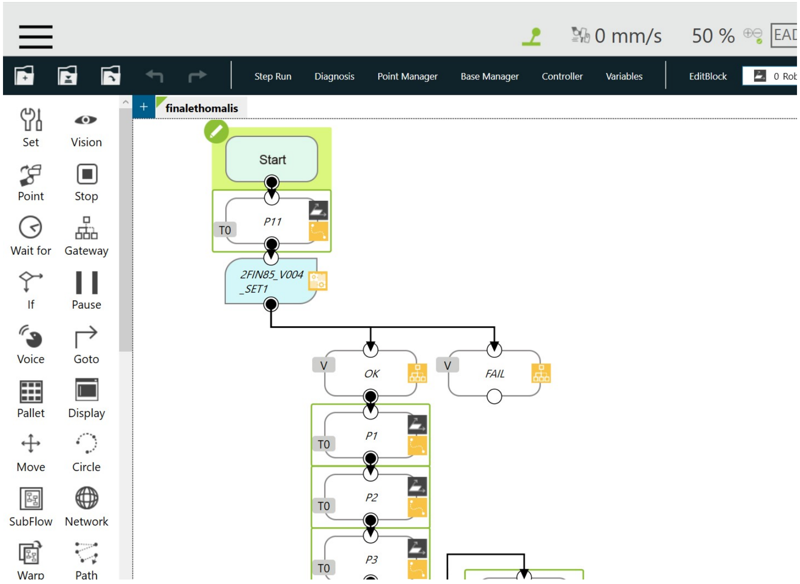


Figure 21: Assembly steps for the container in TMFlow

5.4 DFAA Evaluation of Final Product

Another evaluation of the DFAA methodology of the product was performed on the finished product. This grading highlights improvements made in the design project phase. The DFAA2 index of our design is estimated below:

Table 6: Calculations of DFAA2 index of our initial prototype

Reduce number of parts	Unique parts	Base object	Design base object	Assembly directions
3	6	6	6	3

Parallel operations	Chain of tolerances	Disassembly	Packaging	Sum
3	9	6	1	42

The indices in the table above are used to estimate the DFAA2 index as follows:

$$DFAA = \left(\frac{\text{sum}}{81}\right) \times 100 = 42 \qquad (4)$$

Improvements from the initial DFAA:

- **Unique parts:** The number of unique parts has been reduced due to the lid mechanism converging to only one solution.
- **Base object:** The intent of the main bracket is clearly defined as the base object, with all containers attached to it.
- **Design base object:** The main bracket now comes in two configurations, twist or magnet. This is a better product than three solutions in one.
- **Disassembly:** Disassembly of the purely magnetic clip version is significantly simpler than a varied one. However, the twist version is slightly more difficult, resulting in a more modest upgrade.

6 Discussion

6.1 Industry 5.0 Implementation

The implementation of Industry 5.0 principles in this project focused on achieving a balance between human-centric tasks and automation. Collaborative robots were employed to handle repetitive precision tasks, such as fetching 3D-printed parts, positioning them, and performing assembly operations like lid fitting and container assembly. Human operators oversaw the production line, managing quality control and addressing complex problem-solving scenarios. This integration allowed robots to manage labor-intensive processes while enabling humans to focus on strategic and creative tasks.

Sustainability was embedded in the design through additive manufacturing, which minimized waste and utilized modular components. The modular architecture ensured that individual parts could be upgraded or replaced without discarding the entire product. This approach not only improved resource and energy efficiency but also enhanced product longevity. Additionally, resilience was achieved by leveraging 3D printing for rapid adaptation and modification of designs, facilitating flexible manufacturing processes.

The collaborative robots in the manualab worked seamlessly with human operators to ensure precise and adaptive handling of tasks like lid fitting and bracket installation. This synergy exemplifies the principles of Industry 5.0, where technology is designed to complement human capabilities.

6.2 Industry 4.0 Implementation

The project incorporated key Industry 4.0 technologies to enhance the production process. Additive manufacturing was used to create custom components such as the main bracket, containers, and lids, allowing for flexible, on-demand manufacturing with minimal material waste. Collaborative robots automated post-printing tasks, including component retrieval and precise assembly operations, reducing the need for human intervention.

Simulation tools played a crucial role in optimizing designs before production, minimizing the reliance on physical prototypes. Furthermore, the integration of the Industrial Internet of Things (IIoT) enabled machine-to-machine communication. This interconnected system allowed tasks like part fetching and assembly to be seamlessly coordinated, improving efficiency, adaptability, and responsiveness to real-time data.

6.3 Lean Manufacturing Implementation

The project adopted lean manufacturing principles to prioritize long-term success over short-term gains. The focus was on creating high-quality, reliable products that benefited the business, employees, customers, and society. The process was optimized to ensure a continuous flow of materials and information while eliminating waste ([4]). Key steps in the workflow included design, material selection, prototyping, 3D printing, and automated assembly.

Cycle Time Analysis:

$$\text{Cycle Time} = \text{Processing time} + \text{Wait time} = 2h16m + 3 \times 2m = 2h22m \tag{5}$$

Takt Time Examples:

$$\text{Takt Time (Realistic)} = \frac{\text{8 Hours } \times \text{230 Days}}{\text{5000 Orders}} = \text{22 min} \tag{6}$$

$$\text{Takt Time (Optimal)} = \frac{\text{365 Days}}{\text{5000 Orders}} = \text{105 min} \tag{7}$$

Although the takt time was not achievable due to the extensive printing duration, implementing a Kanban pull technique could significantly reduce wait times. By maintaining a set ready for manufacturing, the workflow could sustain continuous production.

6.4 Product Architecture Implementation

The modular architecture of the product facilitated flexibility, scalability, and maintenance. Distinct components such as lid, container body, and bracket could be independently modified or replaced. Standardized interfaces, such as mounting mechanisms and seals enabled easy assembly and disassembly. This resulted in an adaptable product based on customer need, for example deep underwater sampling.

Component modularity ensures universal adaptability for various tasks. The container body features standardized interfaces, while the lids are designed with O-rings for airtight sealing. Brackets are customizable with options for magnet or twist configurations. This design supports easy repairs, mix-and-match customization, and future scalability. Standardized parts also lowers manufacturing costs, enhances quality, and streamlines automated assembly.

6.5 Challenges Faced

The project encountered several challenges during design and assembly. Initial container designs failed to achieve proper lid fitting due to inadequate extensions on the outer surface. The twist-lock mechanism required precise tolerances, which led to issues with lid alignment and secure closure. Multiple design iterations were necessary to ensure a reliable seal.

The bracket system presented difficulties in robotic assembly, such as aligning the magnet side correctly and achieving precise component placement. Calibration of the robotic vision system was critical to overcome these issues. Inconsistent tolerances in early components necessitated frequent adjustments, which slowed the assembly process. However, final design modifications resolved these problems, ensuring better tolerance consistency.

6.6 Further Work

Future improvements include automating the assembly for the twist-lock solution, enhancing material resistance to saltwater interactions, and integrating Industrial IoT for fully autonomous production. Additionally, refining design solutions for greater efficiency and robustness will be prioritized.

6.7 Retrospective Analysis (Lessons Learned)

The project highlighted the importance of precise calibration of robotic systems to ensure accurate component placement. Standardizing components to minimize tolerance variations emerged as a critical factor for efficient automated assembly. Developing a robust gripping mechanism for the robots was also essential to handle the specific weight and shape of components reliably.

Prototyping and testing phases proved invaluable for identifying potential issues early. Conducting comprehensive testing under realistic conditions would help address challenges like inconsistent tolerances and inadequate grip strength. Flexibility in robotic programming was another key takeaway, as adaptive algorithms could accommodate minor discrepancies, reducing the need for manual reprogramming.

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Appendix

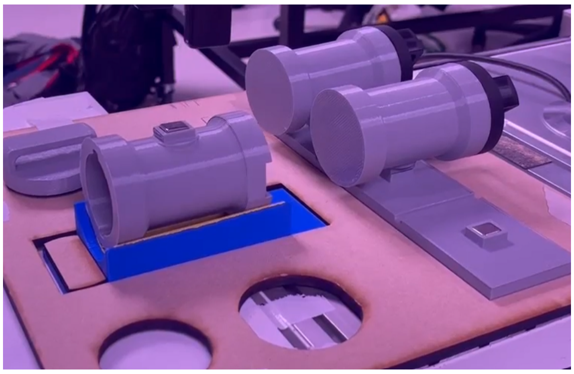

Figure 22: Containers used for final demostration

PETG Technical Data Sheet (TDS)

Polyethylene Terephthalate Glycol-modified (PETG) is a tough and durable material that is easy to use. Its strength makes it suitable for food packaging, and its chemical non-reactive characteristic makes it valuable in the medical field, commonly used for orthopedic and prosthetic devices.

IEMAI 3D high-performance PETG filament is based on FFF/FDM technology, with a commonly used diameter of 1.75 mm, 210–235°C printing temperature, 50–80°C bed temperature, and excellent interlayer adhesion, greatly improving the strength and shock resistance of the prototype.

PETG is a very waterproof material, making it an excellent choice for outdoor activities. It also has excellent chemical resistance, making it suitable for both acidic and alkaline environments. Its strong impact resistance makes it a substitute material for PMMA and PC.

Physical Conditions

Property	Test Method	Typical Value
Density	ASTM D792	1.24 g/cm^3 at 21°C
Bulk Density	–	0.73 g/cm^3
Intrinsic Viscosity	ISO 1628-5	0.80 dl/g
Water Absorption	ASTM D570	0.12%
Colour (b*)	ASTM D6290	≤ 1
Colour (L*)	ASTM D6290	≥ 64

Mechanical Conditions

Property	Test Method	Typical Value
Tensile Modulus	ISO 527-2	3000 MPa
Tensile Yield Stress	ISO 527-2	53 MPa
Elongation at Yield	ISO 527-2	4%
Tensile Strength	ISO 527-2	53 MPa
Elongation at Stress	ISO 527-2	4%
Stress at Break	ISO 527-2	19 MPa
Nominal Elongation at Break	ISO 527-2	31%
Flexural Modulus	ISO 178	2040 MPa
Flexural Stress	ISO 178	171 MPa

Deflection at Flexural Strength	ISO 178	8.6 mm

Impact Conditions

Property	**Test Method**	**Typical Value**
Notched Izod Impact Strength (23°C, 50% RH)	ISO 180	4.5 kJ/m^2
Unnotched Izod Impact Strength (23°C, 50% RH)	ISO 180	No Break

Hardness Conditions

Property	**Test Method**	**Typical Value**
Shore Hardness	ASTM D2240	70

Thermal Conditions

Property	**Test Method**	**Typical Value**
Heat Deflection Temperature (0.45 MPa)	ISO 75-2	68°C
Heat Deflection Temperature (1.8 MPa)	ISO 75-2	62°C
Vicat Softening Temperature	ISO 306	78°C
Glass Transition Temperature	ASTM D3418	80°C

Print Recommendations

Parameter	**Value**
Nozzle Temperature	210–235°C
Bed Temperature	50–80°C
Print Speed	30–70 mm/s
Chamber Temperature	50–70°C
Cooling Fan	0–100%