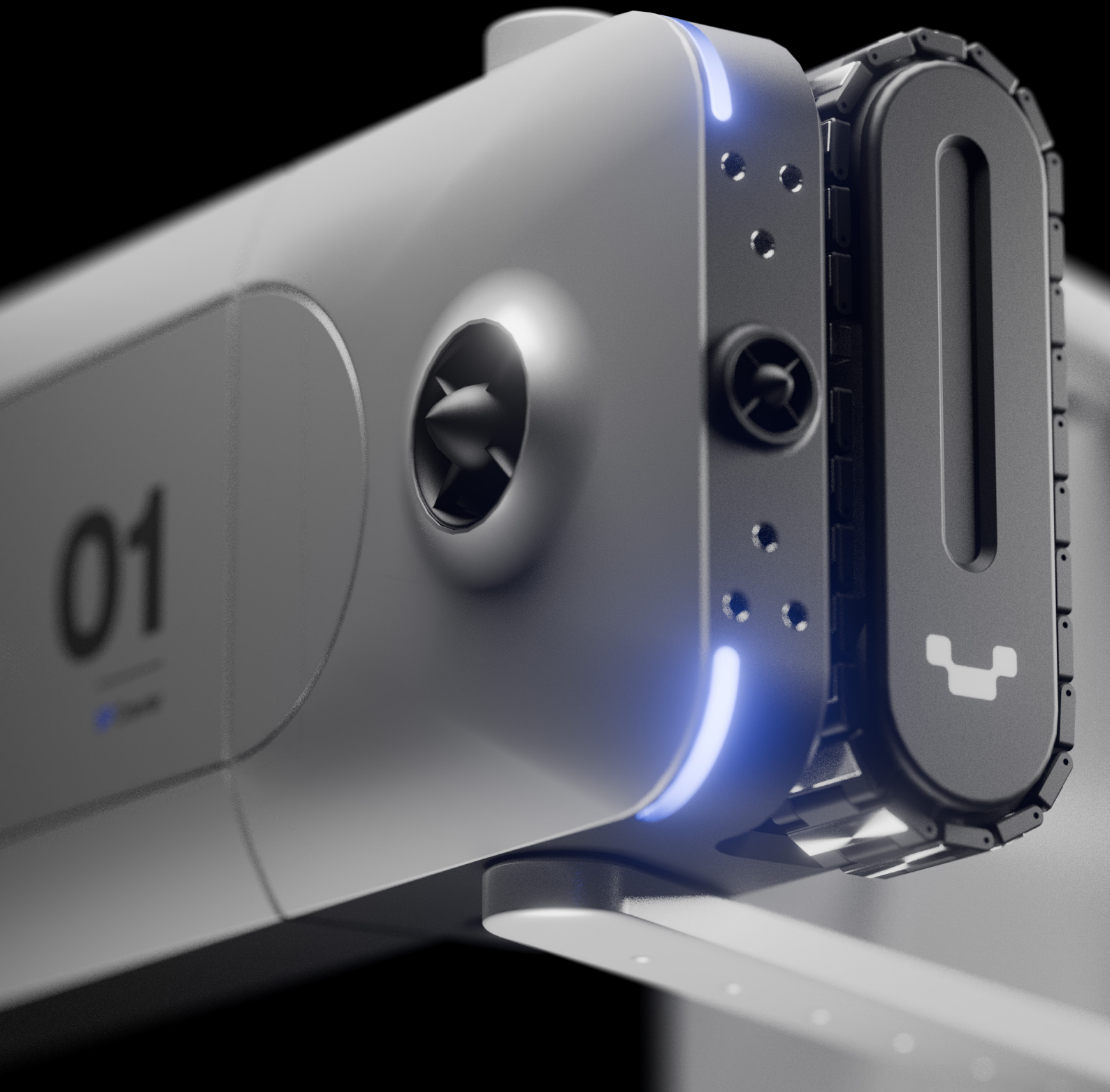


Design and Development of Key Subsystems for a Sheet Pile Inspection Device

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- Thomas van Leeuwen



Abstract

Sheet pile walls are a key part of Dutch maritime infrastructure. As these structures age, inspections are becoming increasingly important, particularly in areas where corrosion is difficult to detect. Current inspection methods, such as divers, cofferdams, and elevated platforms, are effective, but they are often slow, costly, and disruptive to daily port operations. This project, carried out in collaboration with AquaSmartXL, explores how a different type of inspection platform could make the inspection process more efficient.

The research phase mapped out what makes sheet pile inspection difficult. Corrosion concentrates in the splash zone and near the mudline, visibility underwater is unpredictable, and while sheet pile profiles vary widely, their outer face stays consistently flat and free of obstacles like anchor heads. These findings pointed toward a clear direction: a platform that attaches to the outer surface, moves vertically along the wall, and carries swappable modules for cleaning, measuring, or visual inspection.

Several attachment methods were tested early on. Clamping failed because the angled sheet pile profile causes gripping forces to slide off rather than lock on, and suction could not form a reliable seal on corroded, uneven steel. Magnetic wheels worked best, but attaching and detaching them safely meant dealing with how strongly and unpredictably the magnetic pull increases at close range. This led to a ramp-shaped separator mechanism that gradually increases the distance between the magnets and the steel, releasing the wheels smoothly instead of forcing them off.

A working prototype combining magnetic wheels, thrusters, and the separator was built and tested in a water filled sea container, used as a stand in for a sheet pile wall. The thrusters moved and aligned the prototype reliably, the magnetic wheels held firmly even when wet, and the separator released the wheels consistently, with an average gap of 4.91 mm before detachment. Belt tension turned out to matter more than expected, as insufficient tension caused the drive belt to skip under the magnetic load.

The tests show that combining magnetic wheels, thrusters, and a separator mechanism allows a platform to move, attach, climb, and detach from a steel surface underwater. Building on this, a final concept was developed: the SP Crawler, a modular platform that can be fitted with different inspection tools depending on the job at hand.

Testing on real sheet piles, with marine growth and corrosion present, is needed to confirm how the system holds up outside a controlled test setup.

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Chapter 1 Introduction

- 1.1 Context & Background
- 1.2 AquaSmartXL
- 1.3 Problem Definition
- 1.4 Key Questions
- 1.5 Approach and Methodology



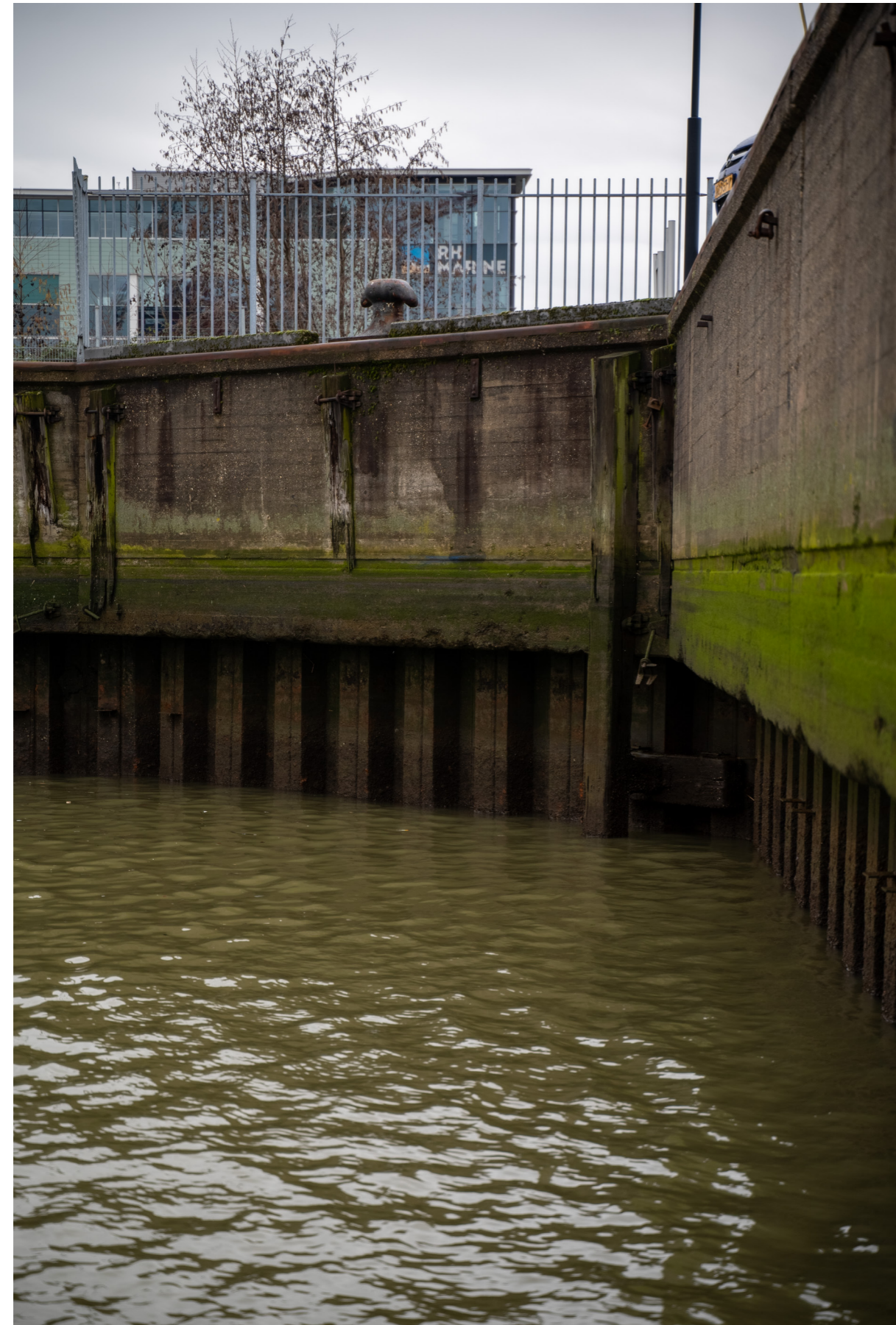


Figure 1 – Sheet Piles in Port

1.1 Context & Background

You have likely seen them before. Along canals. At ports. Around construction sites. Steel elements standing vertically in the ground. Most people pass them without thinking twice.

But what do they actually do?

Sheet pile walls play a crucial role in civil and maritime engineering. They retain soil, hold back water, and make construction possible in areas where the ground alone would not provide sufficient stability. Without them, many quay walls, waterfront structures, and underground constructions simply would not exist.

In countries such as the Netherlands, where land and water constantly interact, sheet pile structures are part of everyday infrastructure. They resist soil pressure, water pressure, and dynamic forces from waves and vessels. Although they may appear simple, their structural function is essential. Many of these walls were installed decades ago and remain in service today. Over time, exposure to salt water, oxygen, and marine growth leads to corrosion and gradual material loss. The challenge is that much of the structure is hidden below water level or underground. Damage develops out of sight. So how do we assess the condition of structures we can barely see?

Current inspection methods rely on divers, temporary cofferdams, or mobile elevated work platforms (MEWP) to access the sheet piles. While these approaches provide valuable information, they are labor intensive and may interrupt daily operations in busy port environments. In addition, the collected data can vary in precision and consistency depending on the method used. Inspections typically focus on specific accessible areas rather than providing a complete and detailed understanding of the structure. As infrastructure continues to age, the need for more efficient, accurate and repeatable inspection methods becomes increasingly important (PIANC, 2014).

New ways of inspecting underwater structures are being developed to improve safety and efficiency. AquaSmartXL is one example of a company working on inspection technologies for maritime environments. Their current work focuses on different underwater inspection challenges. This project builds on that experience and explores how similar ideas can be applied to inspecting steel sheet pile structures

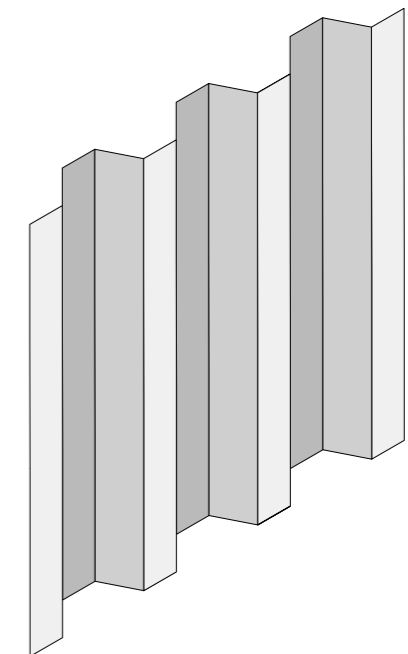


Figure 2 – Isometric Illustration of Sheet Piles

1.2 AquaSmartXL

AquaSmartXL began with a simple idea. How can underwater structures be inspected without sending people into the water every time? Early experiments focused on small remote controlled boats equipped with cameras. These platforms were used to capture images underneath docks and quay structures. The goal was to gain visual insight into areas that are normally difficult to reach.

Over time this idea evolved through many iterations. The systems became more advanced and were expanded with underwater drones and unmanned surface vehicles. These platforms allowed inspections to be carried out more safely and more efficiently compared to traditional methods. By capturing large sets of images the company created digital 3D twins using photogrammetry. This made it possible to document structures in detail and revisit the data later and compare it to the new data.

These solutions proved effective for many inspection tasks. However new challenges quickly became clear. Not all underwater structures can be inspected easily with existing systems. Low visibility, marine growth, and complex geometries can limit what cameras are able to capture. Some areas remain difficult or even impossible to inspect using standard remotely operated vehicles.



Figure 3 – AquaSmartXL USV

As a result AquaSmartXL started exploring more problem specific solutions that go beyond general inspection tools. This graduation project is part of that exploration. The focus is on understanding how similar approaches can be adapted to the inspection of steel sheet pile structures, where accessibility, visibility, and reliable data collection are key challenges.

More information about AquaSmartXL and their work can be found at www.aquasmartxl.com.



Figure 4 – AquaSmartXL USV

1.3 Problem Defenition

Sheet pile walls are a key part of maritime infrastructure. Many quay walls, ports, and waterfront structures depend on them for stability and safety. In the Netherlands alone, large parts of our infrastructure rely on steel sheet piles. The Port of Rotterdam for example contains more than 80 kilometers of sheet pile walls that support daily operations (Port of Rotterdam, n.d.).

Because these structures are so important, inspections are necessary to keep them safe and operational. At the same time, inspecting them is not straightforward. Large sections are underwater or difficult to reach. Safety requirements and working conditions can limit how inspections are performed. In busy ports this can lead to time consuming processes and operational disruptions.

This creates a clear challenge. Inspections need to provide reliable information while reducing the impact on daily operations. The process should be efficient, repeatable, and capable of working in environments where access and visibility are limited.

Rather than replacing existing inspection methods entirely, there is an opportunity to rethink how inspection is approached. By focusing on specific subsystems and tools designed for steel sheet pile structures, it may be possible to support inspectors with more structured data collection and reduce time spent on site.

This project explores this potential in collaboration with AquaSmartXL. The aim is to investigate how new inspection approaches can improve reliability, efficiency, and usability in underwater sheet pile inspection.

To explore this further, it is first necessary to better understand the context in which sheet pile inspections take place. This includes understanding the characteristics of the structures themselves, the challenges of underwater environments, and the requirements of inspectors and sheet pile owners. These considerations lead to the following key questions that guide the development of this project.

“Current ways of inspecting sheet pile walls are difficult, slow, and not always reliable, especially underwater and in busy ports.”

1.4 Key Questions

KQ1 What are sheet piles?

What types of sheet piles exist, how are they constructed and installed, and what is important to understand about their design, behavior, and use within maritime infrastructure?

KQ2 What are current inspection solutions?

How are sheet pile inspections currently performed, and what are the advantages and disadvantages of these approaches?

KQ3 What are the inspection needs?

What requirements and challenges should be addressed to improve inspection of steel sheet pile structures?

KQ4 What makes sheet pile inspection underwater challenging?

How does visibility, marine growth, accessibility, and sheet pile geometry affect what an inspection solution needs to handle?

1.5 Approach and Methodology

To approach these challenges, they are broken down into many smaller pieces. This starts with desk research. The goal is not only to learn new information, but also to understand what is not yet known and where more insight is needed.

Alongside desk research, field work and interviews take place. This includes joining an inspection with AquaSmartXL to better understand their workflow and to experience the environment in which the solution needs to operate. Understanding the real world context is essential for making realistic design decisions.

Throughout the project there is a continuous back and forth between thinking and making. Iterative thinking and rapid prototyping are used to explore whether certain solutions might work or not. Rapid prototyping follows a layered approach. When a prototype would require significant time or effort to build, smaller experiments, research, or rational evaluation are carried out first before committing to larger builds. This layered approach allows ideas to be tested quickly and efficiently while validating design constraints.

In this process, proof that something does not work is just as valuable as proof that something does. Each iteration generates new insights and often new questions that guide the next steps. Many of these activities happen at the same time rather than strictly after one another. Interviews, prototyping, and desk research run in parallel and continuously influence each other. Instead of stacking steps on top of each other, they develop alongside one another to create a stronger foundation.

To zoom out and describe the overall process, the commonly applied Double Diamond model is used. The first phase focuses on diverging: gathering knowledge, exploring the problem space, and understanding the context as broadly as possible. This is followed by a convergence phase where the research findings are translated into key findings, scope, and requirements. The second diamond focuses on exploring technical and mechanical approaches through prototyping and concept development. Finally, these explorations converge into a final concept and prototype, which are documented in this report.

1.5.1 Double Diamond

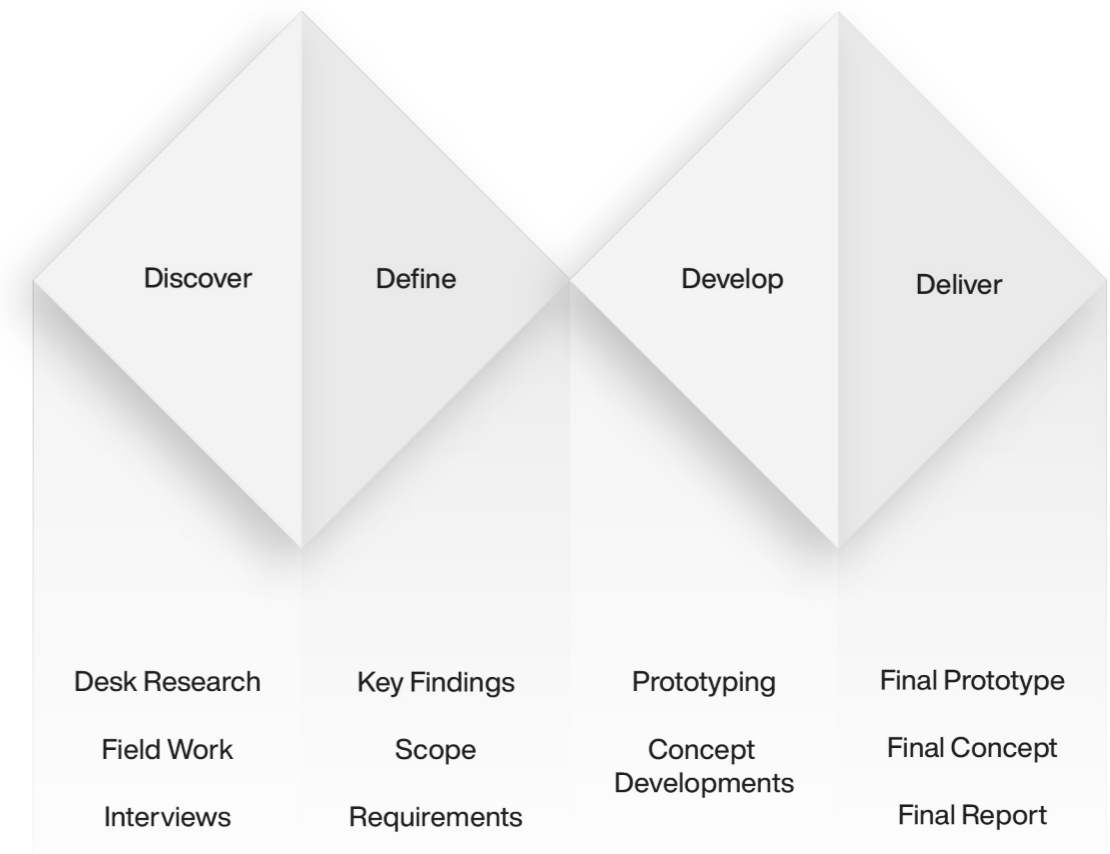


Figure 5 - Double Diamond



Figure 6 - Sheet Pile with Marine Growth

2

Chapter 2 Background Research

- 2.1 Sheet Piles
- 2.2 Mechanics
- 2.3 Corrosion
- 2.4 Visibility
- 2.5 Accessibility
- 2.6 Inspection
- 2.7 Current Inspection Methods
- 2.8 Inspection Strategy and Segmentation
- 2.9 Key Findings



2.1 Sheet Piles

2.1.1 Sheet Pile Materials

Steel Sheet Piles

Steel sheet piles are the most commonly used type of sheet piles and are widely applied in ports, canals, quay walls, and underground structures. They provide high structural strength while remaining relatively thin and efficient to install. Individual steel profiles interlock with each other, forming continuous walls capable of resisting soil pressure, water pressure, and dynamic loads such as those generated by waves and vessels. Steel sheet piles are typically manufactured using either hot rolled or cold formed processes (ArcelorMittal, 2022) and are available in several cross sectional shapes, including Z profiles, U profiles, and straight web sections. Steel sheet piles are manufactured from structural steel grades such as S270GP, S355GP, or S430GP, following the European standard EN 10248.

One of the main advantages of steel is its flexibility combined with a high strength to weight ratio. Steel sheet piles can be driven to significant depths and are suitable for both temporary and permanent structures, making them highly versatile. Additionally, steel elements can often be removed and reused, which supports circular construction practices in temporary works.

At the same time, steel has its challenges. Steel sheet piles are more susceptible to corrosion than alternative materials (Melchers, 2008), particularly when exposed to salt water and oxygen (we will dive deeper into this process in chapter 2.3). Over time this results in material loss and reduced structural capacity. Because much of the structure is located below the waterline or buried in soil, monitoring its condition becomes harder but remains essential for long term safety and performance.



Figure 7 – Metal Sheet Pile Construction

Wood

Wooden sheet piles are one of the earliest types of sheet piling and were widely used before steel became the industry standard, especially in smaller waterfront projects and temporary structures. Timber sheet piles typically use tongue and groove connections or independent boards placed side by side to form a continuous barrier (figure 8). Timber was historically popular because it is relatively lightweight and easy to work with, making it a practical solution prior to modern steel production.

Under the right conditions, timber can last much longer than often expected. When wooden sheet piles remain fully submerged, low oxygen levels slow biological decay, allowing timber structures to remain functional for decades. Problems usually occur when the material is exposed to alternating wet and dry conditions, which accelerate deterioration through rot, fungal growth, and damage from marine organisms.

Because of these limitations, and their lower structural strength compared to other materials, timber sheet piles are used less often in modern large scale infrastructure where long term performance is required. Today they are mainly applied in smaller projects.



Figure 8 – Wooden Sheet Piles

Concrete

Concrete sheet piles are used in projects where a permanent and durable solutions are required. They are typically reinforced with steel to increase tensile strength and reduce the risk of cracking under load. In many cases concrete sheet piles are prestressed to improve handling during installation and to reduce cracking during driving. Compared to steel sheet piles, concrete provides strong resistance against corrosion and chemical exposure.

Concrete behaves differently from steel. It is heavier and more rigid. Installation becomes more demanding and requires heavier equipment. Because of its stiffness, concrete does not accommodate ground movement as easily. Moving soil must be carefully considered during design, since concrete does not tolerate deformation as much as other materials do, such as steel.

When properly designed and installed, concrete provides a reliable solution with relatively low maintenance. It is commonly used in foundations, retaining walls, and structures intended to remain permanently in place rather than being removed or reused.

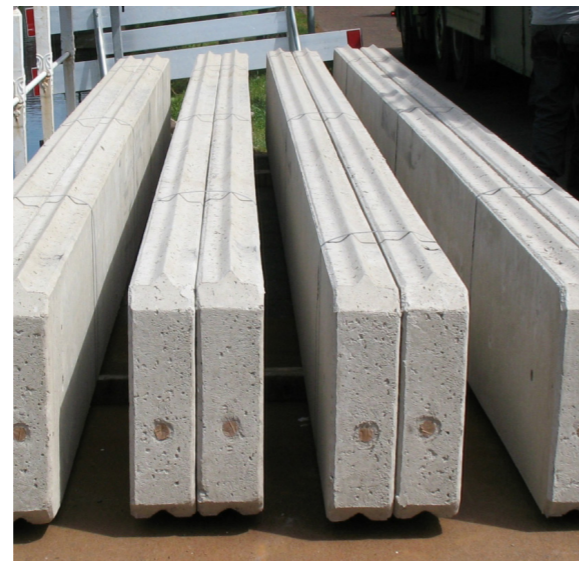


Figure 9 – Concrete Sheet Piles

Plastic and Composite

Plastic and composite sheet piles are used in specific situations where corrosion resistance is important. These materials are often lightweight and easier to handle compared to steel or concrete. Because they do not corrode like steel, they are suitable for environments with high chemical exposure. They are also cheaper to produce in comparison to the other options.

However, plastic and composite materials behave differently from traditional materials. Their structural capacity is generally lower than steel. In addition to lower strength, these materials typically have lower stiffness, which can lead to larger deflections under load.

They are more commonly used in smaller waterfront projects, erosion control systems, or environmental applications where loads are more moderate.

Despite these limitations, their resistance to corrosion and relatively low maintenance requirements make them an interesting alternative in certain contexts.



Figure 10 – Plastic and Composite Sheet Piles

Most Commonly used Material

Although different materials can be used for sheet pile walls, steel is by far the most commonly applied material. Most quay walls, port structures, retaining walls, and flood protection systems are constructed using steel sheet piles. This is mainly because steel has a few benefits. It has a high strength to weight ratio, it is available in many standardized profiles thus making it easy to apply in many situations, and it can be installed efficiently in a wide range of soil conditions (U.S. Army Corps of Engineers, 1994).

Engineering manuals also confirm the dominant position of steel sheet piles. The U.S. Army Corps of Engineers describes steel as the most common material for sheet pile walls due to its strength, weight efficiency, and long service life (U.S. Army Corps of Engineers, 1994). Major manufacturers such as ArcelorMittal show that the majority of sheet pile production worldwide consists of hot rolled steel profiles used in civil and maritime infrastructure (ArcelorMittal, 2023).

Since a large portion of existing sheet pile infrastructure consists of steel structures, inspection and maintenance efforts mainly focus on steel behavior, especially corrosion and material degradation over time (U.S. Army Corps of Engineers, 1994). For this reason, this project focuses specifically on the inspection of steel sheet piles.

2.1.2 Metal Sheet Pile Profiles

Steel sheet piles exist in many different profile shapes (ArcelorMittal, 2022). The most commonly used profiles are Z and U profiles, but other types such as Omega profiles and combi walls also exist. These different shapes allow engineers to choose a profile that fits the structural and environmental requirements of a specific project as well as counting in the economic factors.

Flat

Flat sheet pile profiles are designed for the construction of closed cellular structures. The stability of these structures mainly comes from the weight of the soil enclosed within the cell. In general, flat sheet pile profiles are used in projects where solid rock is located at a relatively shallow depth below ground level, where excavation depth is significant, or where anchoring a conventional sheet pile wall is difficult or not possible.

Z / AZ - Profile

A Z-profile sheet pile has, as the name suggests, a Z-shaped cross section. This type of profile can be produced using either hot rolled or cold formed manufacturing processes. The geometry of the Z-profile places the interlocks at the outer edges of the section, which creates a continuous wall when multiple elements are connected.

Combi Walls

These sheet pile walls are a combination of hollow steel tubes connected with either U or Z sheet piles. Combi walls are mainly used in large maritime projects such as quay walls, harbors, and other waterfront structures. They are often chosen in situations where the wall needs to handle high loads, large height differences between water and land, or heavy forces from ships and soil pressure.

Omega

Omega profiles are a type of steel sheet pile characterized by a shape that resembles the Greek letter omega. Compared to more common U and Z profiles, omega profiles are used less frequently. Their shape creates a larger flat surface area, which can be useful in situations where a smoother wall face is needed or where attachments need to be made directly to the wall surface.

U - Profile

A U-profile sheet pile has a more symmetrical cross section compared to a Z-profile. Similar to Z-profiles, U-profiles can be manufactured using both hot rolled and cold formed processes. The main difference between U and Z sheet pile profiles lies in their cross sectional geometry and the position of the interlocks. U-profiles have a symmetrical shape, with the interlocks positioned closer together near the center of the section. Z-profiles, on the other hand, have their interlocks located at the outer edges of the profile and a more distributed cross section.

Because of this geometric difference, the structural behavior of the two profiles is not the same. The position of the material and the interlocks influences how bending forces are carried and how the wall behaves under load.



In short, there are many different types, shapes, and sizes of sheet piles used in practice. This is useful for engineers because it allows them to choose the right profile for each specific project. However, it also means that sheet piles are not fully standardized. Because of this, it is important to consider these differences during the design process. Any inspection solution should be able to handle variations in geometry, dimensions, and connection types.

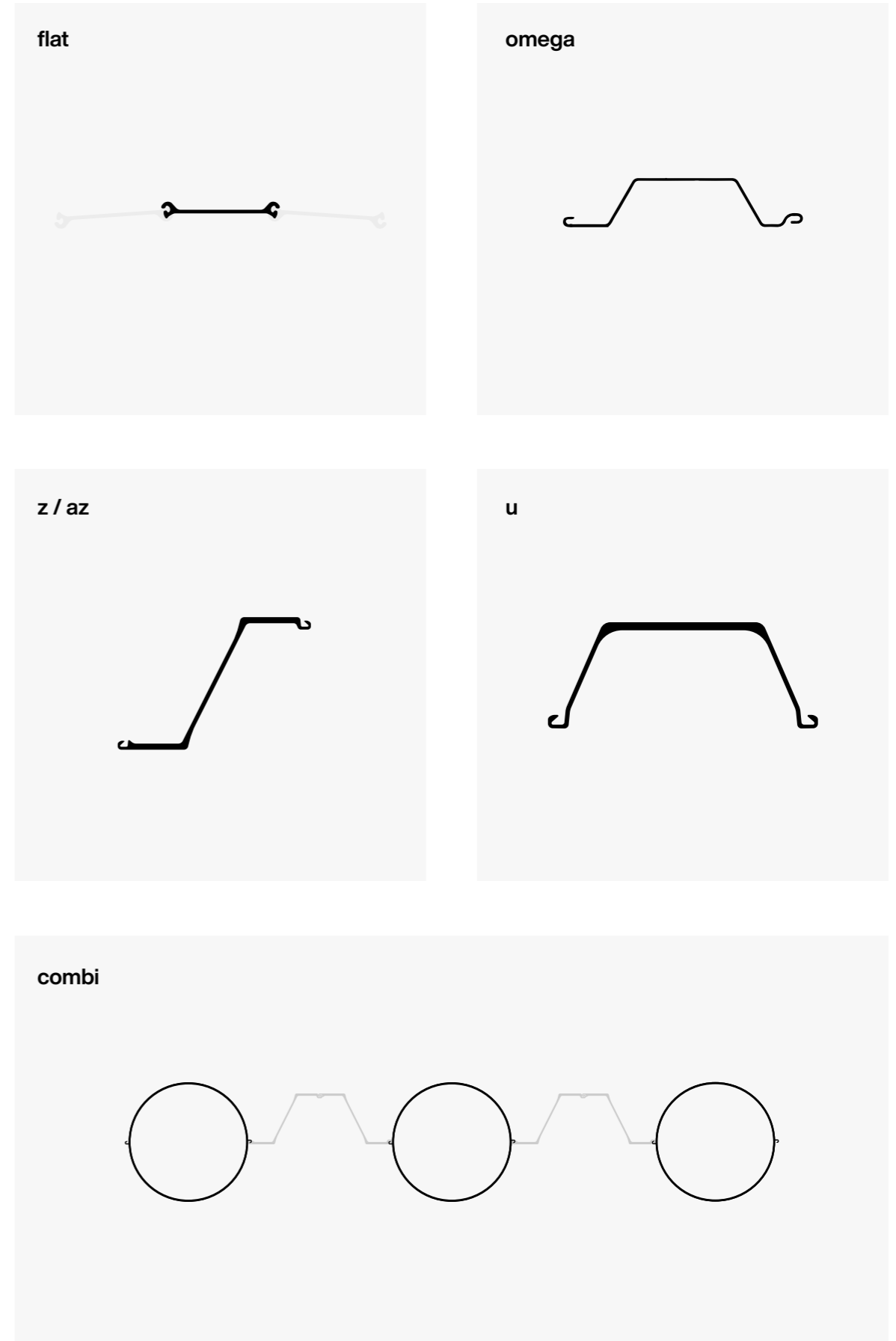


Figure 11 – Overview of different sheet pile profiles

2.1.3 Interlocks and Connector Pieces

Sheet piles are connected through interlocks, which are specially shaped edges that allow individual piles to slide into each other and form a continuous wall. These interlocks are not fully rigid connections. Instead, they are designed to allow a certain amount of movement between adjacent piles. This flexibility is necessary during installation because sheet piles are driven into the ground and small alignment deviations must be accommodated. Interlocks typically allow several degrees of angular displacement around the vertical connection axis, meaning adjacent piles can angle slightly away from each other horizontally. This is often around 4 to 5 degrees, depending on the profile and manufacturer (ArcelorMittal, 2022; Tomlinson & Woodward, 2014). This freedom makes it possible to construct curved walls or correct alignment during driving.

For inspection design this matters. The wall surface is not perfectly flat. Adjacent piles can sit at slightly different angles, which means a system moving along the wall needs to handle these small steps and angular changes between panels.

Different types of interlock connections exist. One common example is the Larssen interlock, widely used in hot rolled steel sheet piles, which forms a strong yet flexible mechanical connection. Ball and socket interlocks allow more rotational flexibility, which helps during installation and in combined wall systems. Cold formed sheet piles often use hook and grip interlocks created by bending the steel edges during manufacturing.

Besides the interlocks, connection pieces are also used. These include corner connectors and T-connectors. In combi walls, special connectors link tubular piles with U or Z sheet piles.

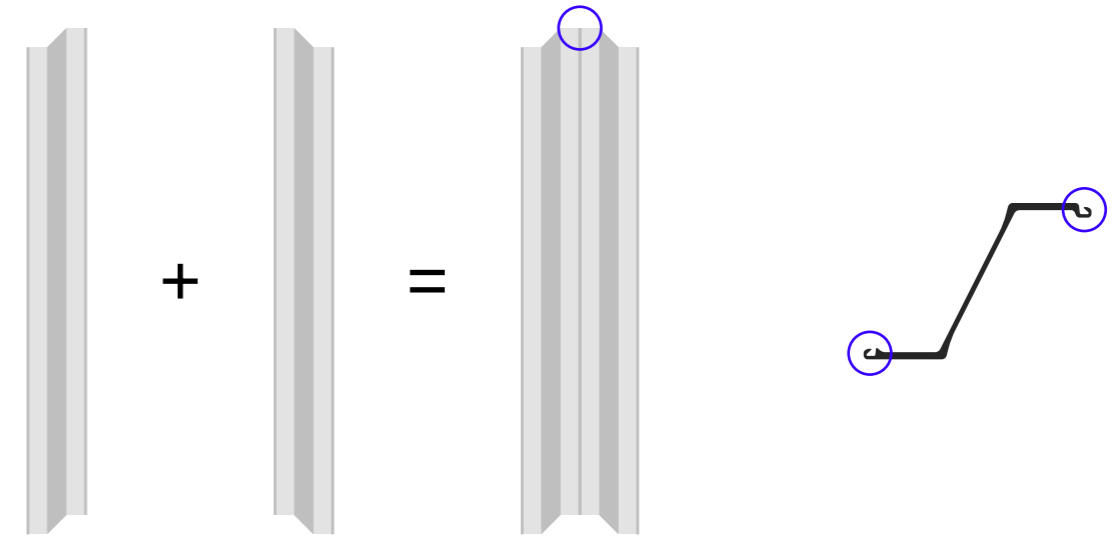


Figure 12 – Metal Sheet Pile Construction

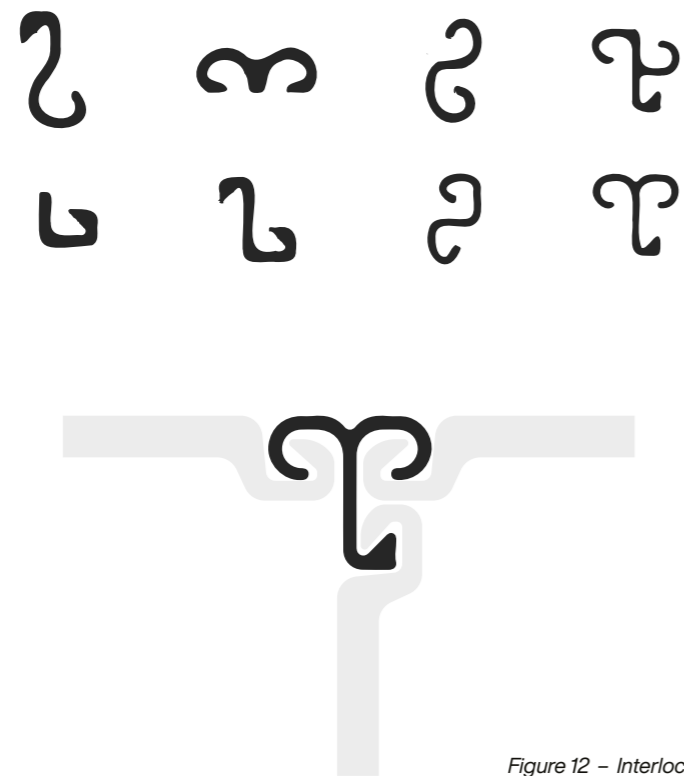


Figure 12 – Interlocks

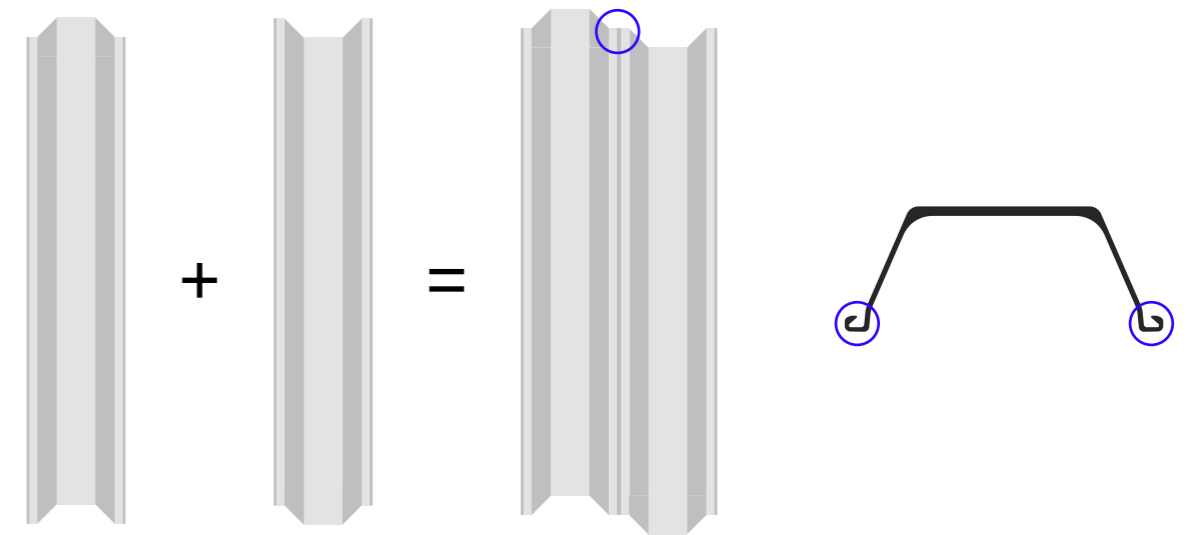


Figure 13 – Interlocks integrated in the sheet

2.1.4 Installation and removal of steel sheet piles

Steel sheet piles are driven into the ground to create a continuous wall. Each pile connects to the next through interlocks, so the wall gradually forms as more elements are installed. Alignment is important during installation, since small deviations at the start can easily grow into larger misalignments further down the wall. Several installation methods are used in practice. The choice mainly depends on the soil, nearby structures, and project constraints. Common methods include vibration driving, impact driving, and hydraulic pressing.

Understanding installation methods is also relevant from an inspection perspective. Some clients want to verify the quality of a newly installed wall, checking whether the piles are correctly driven, properly aligned, and free from installation damage.

Vibratory driving

Vibration driving is the most commonly used method for installing and removing steel sheet piles in the Netherlands (Gooimeer BV, 2024). A vibrating hammer is attached to the top of the sheet pile. The hammer makes the pile move up and down very quickly. This movement reduces the resistance between the soil and the steel, which makes it easier for the pile to go into the ground under its own weight and the force of the machine.

Different types of vibrating hammers exist. Some use electric motors and others use hydraulics. Newer machines try to reduce vibration in the surrounding area. This helps protect nearby buildings. Still vibration driving does not work the same in every soil type. In some cases vibration limits make it harder to use this method.

A variation of this method is called resonance installation. Instead of only vibrating the pile the machine uses resonance vibration of the sheet pile. This helps the pile move more easily through the soil. The ground vibration is almost completely gone using this technique. (Tomlinson & Woodward, 2014)



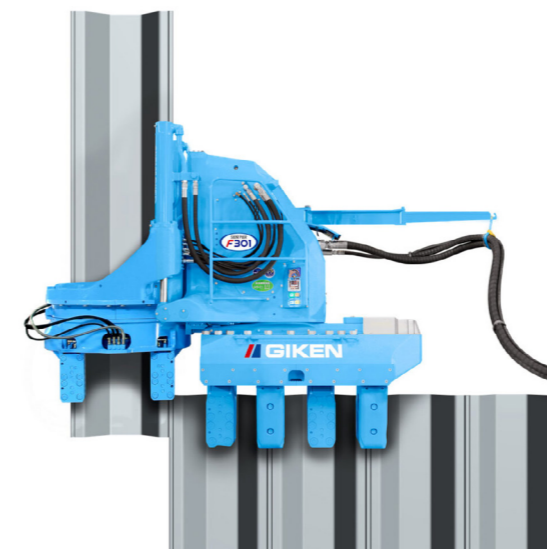
Figure 14 – Vibratory Driving



Hammering

Impact driving is another method used to install both steel and concrete sheet piles. In this method a hammer repeatedly hits the top of the pile to drive it into the ground. The repeated blows push the pile deeper with each strike. This technique is often used when vibration driving is not suitable or when stronger force is needed to reach the required depth.

Figure 15 – Hammering



Pressing

Another method is hydraulic pressing. In this method sheet piles are pushed into the ground using hydraulic force instead of vibration or hammering. The machine pushes against already installed piles or a heavy frame to create the needed force. This method produces very little noise or vibration, which makes it suitable for sensitive locations such as city centers or near existing structures. The main disadvantage is that the process is slower compared to vibration driving or

Figure 16 – Pressing

Removal

Removal is usually done using vibration. The vibration reduces the resistance between the soil and the steel, allowing the pile to be pulled out. When the piles are being pulled out of the water, sometimes simply pulling the pile is sufficient.

Sheet piles are removed when they are used for temporarily. For example after construction is completed and the permanent structure is in place. The sheet piles are pulled out and reused if possible. Removal also takes place when an existing sheet pile wall needs to be replaced or upgraded. For example when it is damaged.



2.2 Mechanics

So far the focus has been on what sheet piles are. The materials they are made from, the different profile shapes, how they connect, and how they are installed in the ground. These aspects explain the physical form of a sheet pile wall. The next step is to understand how they actually behave once they are in place.

In real conditions sheet piles are constantly exposed to forces from soil pressure, changing water levels, and activities around them. These forces influence how the wall bends, moves, and carries stress over time. Understanding this behavior is important because it shows where stresses build up and where failure risks are more likely to occur. This is relevant for the design of the inspection solution. Knowing how the structure behaves helps decide where to inspect, what to measure, and which areas are most critical or not.

2.2.1 Loads

The example shown in the figure illustrates how loads are distributed along a sheet pile wall. On the land side, the retained soil applies lateral pressure that increases with depth due to the weight of the soil above (U.S. Army Corps of Engineers, 1994). This creates a non uniform load distribution where the lower sections of the wall experience higher forces compared to the upper parts.

On the water side, hydrostatic pressure also increases with depth, but in tidal environments this condition is constantly changing. The tidal zone introduces a dynamic area where parts of the structure are alternately submerged and exposed, leading to varying loading conditions over time (Das, 2016).

Because of these differences, the sheet pile wall does not behave uniformly along its height. The combination of soil pressure, water pressure, and changing boundary conditions causes the wall to bend and transfer forces into the ground in specific ways (EN 1993-5, 2007). Understanding this load distribution helps identify where stresses concentrate and where potential failure risks may occur. This insight is important for inspection design, as it highlights which areas are structurally more critical and therefore require greater attention.

What we actually happens due to these forces:

“The sheet pile tends to rotate slightly towards the water side, showing a natural bending behavior under load.”

- Michiel, Interview 1, 2026

This bending behavior can also be seen as an indicator of the structural condition. Increased outward movement may indicate that parts of the structure are starting to lose their load carrying capacity. When this happens, the wall begins to lean further towards the water side.

However, once deformation becomes large enough to be clearly measurable, the structure may already fall outside what is considered acceptable risk, leaving little room for preventative action. Therefore, designing a solution that can be used more easily and more often is a valuable step toward preventing this. Usually this means new sheet piles need to be installed in front of the existing ones. This has a significant impact on the port layout. Space along the quay is often limited because ships need enough room to dock and manoeuvre, and moving the wall forward reduces this available space. The installation process is also disruptive, since this section of the port cannot be used during construction.

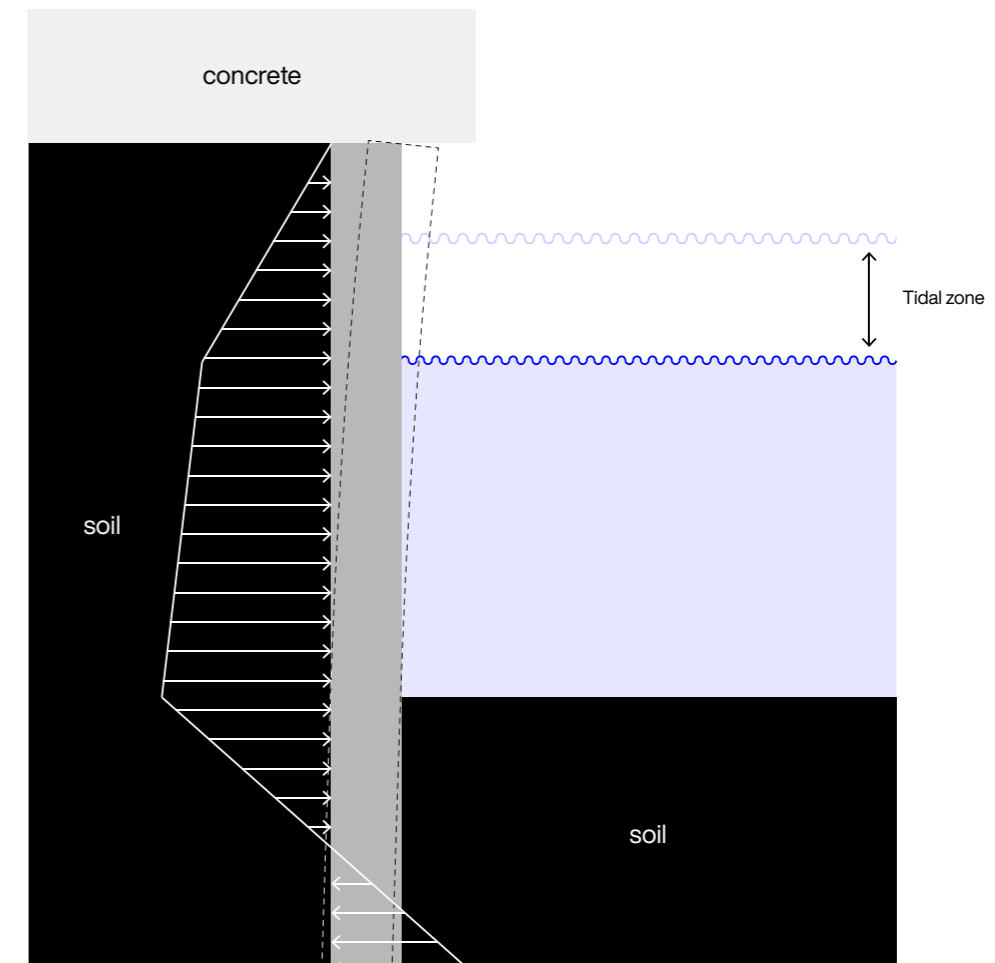


Figure 17 – Loads Illustration



This shows that relying on visible deformation is often too late. Critically, the most significant deformation occurs underwater, where it cannot be observed from above and where inspection is far more difficult. Detecting these problems early, before they become visible, is therefore essential.



Figure 18 – Anchor Heads

2.2.2 Anchor points

To reduce outward bending, sheet pile walls are often supported using anchor systems. These anchors are installed in the ground behind the sheet pile wall and connected to the structure itself. Their main function is to counteract the lateral forces from the retained soil and help maintain stability.

What that means in practice:

“If the anchor head corrodes and the nut disappears, the anchor simply stops doing its job.”

- Michiel, Interview 1, 2026



This highlights that anchor points are not only structural components but also critical inspection targets. When anchor connections degrade, the sheet pile loses part of its resistance against outward bending. In addition, anchor heads and plates create physical obstructions along the wall, which influence how a possible inspection solution can move along the surface.

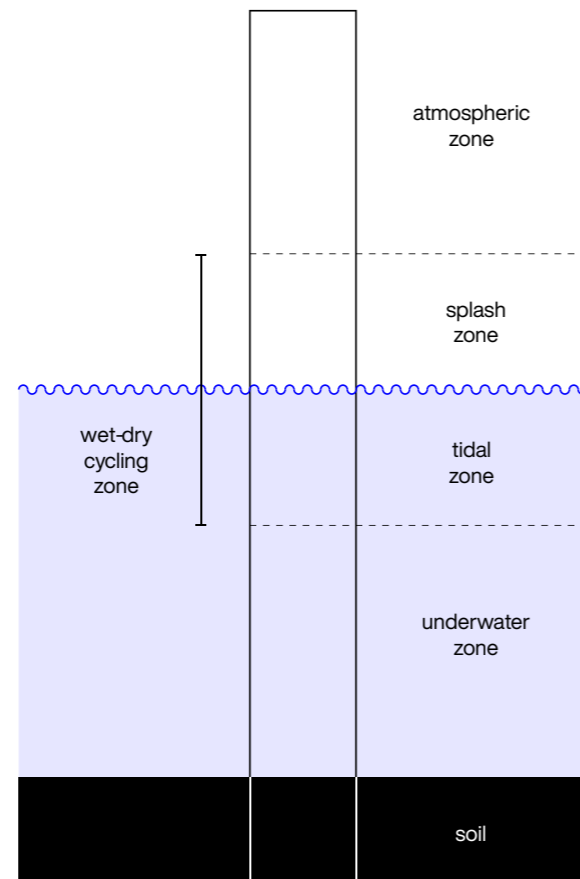
2.3 Corrosion

After understanding how loads act on sheet pile walls and how these forces influence bending, the next step is to look at one of the main causes behind structural degradation: corrosion. Sheet piles operate in harsh environments where steel is continuously exposed to (salt) water, oxygen, marine growth, and mechanical wear. Over time this leads to material loss (Melchers, 2008), and thus structural integrity. Corrosion is not uniform along the height of the wall. Different zones experience different environmental conditions, which results in specific degradation patterns. Understanding where corrosion develops and how it influences structural behavior is important for the inspection design solution.

2.3.1 The Splash Zone

The splash zone is common jargon in the maritime world. Not only sheet piles deal with this condition, but many other maritime structures such as offshore wind turbines, quay walls, and bridge piers are affected by it as well. When looking at different maritime structures, this zone keeps appearing as the place where corrosion accelerates the most.

What makes this zone so critical is the constant transition between wet and dry conditions. During high tide, salt water reaches the surface and penetrates small imperfections, pores, and damaged areas of the steel. Waves and splashes continuously wet the surface, pushing salt water into these small openings. When the water level drops, the surface dries but salt remains behind. At this moment oxygen from the air comes into contact with the wet salt deposits and exposed steel. The combination of water, oxygen, and salt creates an electrochemical reaction that causes iron atoms in the steel to oxidize, forming rust. This process removes material from the structure. At the same time, mechanical action from waves and splashing water can wash away loose ducts and damage protective coatings. This exposes fresh steel underneath, allowing salt water to penetrate deeper. The cycle then repeats itself: wetting, drying, oxidation, and material removal.



In short, the wet-dry cycling accelerates corrosion in two ways. First, the chemical conditions created by salt, oxygen, and moisture promote continuous corrosion reactions. Second, the dynamic forces from waves and splashes physically remove protection and expose new material, allowing the process to continue and gradually “chisel” away at the steel.

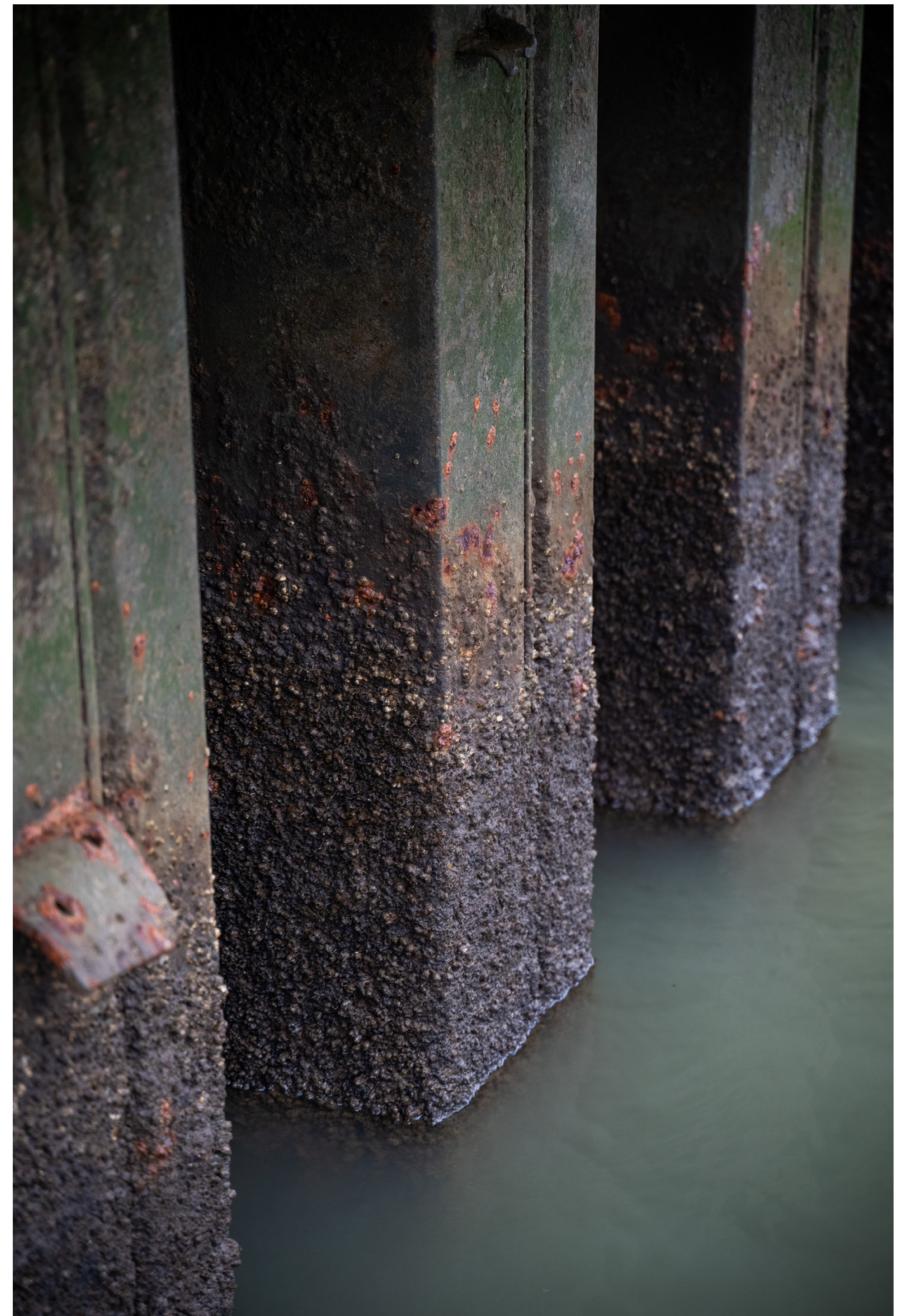


Figure 19 – Sheet Piles in Schiedam

2.3.2 Pitting Corrosion

Corrosion does not always reduce material evenly. In many marine environments it develops locally in the form of pits. Pitting corrosion creates small but deep cavities in the steel surface. Instead of gradually thinning the entire sheet pile, material is removed in concentrated spots. These pits can be much deeper than the surrounding area. Pitting often occurs in aggressive zones such as the splash and tidal areas, where wet-dry cycles accelerate corrosion processes (Wall & Wadsö, 2013; Hosseinpour et al., 2025).



In short, the wet-dry cycling accelerates corrosion in two ways. First, the chemical conditions created by salt, oxygen, and moisture promote continuous corrosion reactions. Second, the dynamic forces from waves and splashes physically remove protection and expose new material, allowing the process to continue and gradually “chisel” away at the steel.



Figure 20 – Corrosion on Sheet Pile

2.3.3 MIC Bacteria

A lesser known but relevant type of corrosion is the MIC bacteria.

MIC stands for Microbiologically Influenced Corrosion. It is corrosion that is influenced by bacteria. Over time they have spread through international shipping and are now also present in Dutch waters. These bacteria like to live in the soft top layer of underwater soil near the sheet pile.

They attach themselves to the steel and form a thin biological layer. The substances they produce speed up corrosion in that exact spot (Liu et al., 2023). Instead of slow and even thinning, the steel can develop



Interestingly the place where these bacteria prefer to live is often the same place where the sheet pile experiences the highest stresses. So the steel becomes weaker exactly where it is working the hardest.

2.3.4 Mechanical Failure

Corrosion does not only make steel thinner. It changes how the entire structure behaves.

Let us go back to the splash zone. This is where corrosion is most aggressive. Over time, material is removed locally. Small pits grow into deeper holes. The thickness decreases. At some point, the steel does not only lose mass, it loses stiffness.

Now imagine what that means in practice.

In many cases, the sheet pile simply becomes weaker and starts bending outward under soil pressure. But in more severe situations, another mechanism can develop. When corrosion creates a hole through the sheet pile, soil from behind the wall can start to wash out. A small empty space forms where soil used to be. Like the start of a sinkhole, the soil above that space slowly moves down to fill it. If a concrete slab or beam is resting on that soil, it moves down with it. As this happens, part of the weight from the slab can start pressing on the top of the sheet pile. The sheet pile is already thinner and less stiff. At the same time, the soil behind it is still pushing horizontally. Now the sheet pile is pushed from the side and pressed from above. The sheet pile ends up buckling under these pressures.



Figure 23 – Quay Collapsed due to Sheet Pile Failure

Another thing that makes these holes dangerous is that you often cannot see them forming. Imagine the soil behind the sheet pile slowly washing away. A small empty space develops underground. On top of that soil lies a heavy concrete slab. At first, nothing looks different. The slab still looks flat. There are no visible gaps. But underneath, the soil that used to carry the load is no longer there. The concrete slab is now partly hanging over an empty space. It can hold itself for a while. Until one day it cannot anymore. Then cracks appear. Or worse, the slab suddenly gives way because there is simply no support left below it.

As Michiel explained during the interview:

“For example, if a container crane drives over this area, you have enormous tires and enormous loads. If the soil underneath has locally settled, the concrete slab can suddenly break through. Then an entire container crane can drop down.”

- Michiel, Interview 1, 2026



What started as a small corrosion pit can slowly grow into many problems.



Figure 21 – Sinkhole Caused by Failure (CROW)



Figure 22 – Sinkhole Caused by Failure (CROW)

2.3.5 Corrosion Protection

Because sheet pile walls are exposed to water and salt, different methods are used to slow down corrosion. The goal is not to stop corrosion completely, but to make the structure last longer.

One common method is applying a coating. This is a protective paint, usually with a primer and one or two extra layers. The coating creates a barrier between the steel and the water. If the coating is damaged, corrosion can still start locally. (PIANC, 2014)

Another method is galvanizing. In this process the steel is dipped in hot liquid zinc. The zinc forms a protective layer around the steel and corrodes instead of the metal sheet pile. (PIANC, 2014)

Below the waterline, cathodic protection is often used. This can be done with sacrificial anodes. These are blocks of metal attached to the sheet pile. They corrode first (sacrifice), protecting the steel behind them. In some cases an electrical current is applied to reduce corrosion even further. Their condition determines whether the corrosion protection is still working properly. Port owners often want to check how worn down an anode is, which is done by visual inspections.

Cathodic protection can also help reduce MIC corrosion. The electrical conditions created by the system make it harder for bacteria to create the aggressive environment they need. This does not always remove MIC completely, but it can slow it down.



For inspection design this is important. Anodes are often mounted on the lower part of the sheet pile wall and can stick out from the surface. This creates obstacles for a system moving up and down along the wall. At the same time, these sacrificial anodes also need inspection. Their condition determines whether the corrosion protection is still working properly.

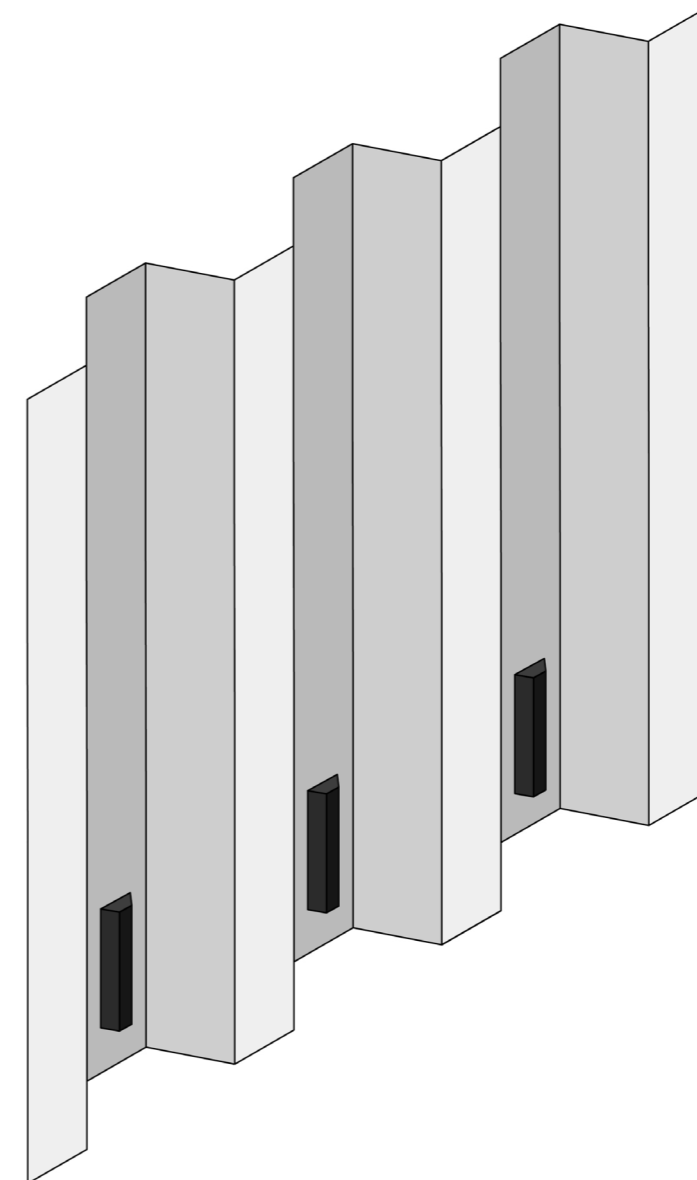


Figure 24 – Isometric image of anodes

2.4 Visibility

Visibility is one of those things that sounds simple until you are actually in the water. And just like everything else with sheet piles, no two situations are the same. What you can see during one inspection can be completely different from what you see the next day, on the same wall.

2.4.1 Marine Growth

Before talking about what you can see, it helps to understand what is growing on the wall. Marine growth does not follow a perfect pattern. One of AquaSmartXL's drone operators described situations where a thick layer of scalps appeared at one depth, then nothing, then scalps again further down.

But in general, this is what we see. The splash zone, as discussed in section 2.3, is mostly free from growth. The constant wetting and drying makes it hard for organisms to settle. What you find here is mostly bare, heavily rusted steel. Going below the waterline, things change. First comes a thin layer of moss. A bit deeper it gets denser, almost like hairy grass on the surface. Then small scalps start to appear. These get larger and more packed as you go deeper. At the bottom, full mussel banks can cover the steel entirely.

This matters for inspection. Dense growth hides the steel surface. For visual inspection that is a problem. For traditional ultrasonic measurements the growth has to be removed first. But this is actually where pulsed eddy current (PEC) might be a great solution. It is a technique that can measure thickness straight through the marine growth, no removal needed. This is especially relevant knowing that in some situations, port operators and asset owners deliberately choose not to remove marine growth or rust deposits. Accumulated corrosion products and biological growth can in fact form a dense layer that limits oxygen from reaching the steel surface below (Melchers & Wells, 2006). Without oxygen, the electrochemical reaction that drives corrosion slows down. Research on actual sheet pile walls has shown that certain microbial communities, including methanogens, can live inside these layers and actively slow down further steel degradation. They do this by consuming oxygen and producing substances that form a physical barrier on the steel surface, a process known as MICI, or Microbially Influenced Corrosion



For inspection design this is important. Anodes are often mounted on the lower part of the sheet pile wall and can stick out from the surface. This creates obstacles for a system moving up and down along the wall. At the same time, these sacrificial anodes also need inspection. Their condition determines whether the corrosion protection is still working properly.

AquaSmartXL is also often asked to inspect newly installed sheet piles and ports. In these cases the goal is to verify that what was delivered and installed meets the agreed specifications. Since these walls have not had time to accumulate any marine growth, visibility is not as much of an issue when it comes

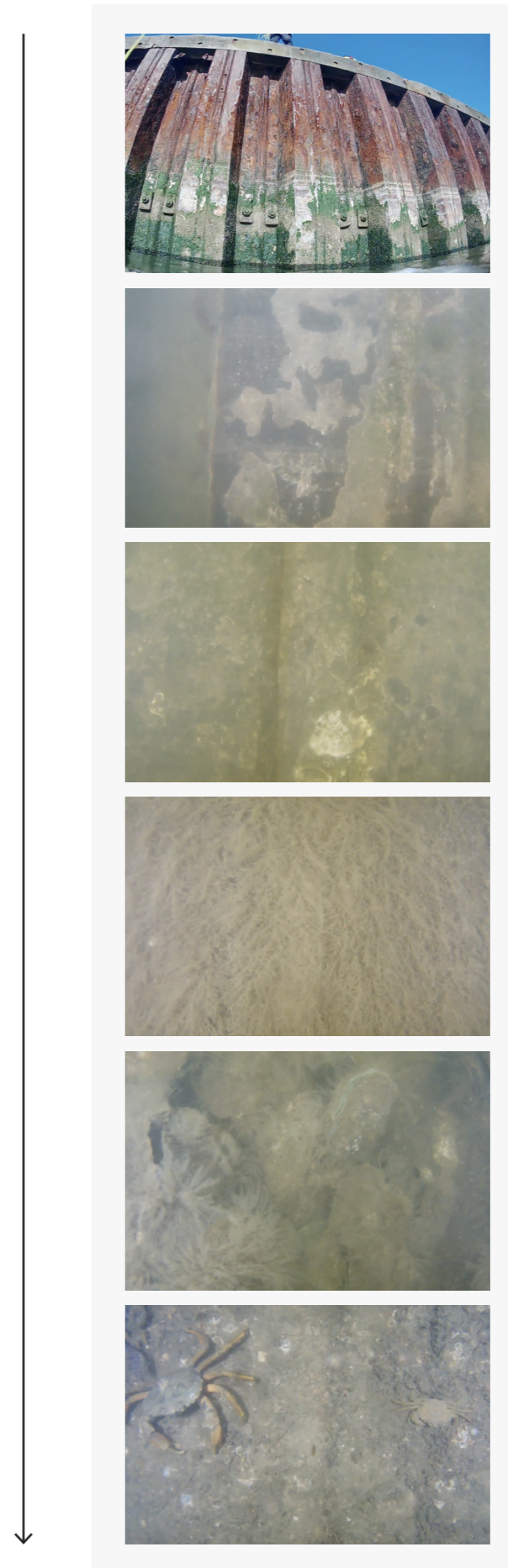


Figure 25 – ROV Footage at different Depths

2.4.2 Water Quality

Poor water quality is a well known challenge in underwater inspection. Turbidity (the cloudiness of water caused by suspended particles), currents, and ship traffic, can make visual documentation of structures unreliable or impossible (Cardaillac & Dansereau, 2025). During field research with AquaSmartXL, this was observed directly. One of the drone operators described a situation where the sheet pile was clearly visible while working, and then current shifted and pushed sediment through the water. Visibility dropped almost instantly.

In Dutch ports the water is often murky as a starting point. You can try to plan around quieter moments, but there are no guarantees. Not everywhere is like this. In clearer waters around the world some companies have been able to perform full 3D photogrammetry scans of underwater structures. In a typical Dutch harbor that is simply not realistic.

This directly affects what an inspection system can do. A solution that depends entirely on cameras is limited by what the water allows. This is another reason why staying close to the

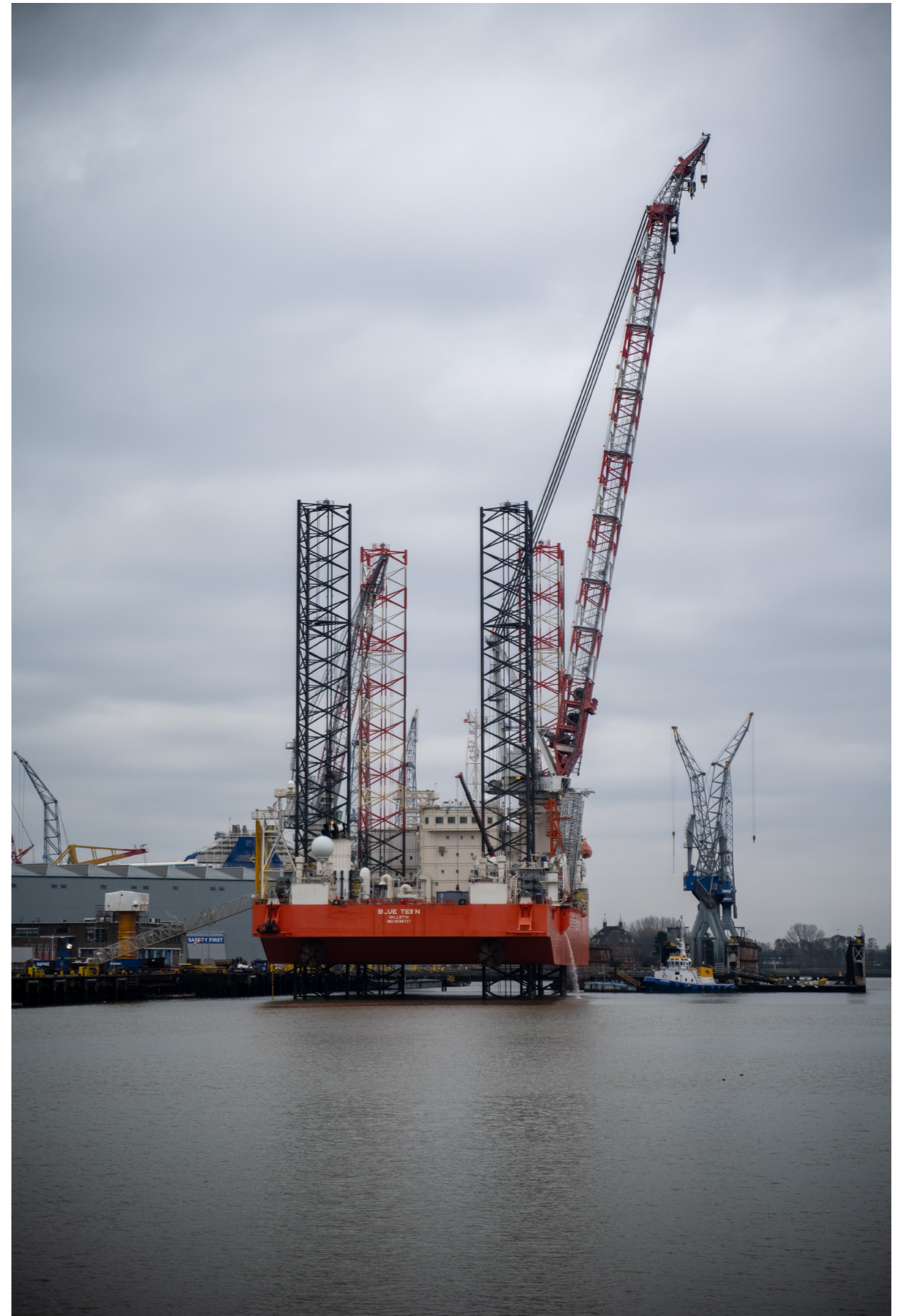


Figure 26 – Port in Schiedam

2.5 Accessibility

Understanding how sheet piles behave and degrade is important. But knowing how they are placed in their surroundings is just as important. Accessibility is one of the key factors in designing an inspection solution. If the structure cannot be reached properly, reliable inspection becomes difficult.

2.5.1 Sheet Pile Locations

Sheet piles can be found in many different places, and each place creates different challenges for inspection. They can be located under bridges, where there is little space and less light. They can be in ports or large waterfront areas, where ships, cranes, and daily activities make access more difficult. They can also be in canals or city areas, where access from land may be easier but water depth and visibility can change. The location therefore influences how the inspection system can be used and what it needs to handle

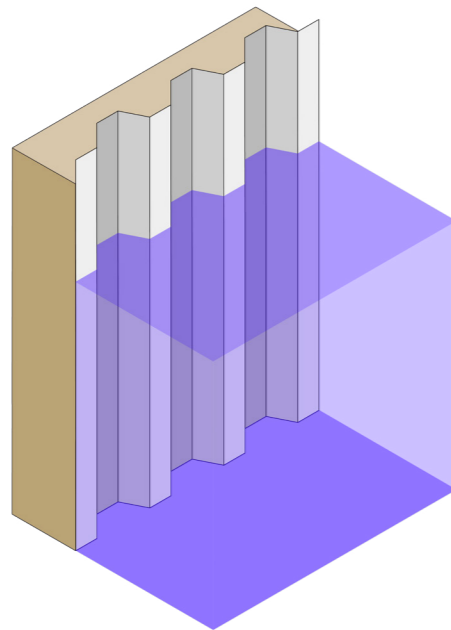


Figure 27 – Isometric Situation 1

SITUATION 1

There is no concrete slab. The soil reaches directly to the top of the sheet pile. This is the simplest situation. The upper section can be reached easily from land.

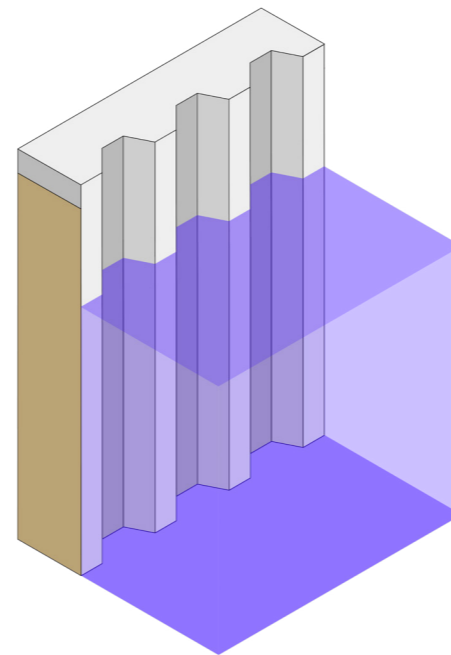


Figure 28 – Isometric Situation 2

SITUATION 2

The sheet pile reaches the same level as the concrete surface or pavement. There is no overhang. In many cases, the upper part of the sheet pile can be accessed directly from land. Inspectors can see and touch the sheet pile at the top.

2.5.2 Sheet Pile Configurations

Besides location, the way the sheet pile is integrated into the surrounding structure also influences accessibility. This could be a quay, a canal wall or a bridge foundation. The three most common configurations are shown in the figures.

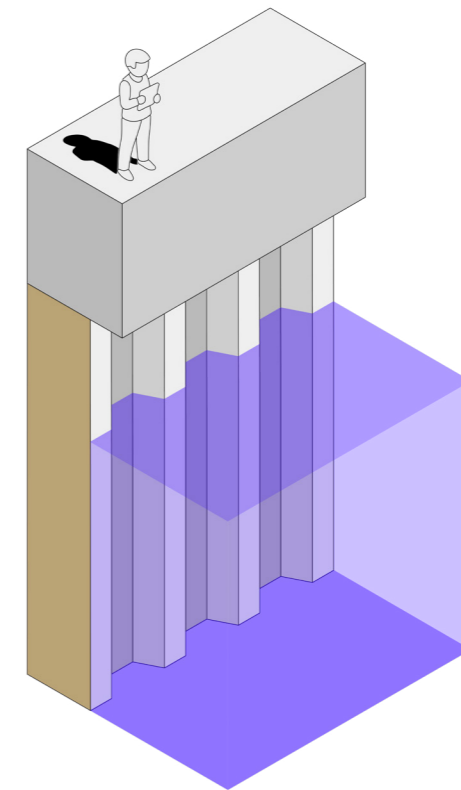


Figure 29 – Isometric Situation 3

SITUATION 3

A concrete slab is built on top of the sheet piles and slightly overlaps them. This makes it hard to reach the sheet piles. In addition to that, during high tide, the sheet pile is completely underwater and not visible. During low tide, part of the sheet pile becomes visible. In addition the concrete slab makes it hard to access from above. A real life situation is shown in figure 29.



These differences immediately raise an important question: how will the inspection system actually reach the sheet piles? In simple cases access from land might be enough. But can the design rely on that or should it also function in the most difficult situation? The hardest case is high tide combined with an overhanging concrete slab. In that situation the sheet piles are fully underwater and difficult to reach from above. To inspect them the solution must move down to the correct depth, attach safely to the sheet piles, perform its measurements and detach safely again. The challenge is not whether this needs to happen, but how it can be done in a reliable and controlled way. Accessibility therefore directly influences how the system must be designed.

This image clearly illustrates Situation one. The concrete slab extends over the sheet pile wall. The green marine growth also shows where the splash zone ends.



Figure 30 – Dummy inspection illustrating concrete overhanging sheet pile.

2.6 Inspection

After understanding how sheet piles behave and how they degrade, the next step is to look at how their condition is inspected.

Global Inspection

The first step is a general visual assessment. Inspectors travel along the wall, typically by boat, and observe it with the naked eye. No measurements are taken at this stage. The goal is to get an overall sense of the condition and to identify sections that require closer attention. As described in practice-oriented inspection strategies, this first layer of assessment is meant to quickly detect obvious structural concerns before moving to detailed investigation (Lee & Chang, 2006). This step helps determine where detailed measurements are needed.

Close-up Inspection

After the global inspection, inspectors move closer and begin measuring. To do this, marine growth is removed where necessary. Depending on the type of inspection, cleaning may be done locally at specific measurement points or over larger sections of the sheet pile.

The most common inspections performed are the following:

Remaining Wall Thickness Measurement

Remaining wall thickness is measured using ultrasonic thickness (UT) equipment. Because corrosion does not develop evenly along the wall (Section 2.3), measurements are taken at different heights to capture this variation rather than relying on a single point. These values are typically used to determine a nominal thickness. This nominal thickness represents an average value, which is then used to calculate remaining structural capacity.

The data is also compared to previous inspections to determine the corrosion rate over time. Being able to compare new data with older datasets is essential to evaluate whether degradation follows

Visual Inspection

A close-up visual inspection is performed to assess cracks, holes, and severe corrosion spots. These areas are measured and often documented using photographs.

One of the challenges is long-term tracking. It can be difficult to determine whether a crack or defect observed today is the same one that was recorded several years earlier. Clear documentation and repeatable positioning therefore become important for reliable monitoring.

Pitting

Pitting corrosion presents a specific challenge. Unlike uniform corrosion, pitting creates small but deep local defects. These pits can significantly reduce thickness at one specific location while the surrounding material remains relatively intact.



Because nominal thickness is based on average values, deep pits may not be fully represented in the data. As discussed earlier and confirmed in Interview 1, this can lead to a misleading understanding of the actual structural condition. A sheet pile may appear acceptable based on average thickness, while locally it is already critically weakened.

2.7 Current Inspection Methods

Now we know what to look for when inspecting a metal sheet pile. We should look at the current inspection methods. What are their advantages and disadvantages. Is the inspection solution going to compete with them or work alongside them?

2.7.1 Divers

The most common method are divers. A trained diver goes down and performs visual inspections and thickness measurements.

+ Advantages

A diver is flexible. They can move around freely and reach complex shapes and tight corners. They can respond to what they see in real time. No heavy installation is needed.

- Disadvantages

Diving is slow and expensive. Safety is always a concern. Visibility underwater is often poor. Soft silt can shift under your feet. Passing ships create waves and movement. Large safety zones are required which means part of the quay cannot be used. That costs money. Some areas are simply too risky to inspect, especially the area where MIC bacteria often settle.

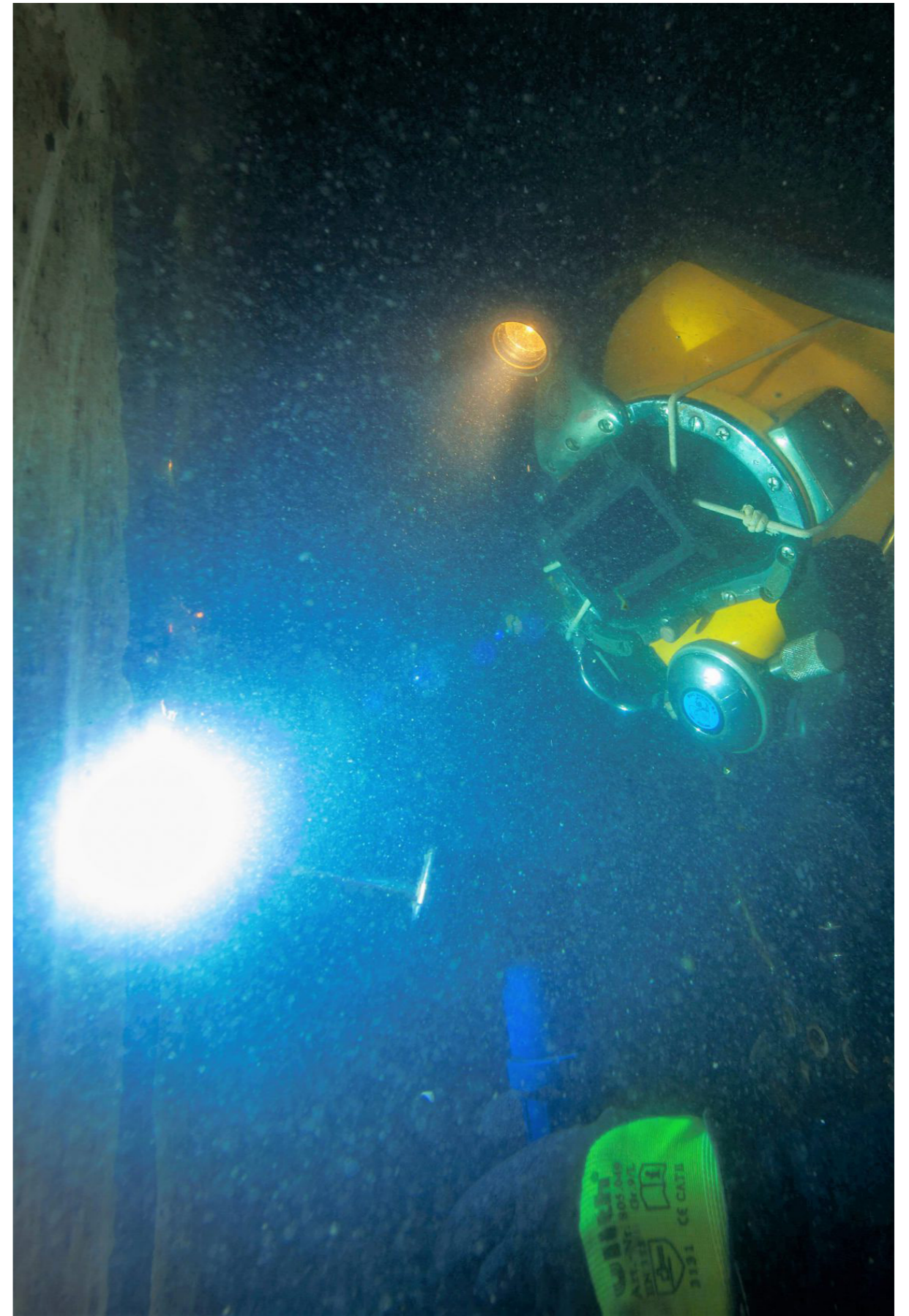


Figure 31 – Diver

2.7.2 Local Cofferdams

Another method is placing a local cofferdam around part of the sheet pile. The water is pumped out so the steel becomes visible.

+ Advantages

You can inspect in dry conditions. Measurements are more accurate. Cracks and corrosion are easier to see. The results are reliable and well documented.

- Disadvantages

It is expensive. It takes time to build and remove. Port operations often have to stop during the process. In busy ports this is a serious drawback. In quieter areas it might be less of a problem.



Figure 32 – Local Cofferdam

2.7.3 Mobile Elevated Work Platforms (MEWP)

In some cases platforms or lifting systems are used to reach the wall from above. These are often used in the splash zone.

+ Advantages

No diving is needed. This improves safety. Setup is fast. It works well for inspections above water level.

- Disadvantages

Access depends on tides. Only the visible part above water can be inspected.



Current inspection methods all work. But they come with trade offs. Diving requires large safety zones which reduce port capacity. Cofferdams take time and interrupt operations. Platforms only cover part of the wall. Some of the most critical areas, like the zone where MIC bacteria prefer to grow, are also the hardest and most risky to inspect.



Figure 33 – MEWP

2.7.4 Similar Inspection Methods in Different

Sheet pile inspection is not the only field that deals with the challenge of inspecting underwater steel structures. It is worth looking at what already exists in other industries and whether any of those solutions could work here.

Underwater inspection robots have been developed for several contexts. Pipeline crawlers move through or along pipes. Remote Operated Vehicles (ROVs) are used for offshore structures and ship hulls. Bridge inspection systems work on concrete and steel in wet environments. Each of these has been refined over time for its specific context.

The closest comparison to sheet pile inspection is ship hull cleaning and inspection. Companies like CLINN Robotics and GE Inspection Robotics have developed magnetic crawlers that attach to steel hulls, move along the surface, and perform measurements or cleaning. The environment is similar in some ways. Steel, salt water, and the need to work without taking the structure out of service.

But ship hulls and sheet piles are fundamentally different in the ways that matter most for this kind of system.

Ship hulls are large, gently curved, and relatively clean surfaces. They are regularly maintained and coated, which gives magnetic wheels a consistent and smooth surface to grip. Sheet piles are the opposite. The surface is rough, heavily corroded, and often covered in marine growth. This alone makes magnetic traction behave very differently.

The geometry is another problem. Existing crawlers are built for flat surfaces. They use rigid frames that cannot adapt to the sharp angles of Z and U profiles. They are too large to fit into the narrow inner pockets of a sheet pile where some of the most critical corrosion occurs. And they cannot handle the obstacles that are common on sheet piles such as anchor heads, bolts, and sacrificial anodes.

Existing systems are placed and removed by hand. Because the magnets are so strong, separation is done using special ramps that slowly peel the robot away from the surface. That works fine on an open ship hull where someone can just walk up to it. On a sheet pile tucked under a concrete overhang, two meters underwater, in an active port, that is simply not an option. This means that for the sheet pile solution has to be able to attach and detach from a distance.

In short, while ship hull crawlers prove that magnetic traction works in principle, none of them can be directly applied to sheet piles. The geometry, obstacles, surface conditions, and access requirements are different enough that an existing system simply does not fit. This is what makes a dedicated solution necessary.

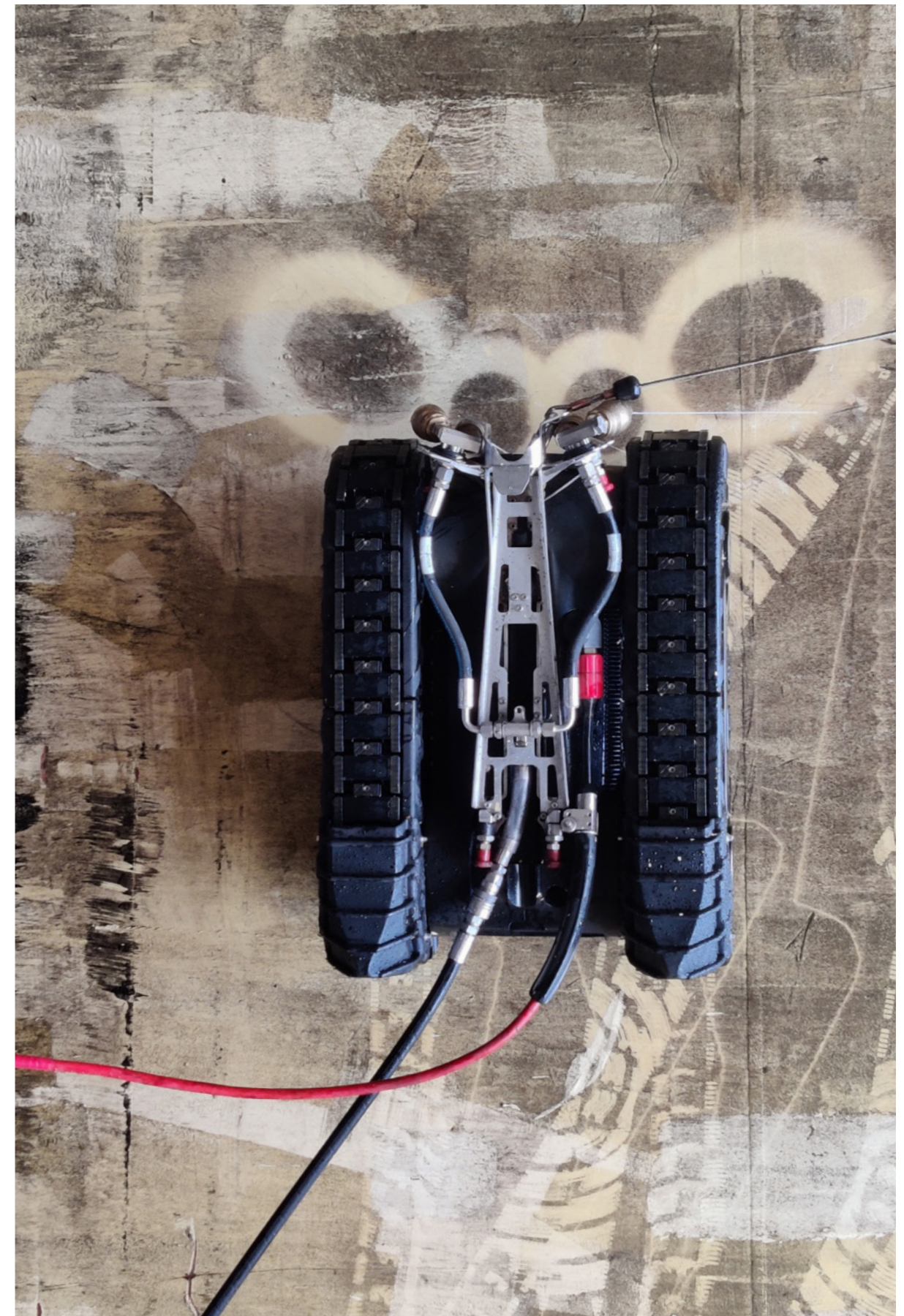


Figure 34 – CLINN Robotics Crawler

CLINN Robotics: <https://cliin.dk>

GE Inspection Robotics: <https://www.sintef.no/globalassets/sintef-digital/arrangementer/erf19-ge-inspection-robotics.pdf>

2.8 Inspection Strategy and Segmentation

Another interesting point is that different port owners like to organise inspections in different ways. There is no single best method. It depends on how the port operates.

Some prefer segmented inspections. This means checking small sections spread out over the full length of the quay. Imagine a 200 meter quay wall. There is only time and budget to inspect 20 meters. One option is to inspect 2 meters every 20 meters. Start at the first spot. Inspect and measure. Then walk 20 meters down the quay and do the next spot. Repeat this until the full wall has been sampled. Like taking small bites instead of eating one big piece at once.

This gives a wider overview of the whole quay. If one area looks very different from the others, it stands out quickly. It also helps check if the wall is degrading evenly or if certain zones are aging faster. Others prefer a different approach. They take those same 20 meters and inspect them as one continuous stretch. For example from 80 to 100 meters. That full section is cleaned, inspected, and measured in detail. A few years later, the next inspection might cover the next 20 meters. This is often easier to plan. Ports are busy places. Some quays are in use 85 to 90 percent of the time. Closing one clear section for a few days is simpler than closing five small sections spread across the quay. It requires less coordination. And it is easier for ships and terminal operators to work around.



Both methods make sense. One gives a broad overview. The other is easier to organise. For a new inspection solution this matters. It should support both ways of working. Small sections spread out over a long wall, and also one larger section inspected in one go.

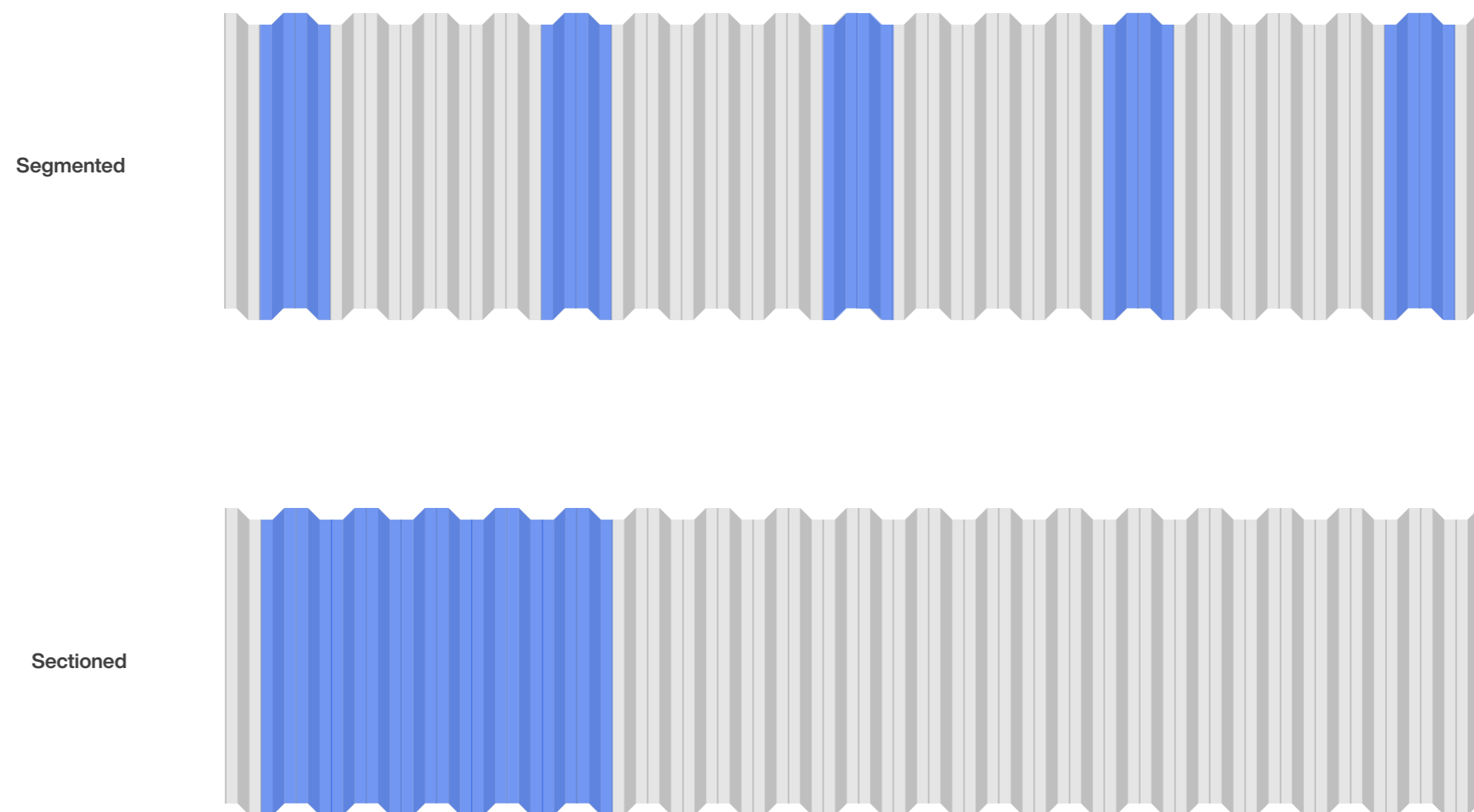


Figure 35 – Segmentation for inspection

2.9 Key Findings

The research phase produced the following findings. They are grouped by theme.

1. **Steel is the dominant sheet pile material, so corrosion in steel is the primary inspection concern.**
 - 1.1 Most quay walls and port structures in the Netherlands are built from steel sheet piles.
 - 1.2 Steel corrodes when exposed to salt water, oxygen, and marine organisms.
2. **Sheet pile geometry varies widely, but the outer face is always a usable surface.**
 - 2.1 Sheet piles exist in Z, U, Omega, flat, and combi wall profiles.
 - 2.2 Interlocks are not rigid. They allow small rotations.
 - 2.3 Despite all this variation, the outer face of a sheet pile is almost always flat and clear. Anchor heads, anodes, and other hardware are nearly always mounted on the inner side.
3. **Corrosion does not develop evenly. The most aggressive zones are also the hardest to reach.**
 - 3.1 The splash zone corrodes fastest because of constant wet-dry cycling.
 - 3.2 Near the mudline, MIC bacteria eat away the steel.
4. **The most dangerous degradation is invisible from the surface.**
 - 4.1 Pitting creates deep local cavities while average wall thickness still looks acceptable. A sheet pile can appear fine while already being critically weakened.
 - 4.2 When corrosion creates a hole in the wall, soil behind it starts to wash out. With cobblestone surfaces, this can actually be seen. The stones move with the soil beneath and start to shift or sink. With concrete slabs it is a different story. The slab bridges over the void and shows nothing until it suddenly breaks through entirely.
5. **Physical access is often blocked by the structure built on top of the sheet pile.**
 - 5.1 In a common worst case scenario, a concrete slab overhangs the sheet pile. During high tide the wall is fully underwater and unreachable from above.
 - 5.2 The system must be deployable from the quay edge or a small vessel. It cannot rely on someone placing it by hand.
6. **Corrosion protection slows degradation but creates new complications for inspection.**
 - 6.1 Coatings, galvanizing, and cathodic protection are all commonly used.
 - 6.2 Sacrificial anodes stick out from the wall. They need to be avoided during movement and inspected for remaining capacity.
 - 6.1 Marine growth and rust layers can actually slow corrosion by blocking oxygen from reaching the steel. Removing them restarts the process.
7. **Visibility in Dutch harbors is unreliable and cannot be planned around.**
 - 7.1 Currents, ship traffic, and sediment can drop visibility to near zero within minutes.
 - 7.2 Marine growth does not follow a predictable pattern. On average, growth increases with depth, from bare rusted steel in the splash zone to dense mussel banks at the bottom. But unexpected patches, sudden gaps, and irregular layers are common enough that no inspection system can assume what it will encounter.
 - 7.3 Dense growth must be removed before traditional ultrasonic measurement. Pulsed eddy current and UT Probes can measure through growth without removal.
 - 7.4 For visual inspection, staying close to the wall is essential. In murky water, image quality drops quickly with distance. A system that presses against the surface captures far more usable data than one floating freely in the water.
8. **No existing method covers the full wall without major trade offs.**
 - 8.1 Divers are flexible but require large safety zones that shut down port operations. The mud line zone is often too risky to reach at all.
 - 8.2 Cofferdams allow dry and accurate inspection but are expensive, slow, and highly disruptive.
 - 8.3 Platforms and cranes only reach the splash zone above water.
 - 8.4 Ship hull crawlers show that magnetic traction on steel works in principle. But their rigid geometry, large size, and manual detachment make them incompatible with sheet pile conditions.
9. **Port operators work differently and a new solution must support both approaches.**
 - 9.1 Some owners inspect small sections spread across the full quay to get a broad picture of how the wall is aging.
 - 9.2 Others inspect one continuous stretch in full detail, which is easier to plan around port operations.
 - 9.2 Quays are in active use 85 to 90 percent of the time.

3

Chapter 3 Development

- 3.1 Scope
- 3.2 Requirements
- 3.3 Develop Ideas
- 3.4 Harris Profile
- 3.5 Concept Development
- 3.6 Concept Refinement



3.1 Scope

The research reveals many challenges. Corrosion develops mostly in the splash zone. Obstacles such as anchor heads and sacrificial anodes interrupt the surface. Sheet pile profiles vary in shape and size. Ports operate under tight logistical constraints. Designing a complete inspection robot within this timeframe is not realistic. The system would become too complex and too broad in scope.

Current methods each solve part of the problem. Divers can get close to the wall but data collection is slow, inconsistent, and comes with serious safety risks. Cofferdams allow accurate inspection in dry conditions but take days to assemble and disassemble. ROVs and surface vehicles struggle to maintain stable close contact with the wall. No current method combines reliable wall contact, safe operation, and practical deployment in an active port.

That is the gap this project addresses.

Before measuring thickness. Before cleaning for inspection. Before creating a digital twin. A system must first be able to reach the sheet pile and move along it in a reliable way. This is the focus of this project. The scope is to develop a mechanical platform that does four things well:

Attachment and detachment: safely attaching and releasing the system in hard to reach areas.

Surface interaction: maintaining reliable contact on a rough, corroded, and marine growth covered surface.

Fit to geometry: adapting to different sheet pile profiles and handling obstacles like anchor heads and anodes.

Stability and movement: moving vertically along the wall in a controlled way.

Staying close to the wall is essential. Cleaning tools require contact with the surface. Thickness measurements depend on a stable distance to the steel. And for AquaSmartXL, operating close to the structure is especially important. Their strength lies in generating detailed 3D models of the structures they inspect. In murky water, image quality and accuracy improve significantly when the platform remains close to the wall.

By focusing on reliable attachment and detachment and controlled movement, this project aims to create the mechanical foundation that future inspection systems can build upon.

The next section defines this scope more clearly by turning it into requirements that help test and compare different design ideas.

After getting a better understanding of the key findings, it is time to turn them into design choices. Before jumping into solutions, the findings first need to be narrowed down into clear requirements. The research shows many possible improvements, but also many caveats. The inspection solution has to deal with limitations like visibility, marine growth, and obstacles. At the same time, the solution is also shaped by something simple: time. This graduation project has a limited scope. Building a fully finished product would be valuable for AquaSmartXL, but it is not realistic within this project timeline. So the focus shifts to the next best thing. A direction that is valuable, testable, and achievable.

This chapter defines that direction. It explains the scope of the physical platform and what is included and excluded. After that, the key findings are translated into concrete requirements.

3.2 Requirements

Based on the research and key findings from Chapter 2, a set of requirements was defined. Because this project addresses a gap that no existing solution has fully solved before, many boundaries are still unknown. Defining too many hard constraints at this stage would close off directions before they have been explored. The requirements below therefore focus on what is known and leave room for the design process to reveal what is not. Where specific values are given, the reasoning is explained. All other values will be refined through testing and iteration. The full requirements list can be found in the appendix.

Main Platform

- RQ.1 Must move vertically along steel sheet pile walls.
- RQ.2 Must fit both U-profile and Z-profile sheet piles.
- RQ.3 Must stay securely attached to the steel surface during operation.
- RQ.4 Must operate both above and below the waterline.
- RQ.5 Must pass obstacles including anchor heads, sacrificial anodes, and interlock ridges.

- RQ.6 Must remain attached during a temporary power loss.
- RQ.7 Must be deployable from a quay edge or small vessel without manual placement on the wall.
- RQ.8 Must be operable by a maximum of 2 people, reflecting standard AquaSmartXL crew size.

Attachment

- RQ.9 Must attach to corroded, uneven, and marine growth covered steel.
- RQ.10 Must support a total system weight of 1 - 20 kg both above and below water.

Mobility

- RQ.11 Must allow controlled upward and downward movement.
- RQ.12 Must be able to stop and hold position at any point along the wall.

Environment and Robustness

- RQ.13 Must operate in wet, splash-zone, and fully submerged environments.
- RQ.14 Must tolerate saltwater exposure without losing functionality.
- RQ.15 Must operate at depths up to 30 m. A safety factor of 2 gives a design target of 60 m.
- RQ.16 Must function in harbor temperatures between 0°C and 25°C.

Safety

- RQ.17 Must be operated from a safe distance without requiring anyone in the water.
- RQ.18 Must not create falling-object risks during operation.
- RQ.19 Must enter a safe state in case of malfunction.
- RQ.20 Must be safely detachable in case of failure, including from a distance.

Modularity

- RQ.21 Must allow future integration of modules such as cleaning tools and sensors.
- RQ.22 Must support phased development, starting with the platform before adding inspection capabilities.

Wishes

- W.1 Should be transportable using a standard passenger van.
- W.2 Should support localized cleaning of inspection areas.
- W.3 Should support integration of ultrasonic thickness measurement sensors.
- W.4 Should allow semi-autonomous inspection modes.
- W.5 Should allow automatic logging of inspection locations.
- W.6 Should be operable by a single person.

3.3 Develop Ideas

With the scope, design direction, and requirements established, the interesting part begins: developing concepts and ideas.

The system is quite complex. Many of its features, such as attachment and movement along the sheet pile, cannot be seen as separate from one another. They are reliant on each other. On top of that, choosing a certain locomotion method can also influence the geometry of the platform, which in turn affects how it handles obstacles. This connected web of dependencies is hard to visualize and easy to lose track of.

To make it easier to understand and to generate many ideas at once, an evolution tree was created. It uses two layers: one for the attachment method and one for the locomotion method. The reasoning is that by thinking about attachment and locomotion together, combinations that simply would not work are eliminated early. This directly addresses the interconnected nature of the design challenge.

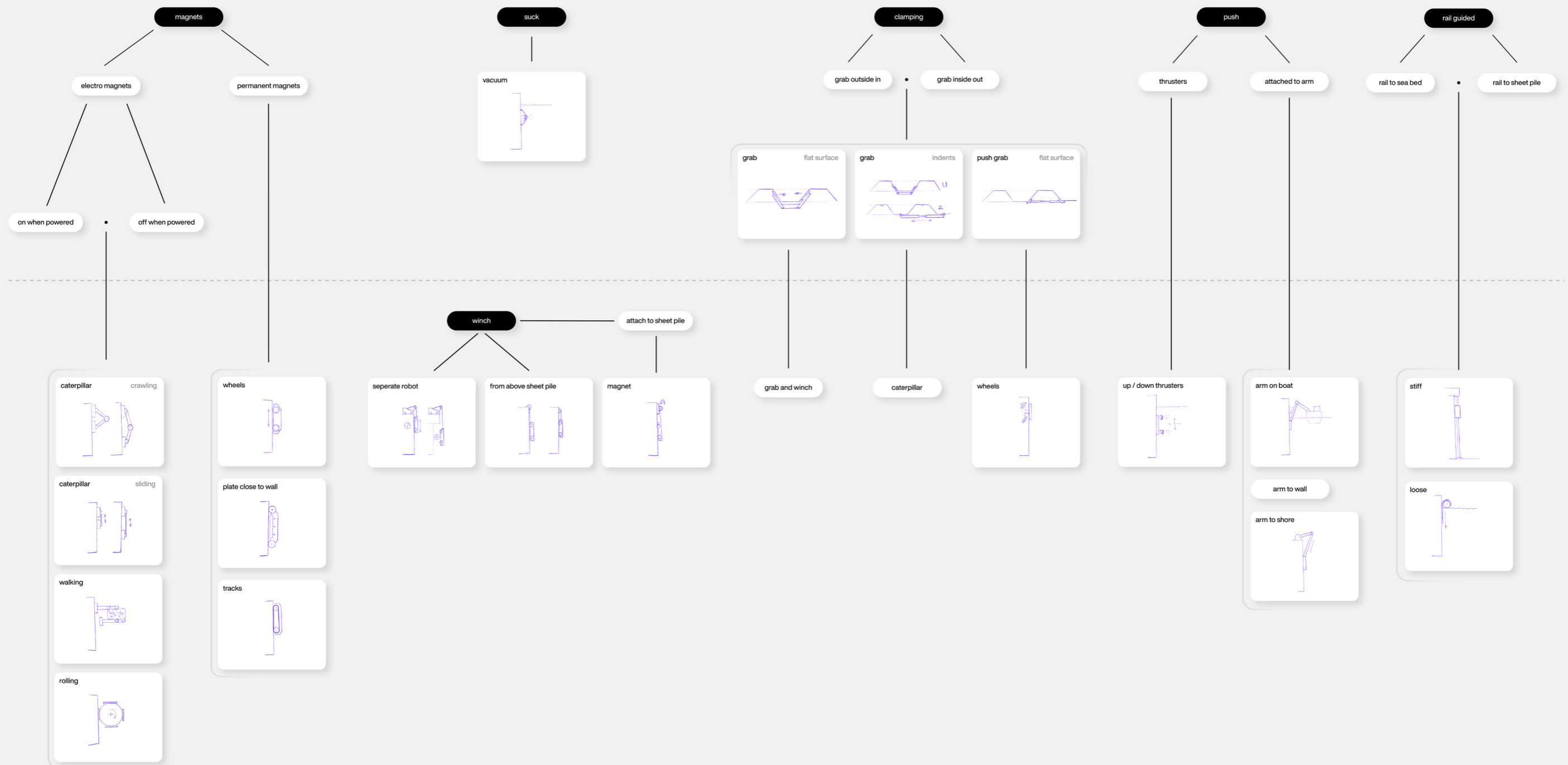


Figure 36 – New sheet piles being installed in Rotterdam

Design Tree

Stick to wall and move up and down

3.3.1 Attach and move up and down





Magnets

Magnetic attachment is the most natural starting point for a steel surface. Steel and magnets are naturally attracted to each other. Because the sheet pile is made of steel, the wall itself becomes the attachment point. No extra system is needed to create that connection.

Two types of magnets are worth considering: electromagnets and permanent magnets. Electromagnets can be switched on and off, and their force can be adjusted. The downside is that they need constant power and extra wiring. Depending on how the platform moves, that wiring quickly becomes a problem.

Permanent magnets are simpler. They hold without any power or extra hardware. The tradeoff is that they are always on. This makes controlled attachment and detachment harder to design for. If all drive systems fail, removing the platform from the wall becomes a challenge in itself.

A challenge with magnetic attachment is that magnets perform best when they are in direct contact with the steel. On a real sheet pile, this is rarely the case. Corrosion, marine growth, coatings, and surface irregularities create a gap between the magnet and the wall. Even a small gap can significantly reduce the magnetic force. This means that the attachment force depends not only on the magnet itself, but also on the condition of the sheet pile.

With permanent magnets, the platform is constantly being pulled toward the steel. This magnetic force creates the normal force needed for movement. Different drive systems can use this force to generate friction and move along the wall. Examples of this are wheels and tracks, which both rely on the magnetic force to maintain grip on the surface.

For sheet piles, surface condition matters a lot. Marine growth, corrosion, and uneven geometry all reduce how well the magnets hold. This is not a reason to abandon magnets. It is a reason to understand their behavior and design around these limitations.

The following section shows the prototypes built to test two of these approaches.

Magnetic Wheels Prototype

The simplest way to use permanent magnets for locomotion is wheels. Few moving parts, straightforward mechanics, and a well understood principle. At this stage of the project, magnetic attachment was one of the concepts under consideration, but it was still unclear how permanent magnets would behave on a sheet pile surface. Since there was little intuition for the forces involved or the practical challenges of moving with magnetic wheels, a first prototype was built. The goal was not only to determine whether magnetic attachment was viable, but also to gain a better understanding of the technology and learn from its behaviour in practice.

The prototype uses two magnetic wheels built from 200N lateral pull force magnets. An ESP32 microcontroller and two TMC2209 stepper drivers control the system, which can be operated remotely via a PS5 controller. Skid steering is used to keep the platform aligned with the sheet pile. In the first version the magnetic force was too strong for the motors to overcome, so planetary gearboxes with a 4:1 ratio were added to generate enough torque to drive the wheels. The full electrical schematic can be found in the appendix.

The results were better than expected. The prototype attached reliably, moved stably, and proved that

Key findings:

- Traction depends entirely on magnetic contact. Surface irregularities created small gaps between the wheel and the steel, reducing grip. Independent suspension per wheel is important to maintain contact on uneven surfaces.
- Steering is a necessity, not a luxury. A system that can only move in a straight line will gradually walk off the sheet pile if it is not perfectly aligned on attachment. The ability to correct alignment during movement is essential.



Figure 37 – Magnetic wheels prototype



Figure 38 – Driving over container wall

Magnetic Plate Close to Wall Prototype

The magnetic wheels prototype showed that magnetic contact works. But it also raised a question: what if instead of concentrating the magnetic force in two wheels, it could be spread across a larger surface area? More magnets in close proximity to the steel should mean more total holding force. This idea led to the second prototype.

The prototype consists of two plates, each holding eight of the same 200N magnets, giving a combined lateral pull force of around 160 kg. Two rubber wheels were placed on opposite ends of the plates. The rubber was chosen to increase grip without changing the distance between the magnets and the steel surface. A screw and bolt mechanism was added to control how close the plates sat to the wall, allowing the distance to be adjusted during testing.

In practice the prototype immediately revealed a fundamental problem. At close range the plates snapped violently onto the steel surface. Maintaining a specific distance proved nearly impossible. The 3D printed parts flexed slightly under the magnetic load, which reduced the gap just enough for the magnets to grab even harder. This created a self-reinforcing effect that was very difficult to control.

This behavior points to something important about how magnets work. The closer a magnet gets to a steel surface, the force does not increase gradually. It increases exponentially. The figure below illustrates this. Because the force changes so fast with distance, even a tiny shift, like the frame flexing slightly, is enough to pull the magnet in harder and harder. This makes it very hard to keep a steady gap between the magnet and the wall.

Key findings:

- A plate based approach generates very high holding force but is extremely difficult to control at close range.
- Magnetic force increases exponentially with proximity, making a fixed standoff distance hard to maintain mechanically.
- Direct contact through magnetic wheels proved more controllable and reliable than a suspended plate approach.

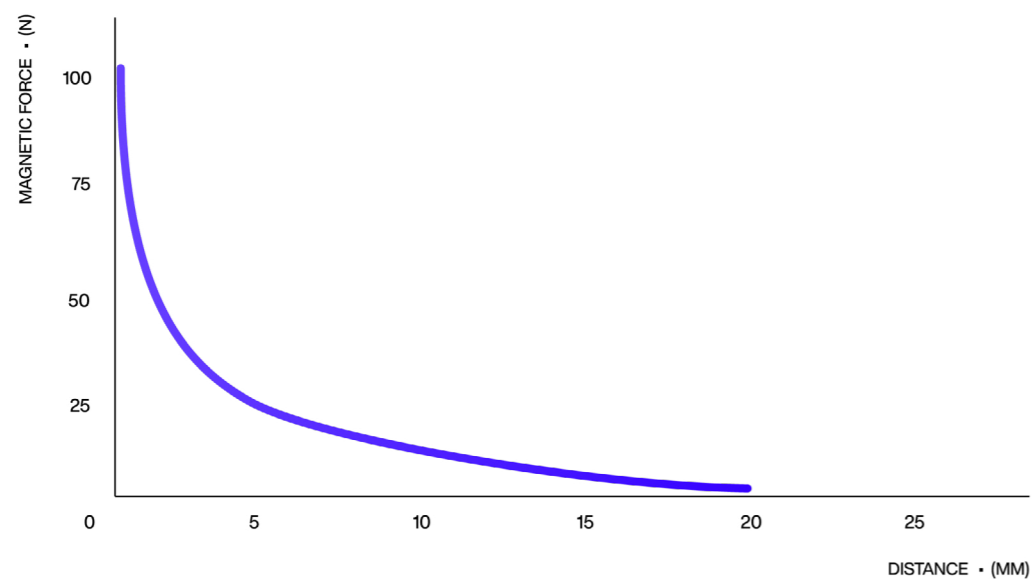


Figure 39 – Table illustrates magnetic force over distance

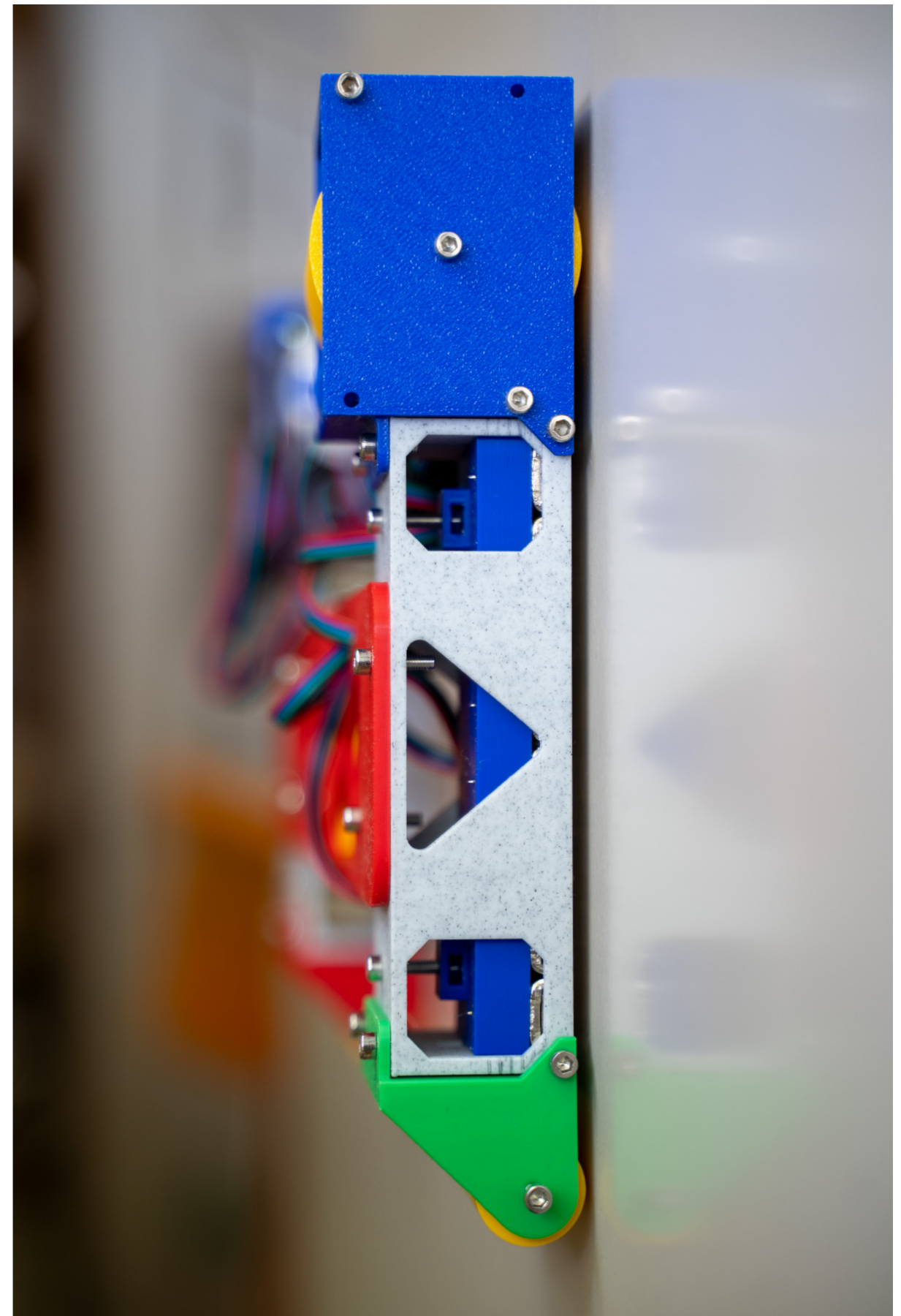


Figure 40 – Magnetic plate close to wall prototype

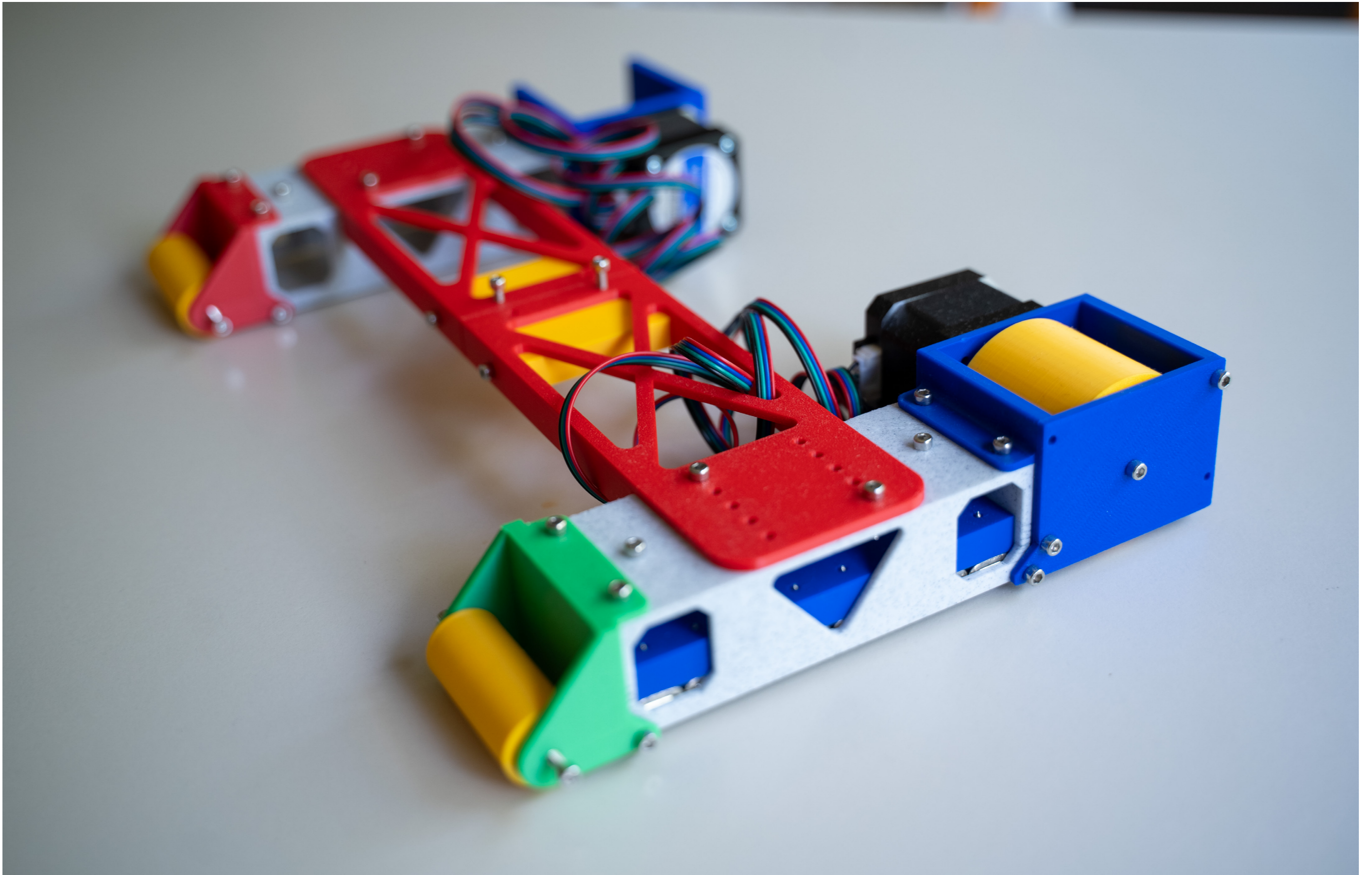
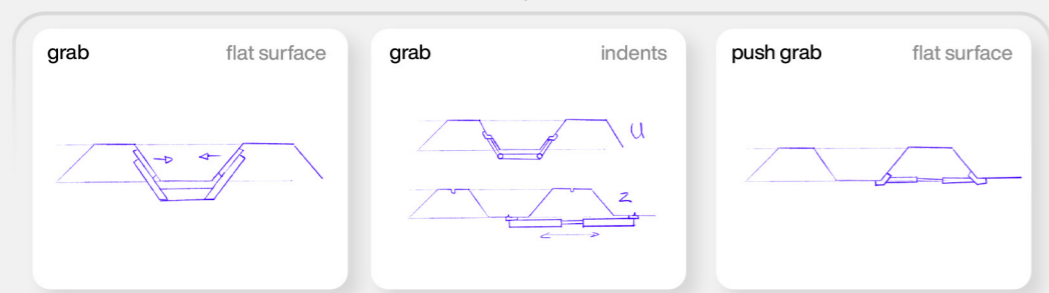
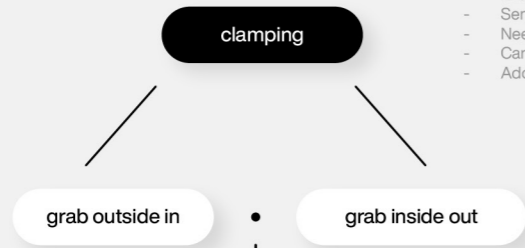


Figure 41 – Magnetic plate close to wall prototype

- + Enables close inspection / cleaning
- Sensitive to surface condition (rust, fouling)
- Needs reliable force/control
- Can get stuck on obstacles
- Adds mechanical complexity



- + Works on many profiles
- + Simple design
- Depends on friction
- Weak in wet/fouled conditions

- + Strong, mechanical lock
- + Less slip
- Needs specific profile
- Harder alignment

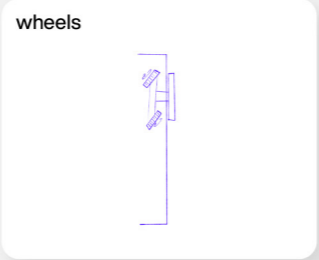
- Needs access inside profile
- Limited space

grab and winch

- + Attached to one solid point
- + Reliable up and down movement
- Cannot move above water
- Swinging
- 2 systems (winch and inspection device)
- Less control near surface

caterpillar

- + Always attached
- + reliable up and down movement
- unreliable grip strength
- many moving parts



- + Continuous motion
- + Simple drive system
- Limited contact area
- Sensitive to surface condition
- Reduced grip on edges / gaps
- Requires sufficient normal force
- Hard to avoid obstacles

Clamping

Clamping is one of the most intuitive ways to attach something to an object without making it permanent. No special material properties needed, just geometry and force pressing against a surface.

For sheet piles however, clamping turns out to be surprisingly difficult. The angled sides of the profile work against any gripping mechanism. When force is applied to clamp onto the sheet pile, the geometry causes it to slide off rather than lock on. As illustrated in Figure 42, there is simply no place to wrap around and create the opposing forces needed to stay in place.

On top of that, friction based clamping depends on knowing how grippy the surface is. On sheet piles this is impossible to predict. Some walls have no marine growth, others are heavily fouled. Different types of growth behave differently under load. A system that relies on friction has to work across all of these conditions, which makes it very hard to guarantee a reliable hold.

A small prototype was built to test this (appendix F). It confirmed the problem quickly: the angled geometry caused the prototype to slide and jump off the profile rather than grip it. The concept was not developed further.

Key findings:

- The angled geometry of sheet pile profiles causes clamping forces to slide off rather than lock on.
- Friction based attachment is unreliable due to unpredictable surface conditions in the field.

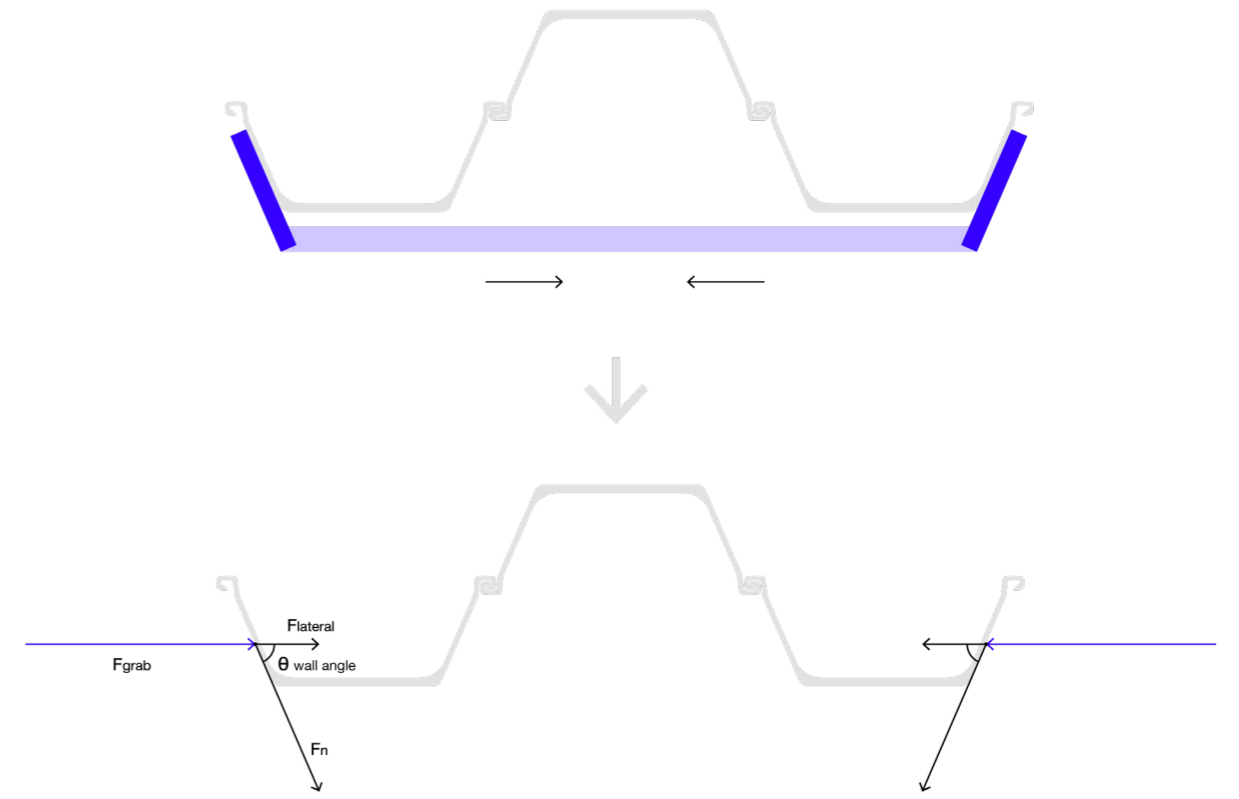
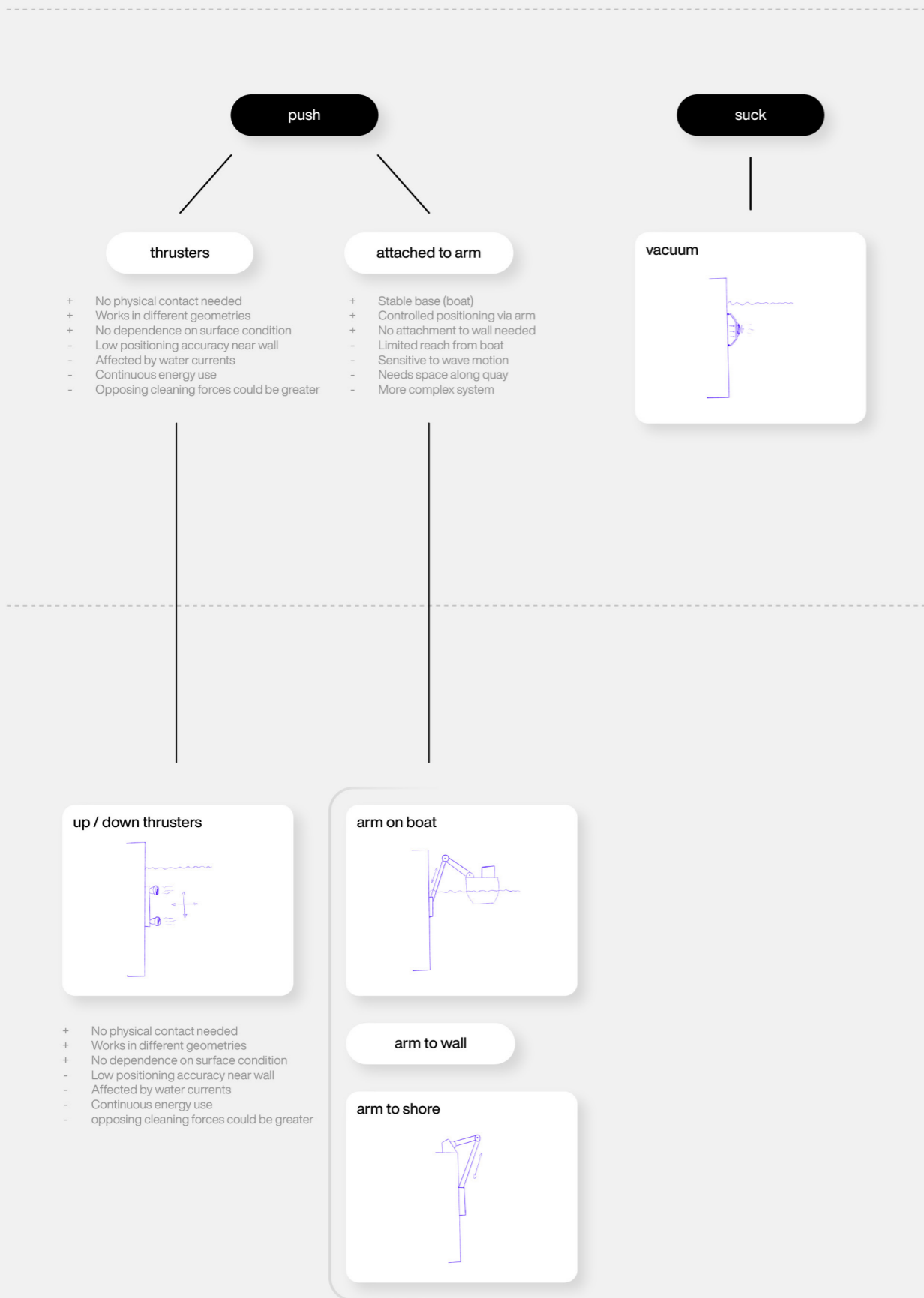


Figure 42 – Illustration of forces when clamping a sheet pile



Push and Suck

Both of these approaches share something interesting: unlike magnets or clamping, they do not rely on the geometry or material properties of the sheet pile itself to attach. Instead, external forces are used to stay close to the wall. In that sense, calling it “attachment” is almost a stretch.

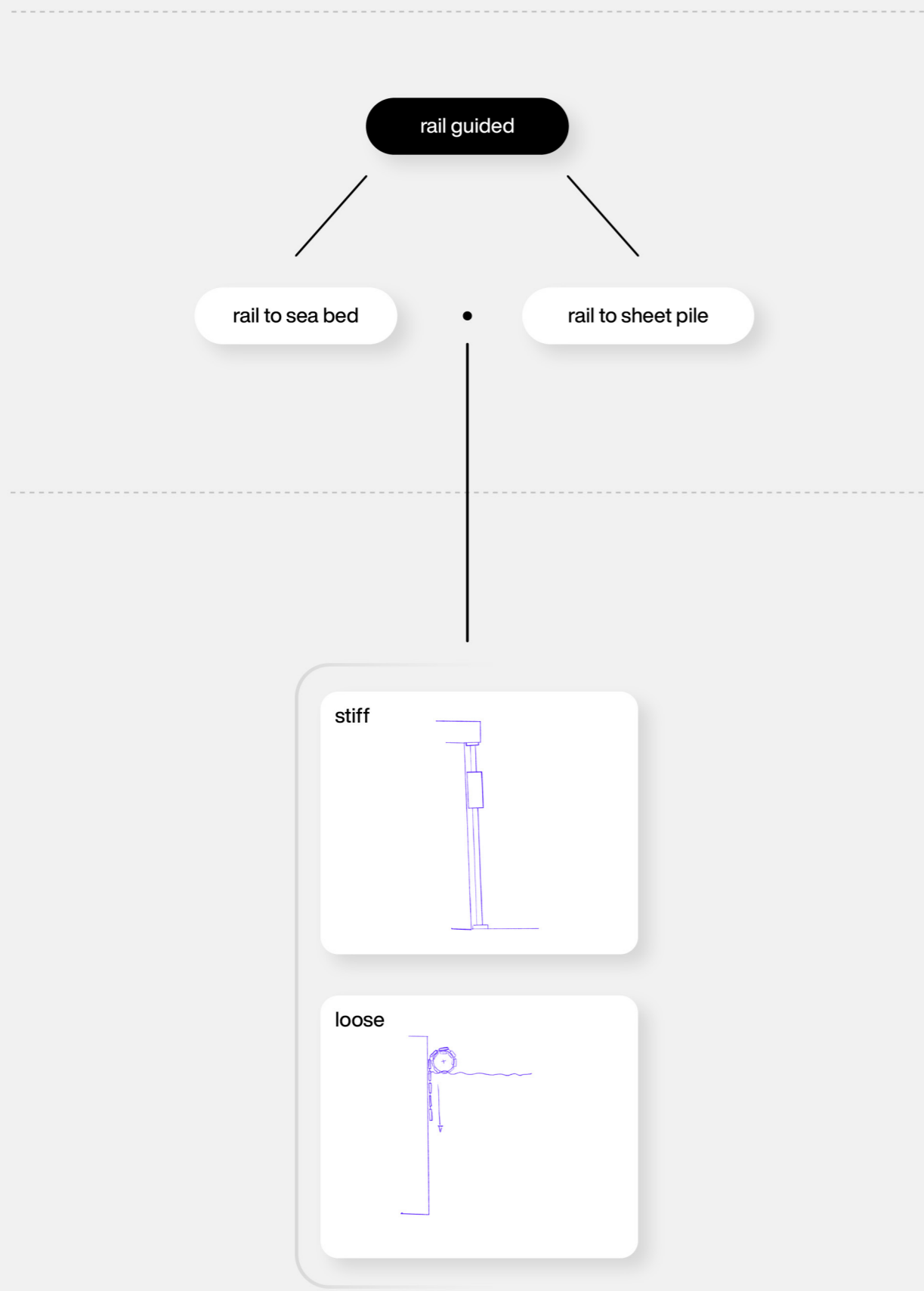
Thrusters are the most compelling case within this category. A thruster pushes the platform against the surface using water pressure. It does not need steel, it does not need a specific profile, and it does not need surface contact. Unmanned surface vehicles already use thrusters to navigate underwater, but staying consistently close to a sheet pile wall without bumping into it is difficult to control reliably.

This is where an opportunity emerges. If thrusters are combined with a platform that is already shaped around the sheet pile geometry, the platform can use that geometry to guide itself along the wall while the thrusters provide the pressing force. No magnetic contact needed, no clamping. The wall itself becomes the guide rail. The limitation is that thrusters only work underwater. A hybrid approach would still be needed to inspect the parts of the sheet pile above the waterline.

An arm mounted on a boat or dock could also create a pushing force, but the scale and complexity this introduces makes it impractical within the scope of this project.

Vacuum attachment is a different story. Technically, it does not need to be perfectly sealed. A lower-pressure zone could still be created with an imperfect seal, as long as enough water is continuously pumped out of the chamber. However, this would mean the system needs a high flow rate to compensate for all the leakage.

For this prototype, that makes vacuum attachment less realistic. Sheet piles are often corroded, dirty, covered in marine growth, and geometrically uneven. On that kind of surface, the suction chamber would probably leak a lot, which would make the attachment unreliable and energy heavy. So while vacuum attachment is not impossible in principle, it is not the most suitable direction for this prototype.



Rail Guided

Instead of relying on the sheet pile itself for attachment and movement, a rail system places an external guide close to the wall. The platform then moves along this rail rather than the sheet pile directly. The rail could be anchored to the seabed, rolled out from a boat, or mounted just above the sheet pile edge.

As a locomotion method this is reliable. Movement up and down is controlled and predictable, independent of surface conditions, marine growth, or profile geometry. In theory it solves many of the problems the other approaches struggle with.

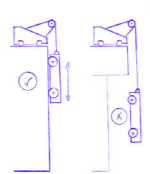
The problem is everything around the movement itself. Installing a rail in a harbor environment is a significant operation. The setup is large, complex, and time consuming. For a system that should be deployable by two people from a quay edge or small vessel, this introduces a level of logistical complexity that outweighs the benefits.

- + Simple vertical motion (cable based)
- + Can support full system weight
- + Continuous movement (no stepping)
- + Controlled up/down positioning
- Needs mounting point above
- Sensitive to swinging (pendulum effect)
- How to handle overhangs?
- Cable management required

winch

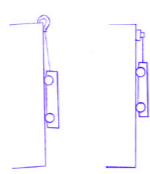
attach to sheet pile

seperate robot



- + Easy to set up
- + Stable platform
- + Independent from wall
- Specific to situation
- Harder to position near wall
- Less direct control at surface

from above sheet pile



- + Easy to set up
- + Stable platform
- + Direct vertical access
- Specific to situation
- Needs top access
- Obstacles

magnet



Winch

A winch uses a cable to control vertical movement. Simple and reliable, it can support the full system weight and moves continuously without the complexity of driven wheels or tracks. In situations where the sheet pile is easily accessible from above, it is a practical solution.

The problem is that sheet piles are often not easy to reach from above. Concrete overhangs, overhanging structures, or locations only accessible by water make finding a solid mounting point difficult or impossible. And even when a mounting point exists, the cable does nothing to prevent the platform from swinging. In open water with currents, keeping the platform close to and aligned with the wall becomes unreliable.

That said, a winch does offer something the other approaches struggle with: reliable controlled movement above the waterline. A hybrid approach that combines wall attachment with a winch for vertical positioning could be worth exploring in future development.

3.4 Harris Profile

At this point there is a lot on the table. The evolution tree has done its job and produced a wide range of possible directions. The challenge now is figuring out which ones are worth developing further.

To do this in a structured way, a Harris profile is used to compare each approach against the criteria that matter most for this project. Each criteria comes directly from what the research and prototyping revealed.

- **Operation above and below the waterline.** As discussed in the research phase, the splash zone is where the most corrosion happens due to wet-dry cycling. This makes it important that the device can work both above and below water. An approach that covers both is more valuable.
- **Surface compatibility.** Corroded steel, marine growth, and irregular geometry make it hard for some approaches to even function on sheet piles. A solution that can handle this without relying on a clean or prepared surface is therefore more interesting.
- **Deployability.** Section 2.5 the different situations a sheet pile can be in. Overhanging concrete or under a bridge the solutions should be able to be deployed in these situations. The solution should also be easier to use than existing methods like temporary cofferdams or divers. Setup time matters, but so does how disruptive the system is. Disrupting port operations as little as possible is a key goal.
- **Attachment and detachment control.** This became a criterion directly from the prototyping work. The magnetic plate prototype made it very concrete how quickly a lack of control over detachment becomes a serious problem. Being in control of when the device attaches and detaches is essential. If that requires additional external hardware, the solution becomes less desirable.
- **Mechanical complexity.** Every extra moving part is a liability in a wet, corroded, and hard to reach environment. Simplicity makes working in water more reliable as well as easier to build in general.
- **Steering and alignment.** The magnetic wheels prototype revealed that a system that can only move in a straight line will gradually walk off the sheet pile if it is not perfectly aligned on attachment. Correcting alignment during movement turned out to be really important. For every problem there is a solution, but an approach that handles this naturally is a more valuable one.
- **Obstacle handling.** Anchor heads, sacrificial anodes, and interlocks protrude from the wall and cannot be avoided. Any approach that cannot deal with these, or

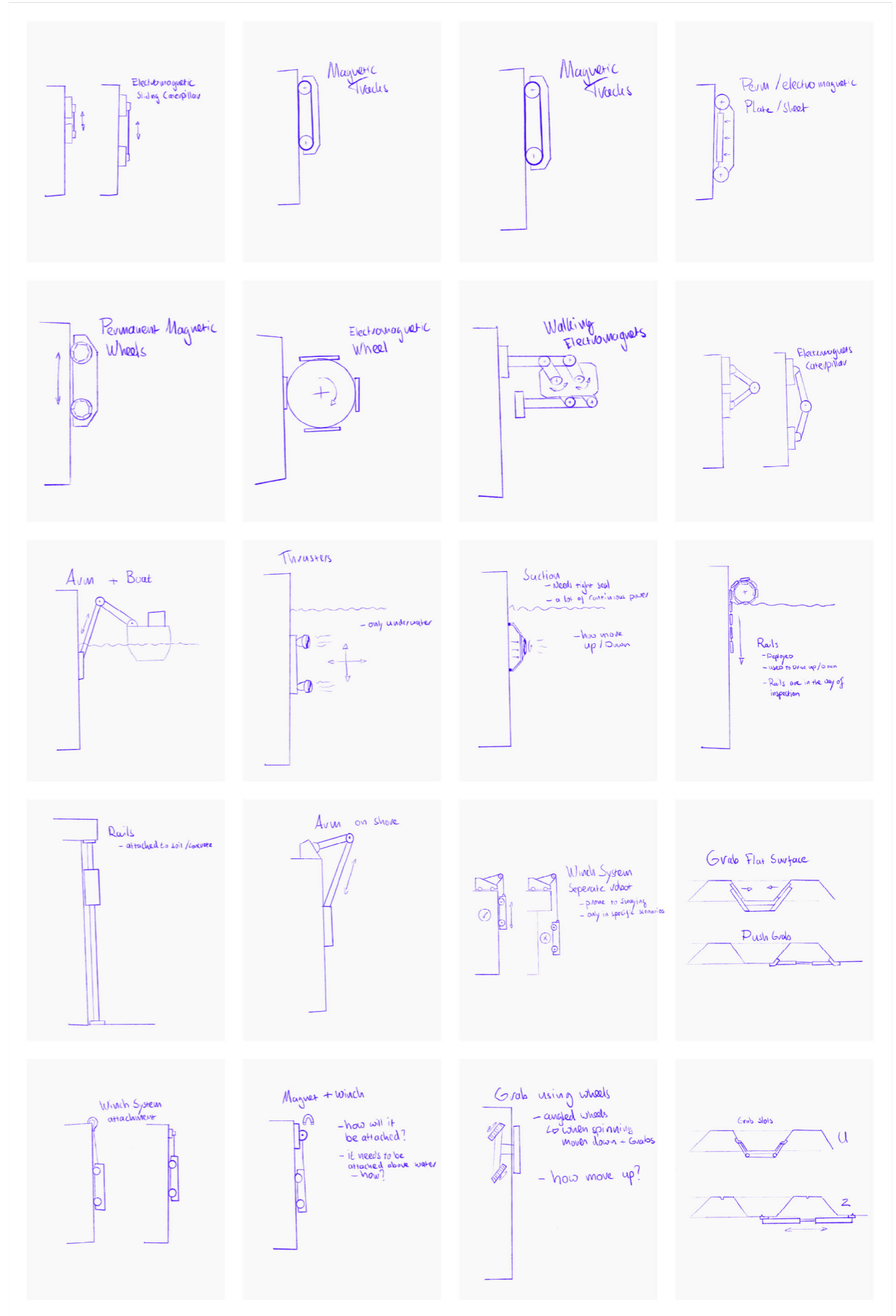


Figure 43 – Collage of design directions

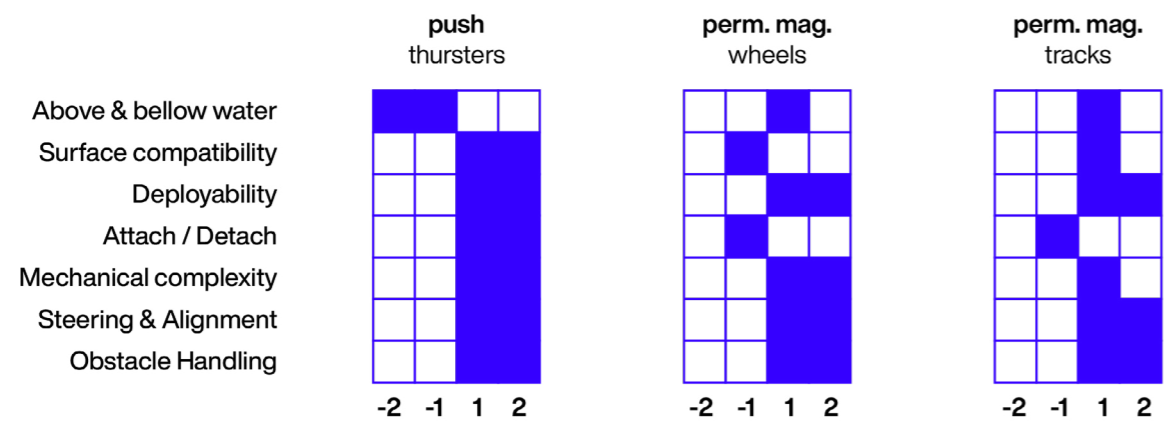


Figure 45 - Highlighted sections of Harris Profile

3.4.1 Results

The Harris profiles showed some interesting results. Two magnetic solutions stood out: permanent magnet wheels and permanent magnet tracks. Their ability to attach to metal surfaces and therefore create the possibility to move up and down the sheet pile make for a great solution. However they still have some shortcomings. Attachment and detachment is difficult to control, as the prototypes showed. Surface handling is also an issue. The deeper the platform goes the more marine growth appears, which can prevent the magnets from gripping the steel surface.

Interestingly this leads us to thrusters, which also scored high on almost everything except the ability to move above and below water, a significant drawback. However lets not discard them because of it. They bring real advantages that magnetic solutions are missing, like surface compatibility and easy attach and detach. On top of that, getting the platform to hard to reach sheet piles is a challenge in itself, and thrusters could play a key role there. And where marine growth prevents the magnets from gripping, the pushing force of thrusters could keep the platform close to the wall instead. In an ideal world one solution would do everything. But a hybrid approach is not out of the equation.

Something else the Harris profile made clear is that winches are a reliable way of handling vertical movement. A stable platform with a winch attached could make for a good solution as well, and is still worth exploring further.

Some directions were clearly not the right fit. Rail guided solutions are too complex and big. Clamping simply is not suitable for the shape and surface condition of sheet piles.

Not every approach turned out to be great, but even the weaker ones helped show where the real advantages lie and what a strong solution needs to be able to do.

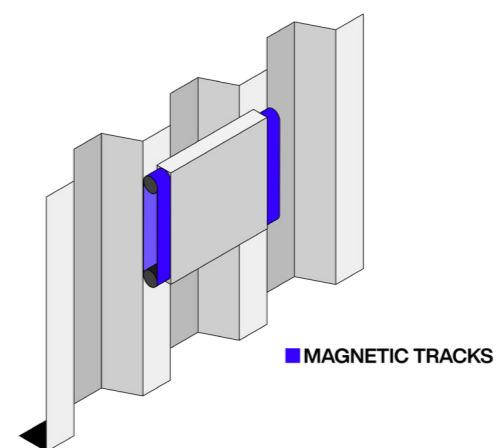
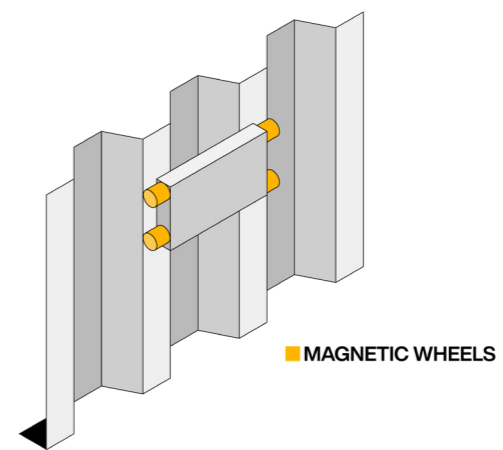
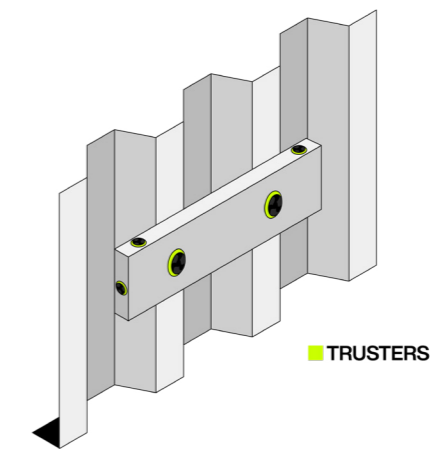


Figure 46 - Isometric Illustrations of design directions

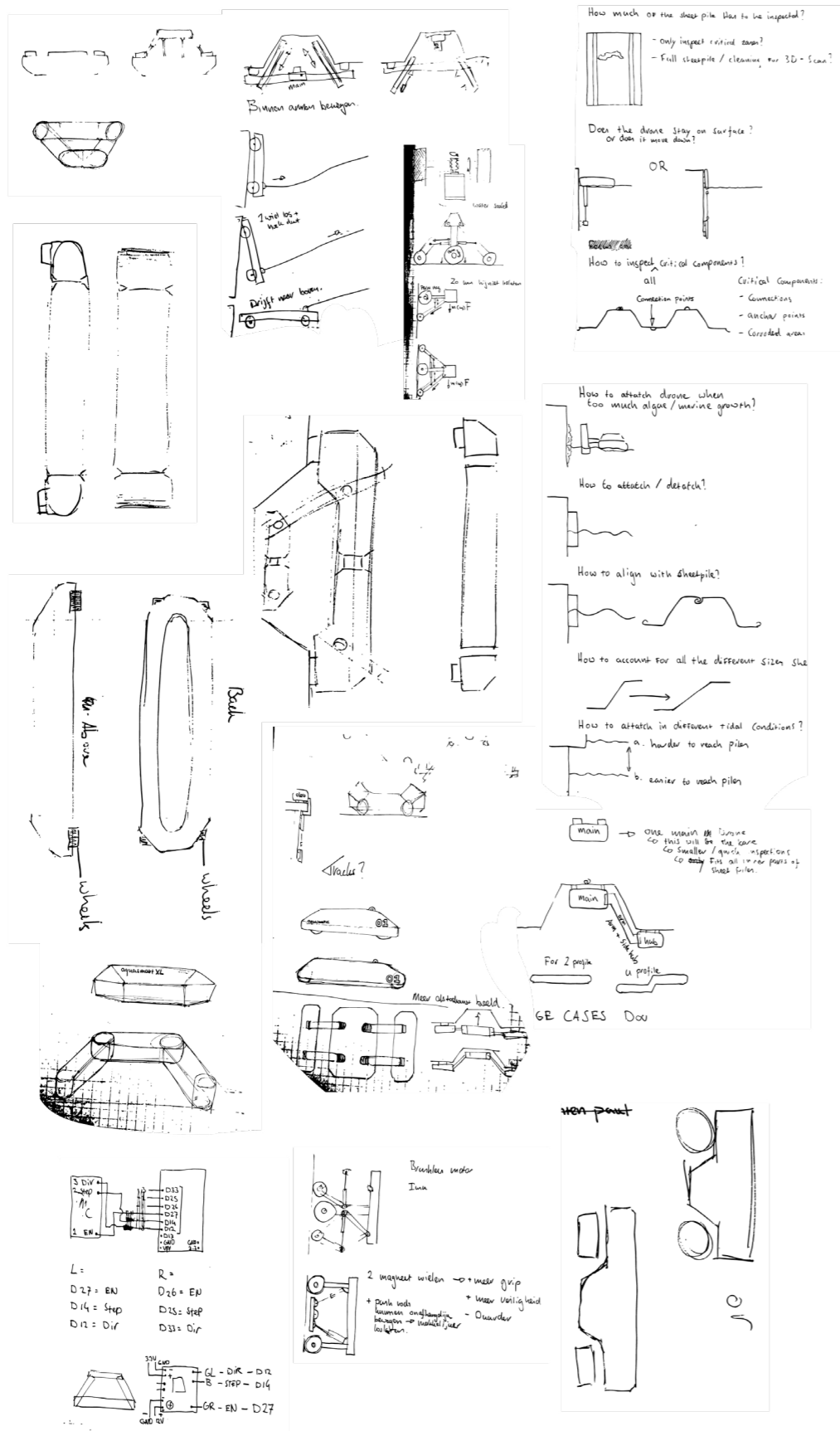


Figure 47 – Collage of several sketches made in notebook

3.5 Concept Development

By now a lot is known about the different approaches. What does not work and why. But more importantly, where the real advantages lie and what a strong solution needs to be able to do.

The Harris profiles already hinted at hybrid directions. No single approach scored well on everything. But combinations started to emerge. Approaches that cover each other's weaknesses.

While a preferred direction gradually emerged throughout the project, the concepts in this section should not be seen as discarded alternatives. Some concepts were explored in greater detail than others, while others were developed to investigate specific capabilities, strategies, and opportunities. Exploring multiple directions also served as a way to critically evaluate the emerging concepts. By continuously asking what alternative approaches could offer, it became possible to identify missed opportunities, challenge assumptions, and strengthen the final solution.

This section works out three of those hybrids. How each one operates, what it does well, and where it falls short. It is the last divergence before converging on a final concept.

Two-Stage System

Controlled Descent

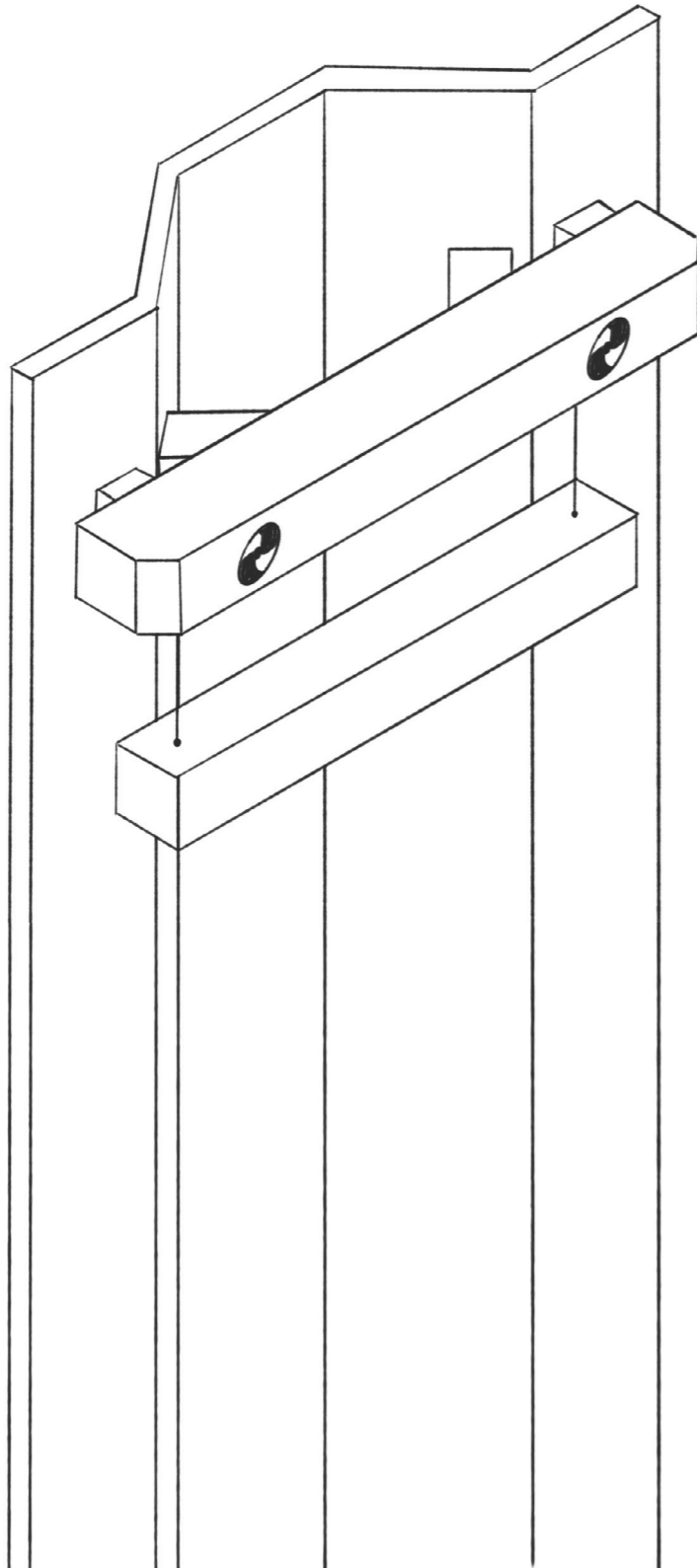


Figure 48 – Two-Stage System

3.5.1 Two-Stage System

The Two-Stage System was born from two insights from the Harris profiles. Thrusters don't need to physically attach to the sheet pile irregular surface. The force of the pushed water alone is enough to stay close to the surface. And winch systems showed a very controlled and reliable way of moving up and down.

The idea was to combine these two and see what happens.

Upper Stage

The upper stage is buoyant. It has built-in thrusters and is shaped to the geometry of the sheet pile, keeping it aligned. The thrusters push constantly against the wall, creating a stable attachment without any physical contact. This stage stays at the waterline.

Lower Stage

The lower stage is not buoyant. It is lowered down from the upper stage using winches on both sides. Attached to this stage are the cleaning tools and stereoscopic cameras. Later on thickness measurement devices can also be added. The controlled descent of the winches makes the movement smooth and predictable.

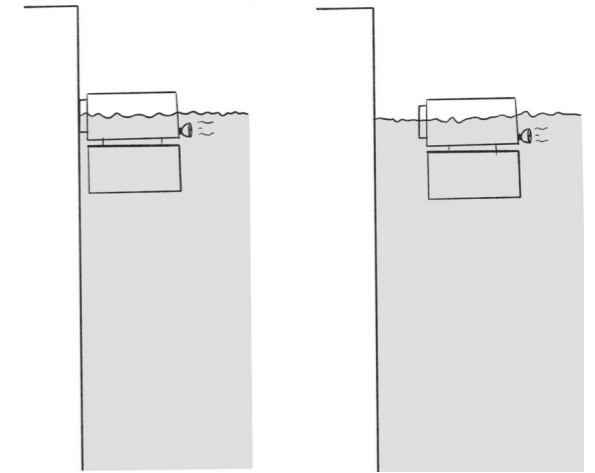


Figure 49 – Arrival of two-stage system

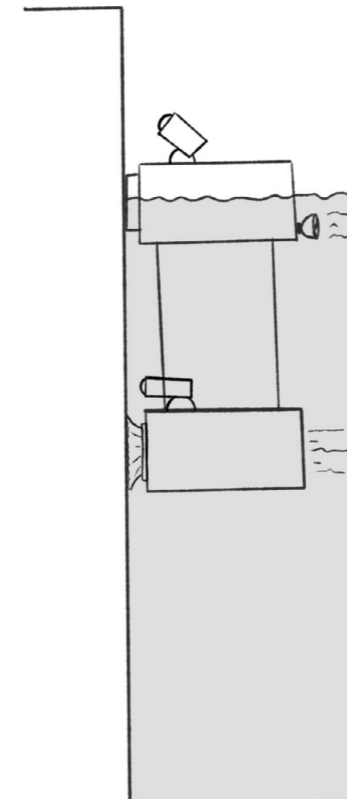


Figure 50 – Lowering stage and cleaning of sheet pile

The wide geometry and smooth descent of this system make it well suited for stereoscopic imaging. Large sections of sheet pile can be inspected in a single pass relatively easily. The system only works at and below the waterline. Thrusters rely on water to generate force. Above the waterline that force disappears, and with it the ability to stay close to the surface. This means thickness measurements above water are not possible with this system. Stereoscopic imaging and 3D modeling can still be done, but any inspection that requires close contact with the steel above water will not be possible.

Carrier and Crawler

Controlled Descend

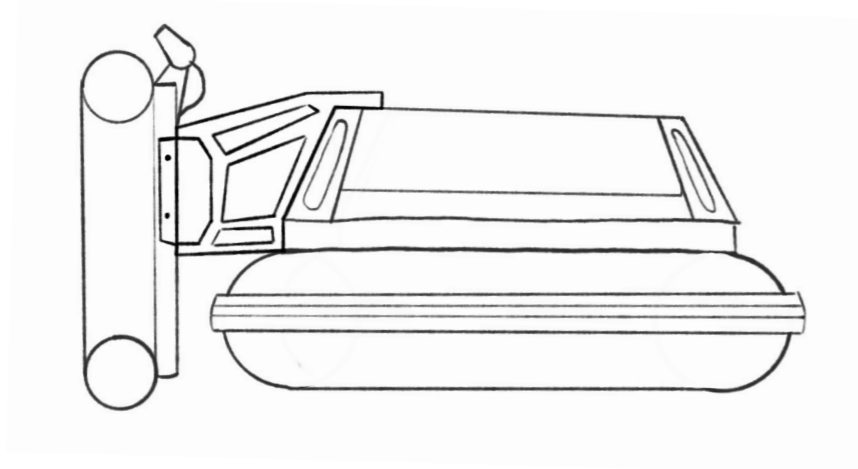


Figure 51 – Carrier and Crawler

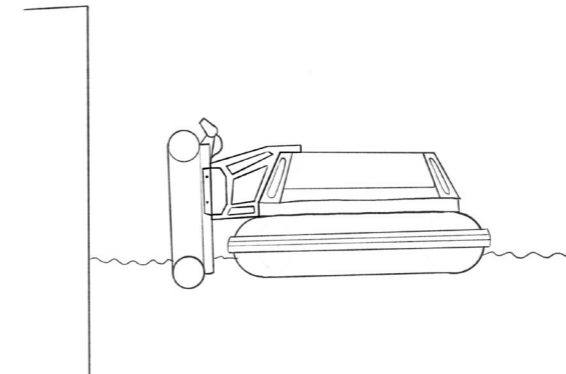


Figure 52 – Driving to Sheet Pile

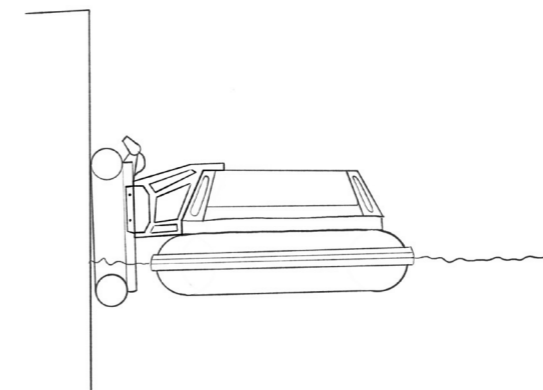


Figure 53 – Attaching Crawler to Sheet Pile

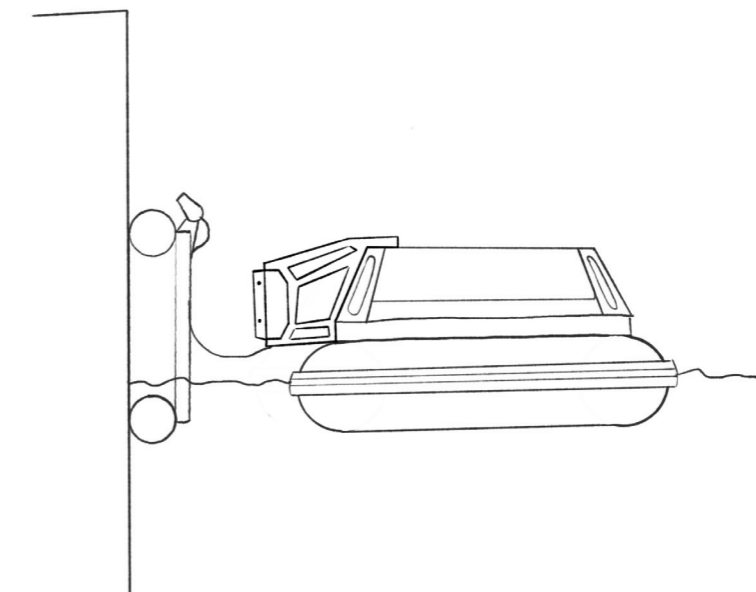


Figure 54 – Crawler detached from carrier

3.5.2 Carrier and Crawler

The Carrier and Crawler concept is inspired by what AquaSmartXL already has. Their platforms are well proven, tested, and familiar to the operators. Rather than starting from scratch, this concept uses an add-on to do the remainder of the job.

The focus is on designing both the attachment that can be put onto the ROV to move the sheet pile crawler to the wall in hard to reach places, and the crawler itself. Once attached to the sheet pile, the crawler can roam around and capture the data needed. It uses magnetic tracks to attach to the steel surface.

As discussed in section 2.8, the inspection solution should support both segmented and long stretches of sheet pile inspection. The device is kept small so it can inspect each surface of the sheet pile. The large existing ship hull crawlers would not be able to fit the geometry of a sheet pile.

When the crawler is attached to the wall, the carrier moves out of the way. The two stay connected through an ethernet cable that supplies the crawler with power and data. The carrier holds the processing. The crawler is designed to be as simple as possible. This keeps the crawler lightweight, which improves the chances of it properly sticking to the sheet pile surface.

■ Sheet Pile Platform

Hybrid solution

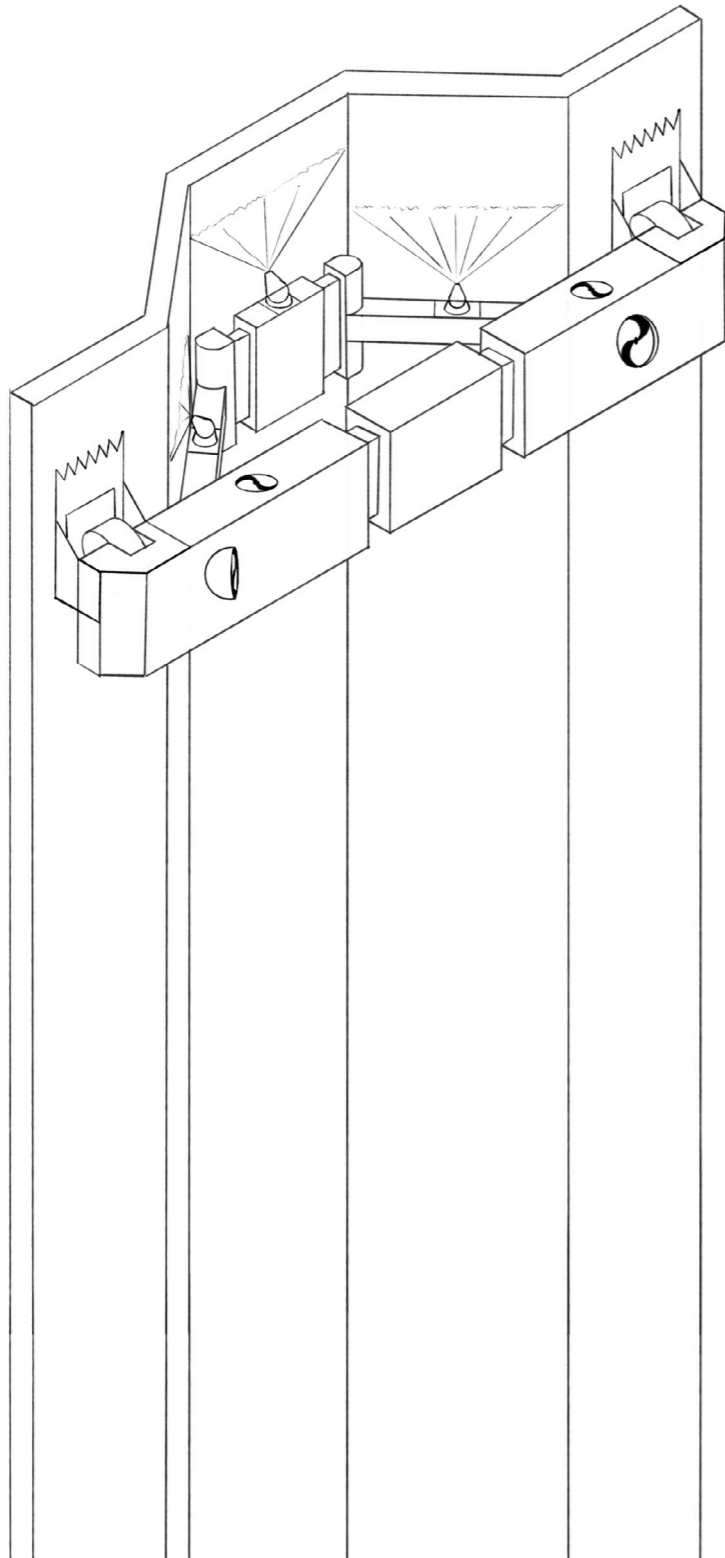


Figure 55 – Sheet Pile Platform

3.5.3 Sheet Pile Platform

The Sheet Pile Platform combines the lessons learned throughout the project into a single inspection concept. Looking back at the Harris profile results, both thrusters and magnetic locomotion showed promising results, each excelling in different situations. Rather than selecting one over the other, this concept combines both approaches. Thrusters provide mobility and positioning underwater, while magnetic locomotion enables stable movement and inspection above the waterline. Together, they allow the platform to inspect a larger portion of the sheet pile while taking advantage of the strengths of each system.

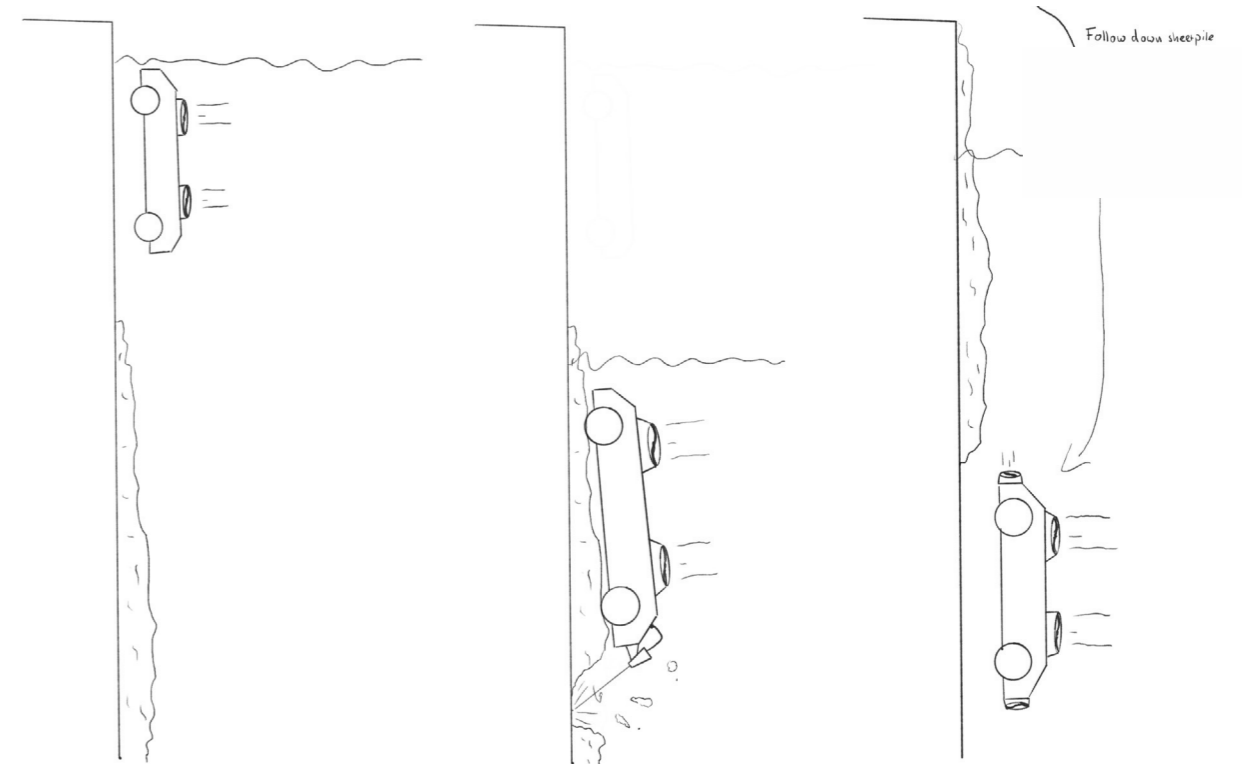


Figure 56 – 3 different scenarios where the Sheet Pile Platform attaches to sheet pile

Accessibility

The integrated thrusters make it possible for the sheet pile platform to move to the sheet pile in hard to reach places. By making the platform neutrally buoyant it can dive to an area that is easier to attach to for the magnetic wheels. Just like in the other concepts, the thrusters keep a constant pushing force when underwater, taking over from the magnets when attachment is simply not possible due to thick marine growth.

The area with the least marine growth is right at the waterline. This makes it possible for the magnetic wheels to take over from the thrusters, making it able to attach thickness measurement devices and inspect the splash zone more thoroughly.

Adaptability

The shape of the platform can be adjusted to the different geometries of both Z and U profile sheet piles. This ensures sensors can be placed close to the sheet pile. The fit also locks the platform into place when using thrusters, creating an even more stable platform.

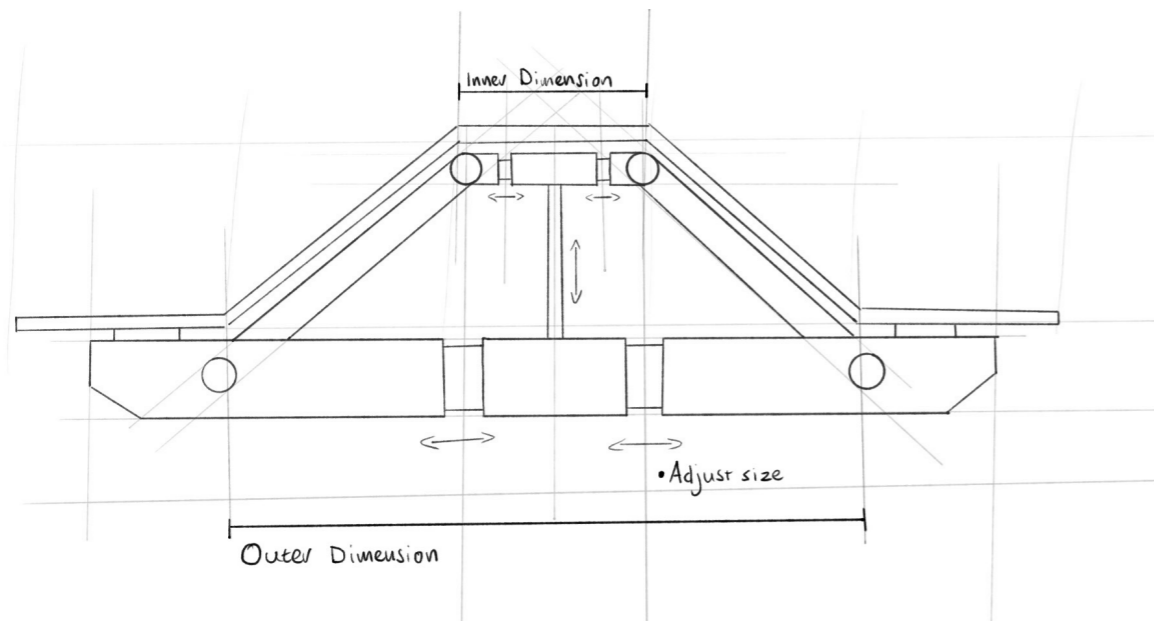


Figure 57 - Size adjustment sketch

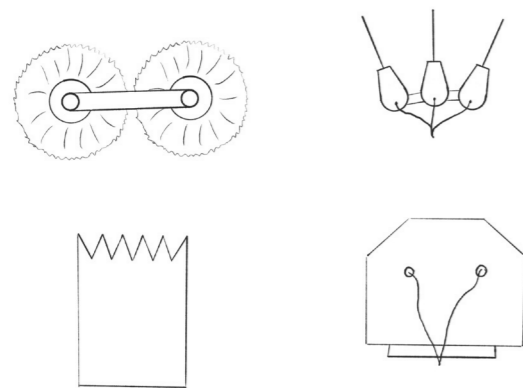


Figure 58 - Cleaning Attachments

Cleaning

Cleaning is done using a range of adapters. This is modular since every inspection is different in many ways, as discussed in the research phase. This can range from different types of marine growth to not wanting to remove the marine growth at all. The options are brush cleaning, cavitation jet washing, and scraping.

Driving

Locomotion is either tracks or wheels. Further research needs to be done to find the best solution for sheet piles.

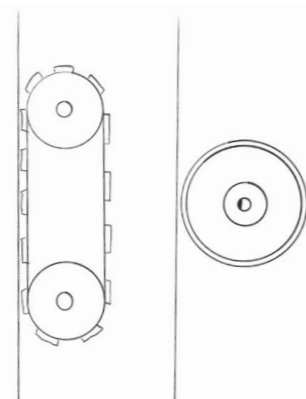


Figure 59 - Magnetic Locomotion

3.5.3 Sheet Pile Platform

Two-Stage System

- + Thrusters push the platform against the wall without needing magnets or clamping. Surface condition and profile geometry do not matter.
- + A winch moves continuously, unlike locomotion methods such as caterpillar tracks or walking mechanisms that move in discrete steps. Smooth and controlled.
- Two stages means two systems that both need to work, underwater, at the same time.
- The lower stage still needs to be pushed against the wall. So it needs thrusters too. At that point, what is the winch actually adding?
- Two cables hanging underwater. Obstacles, marine growth, surrounding structures. It is not hard to imagine one of them getting caught.
- The upper stage sits at the waterline and cannot dive. Concrete overhangs, which the research showed are very common, are simply out of reach.
- In rough conditions, waves push the upper stage up and down. Through the winch cables, that movement goes straight to the lower stage too.

Carrier and Crawler

- + AquaSmartXL already has a carrier platform. No need to build one from scratch, operators already know how to use it, and the new development is only the crawler itself. Cheaper and faster to get to a working system.
- + The propulsion stays with the carrier. The crawler only needs to focus on inspection, which keeps it lighter and gives the magnets a better chance of gripping the surface.
- Surface carriers cannot dive. In situations where concrete overhangs the sheet pile, the carrier simply cannot get the crawler there.
- The deeper the crawler goes, the more marine growth it encounters. At some point the magnets may just not grip anymore. Cleaning first could help, but add a dependency we might not want.
- At the end of the day, it is still two systems connected by a tether. Two systems that both need to work, at the same time, in an underwater environment.

Sheet Pile Platform

- + Fully optimized for sheet pile inspection. The shape fits the profile, the systems are designed around the specific challenges of this environment, and nothing is a compromise.
- + Modular payload means it can be configured for whatever the client needs. Different inspectors, different situations, different goals. The platform stays the same, what it carries changes.
- + Magnets allow it to go above water. Thrusters keep it close to the wall underwater without relying on the magnets. The two systems cover each other's weaknesses, which is exactly the overlap that was missing from every single approach before.
- + It can reach the inner side of the sheet pile, which is an important area to inspect.
- + It can dive underwater to find a clean attachment point, making it easier to reach hard to access places like sheet piles underneath concrete overhangs.
- + One system to deploy and keep an eye on. Once it is attached, it stays attached.
- Fully optimized for sheet piles also means it can only be used for sheet piles.
- Combining thrusters and magnetic wheels in one system adds weight. Whether that becomes a real problem still needs to be figured out.

Conclusion

Looking at all three concepts, a pattern starts to emerge. The Two-Stage System gets complicated the moment a second stage is added. The Carrier and Crawler improves on the magnetic wheel approach, but is still heavily dependent on the surface the magnets can grip. Both concepts revealed valuable opportunities, but also highlighted limitations that would be difficult to overcome.

What became clear during the concept development phase was that no single approach solved every problem. Exploring the different concepts helped identify where each approach worked well and where it struggled. This ultimately led to a new direction: combining thrusters and magnetic locomotion into a single system.

The result is the Sheet Pile Platform. A hybrid concept that uses thrusters to navigate underwater and stay close to the wall, while magnetic wheels take over around and above the waterline where they can provide stable locomotion and support inspection tasks. The concept can also approach difficult situations, such as concrete overhangs, from below and attach where other concepts would struggle.

By combining the strongest elements of the previous concepts, the Sheet Pile Platform offers the most potential and was therefore selected for further development.

With the direction chosen, the focus now shifts to working out the details. The following section refines the Sheet Pile Platform concept by looking at each subsystem individually and further developing the design.

3.6 Concept Refinement

3.6.1 Shape

As discussed earlier, the system needs to stay close to the wall. A snug fit helps with inspection, probing, scanning, and cleaning the surface. At the same time, the shape must work on both U and Z sheet pile profiles. The following concepts explore shapes that follow this idea.

Option 1 - One size fits all

This concept focuses on simplicity. The device is kept small so it can attach to almost any flat part of the sheet pile. Because of its size it can adapt to different sheet pile profiles without needing adjustments.

The drawback is that it only covers about one third of the sheet pile in a single pass. This means multiple passes are required to inspect the full profile.

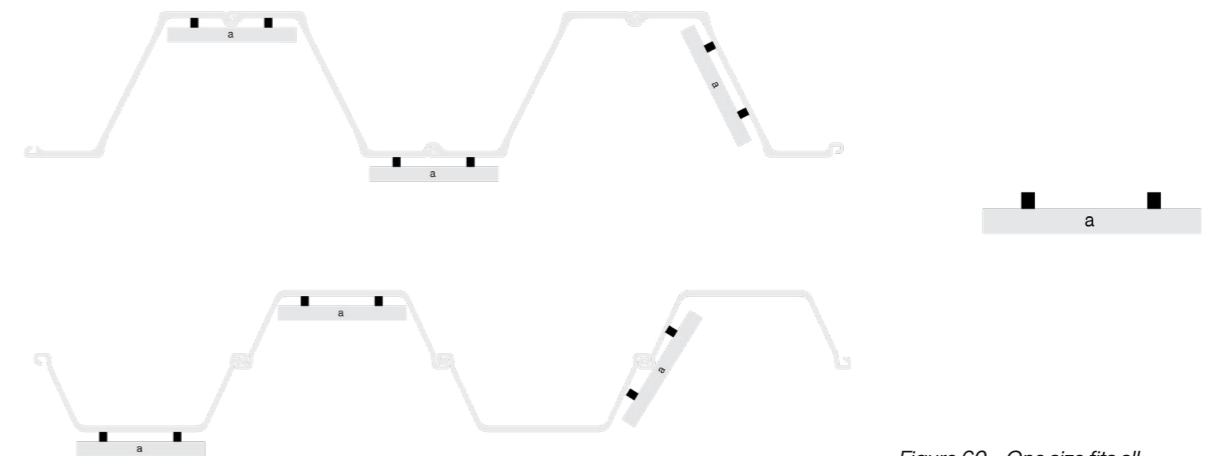


Figure 60 - One size fits all

Option 2 - Z - shape

This concept follows the geometry of the sheet pile more closely. The shape allows the system to cover the inner and outer surfaces of the sheet pile as well as the interlock sections.

However, sections A, B, and Z would need to be adjusted for different sheet pile sizes. In addition, the shape makes it difficult to move around obstacles such as anchor heads.

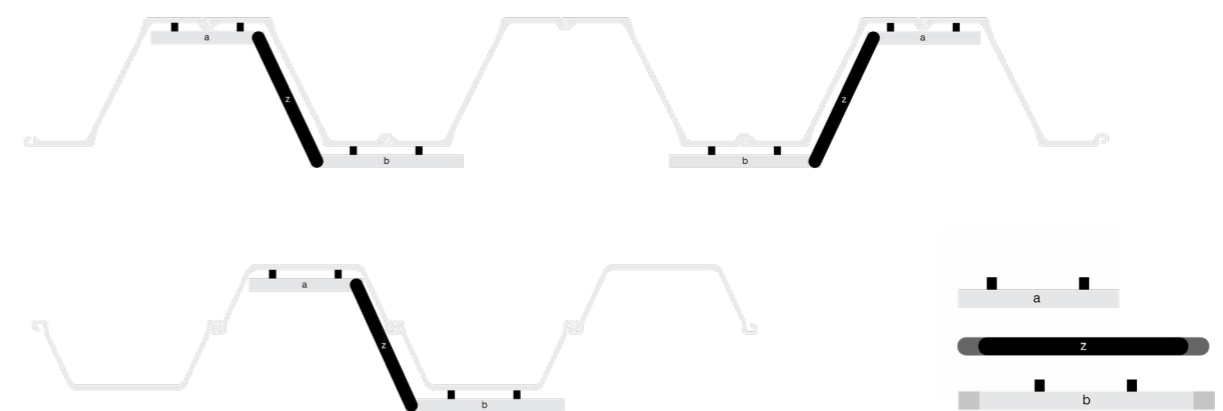


Figure 61 - Z-shape

Option 3 - U - Shape V1

In this concept the system attaches to one section of the sheet pile and uses two arms to reach the rest of the profile. This allows the system to inspect one full sheet pile at a time.

A drawback is that the long arms are not attached to the wall, which can reduce stability. An advantage is that both arms are identical and connected to one main platform. This allows the system to adapt to different situations. To inspect the inner side of the sheet pile, the system has to flip into an inverted U-shape, which makes the design more complicated.

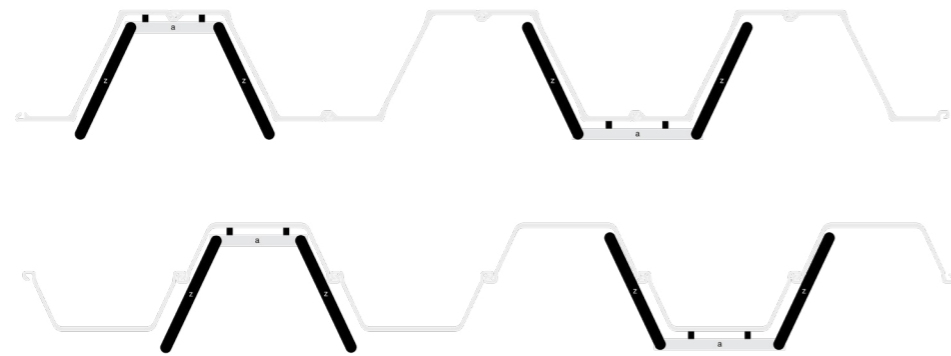


Figure 62 - U-shape V1

Option 4 - U - Shape V2

This concept is similar to U-Shape V1 but improves stability by attaching the system at two points on the sheet pile. These attachment points could use clamping, suction, magnets, or another method.

The two attachment bases are connected by one arm that spans the sheet pile profile. While this improves stability, obstacles such as anchor heads remain difficult to avoid. In addition, the interlocks between sheet piles create ridges that the system must be able to handle.

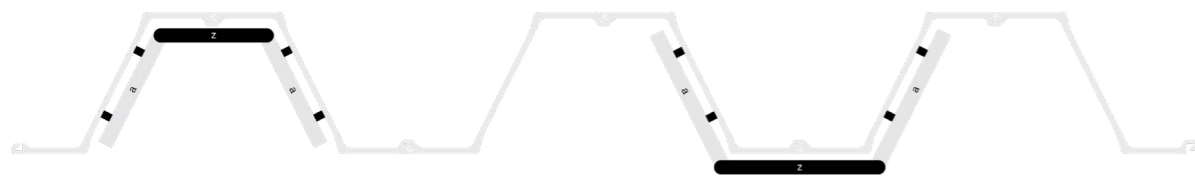


Figure 63 - U-shape V2

Option 5 - Omega shape

The Omega concept was developed to solve the limitations of the U-shaped designs. Those concepts could not fully inspect the interlocks in one pass, which would lead to overlap during inspection.

By adding two additional modules, this design can follow the full shape of the sheet pile. This allows inspection of both the inner and outer surfaces without needing to change the orientation of the system. Like in the U - Shapes solution.

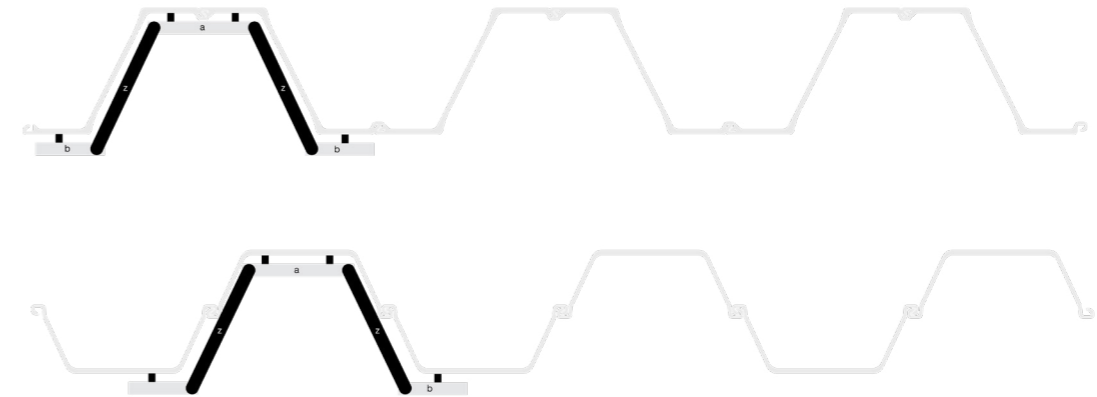


Figure 64 - Omega shape

Option 6 - Flat approach

This idea came up while looking at the obstacles on sheet pile walls. Anchor heads are almost always present, and ladders or other hardware are often attached as well. At first this seems like a big problem. But when looking closer, something interesting becomes clear.

Because of the shape of sheet piles, these elements are almost always placed on the inner side of the wall. This keeps the outer side of the sheet pile flat. And that leads to an important insight. While the inside of the wall can have many obstacles, the outer side of the sheet pile is usually clear and flat.

This flat and consistent surface can be used to attach the system and move up and down along the wall. The Z section can then adapt to the shape of the sheet pile and move around obstacles where needed.



Figure 65 - Flat approach

3.6.2 Staying Close to the Wall

To inspect a sheet pile thoroughly, the platform needs to stay close to every surface, both the outer flat section and the angled inner walls. Covering only part of the profile in a single pass means multiple passes are needed, which adds time and operational complexity (chapter 2.8 and 3.3.2). Knowing the platform attaches using the flat approach, a mechanism and shape are needed that follow those angled surfaces while still being able to move out of the way when obstacles like anchor heads or sacrificial anodes appear. On top of that, whatever follows the wall needs to provide a stable base for sensors and cleaning tools. How this mechanism is actuated falls outside the scope of this project but a potential way of doing this is discussed. What this section covers is the exploration that shaped the final concept.

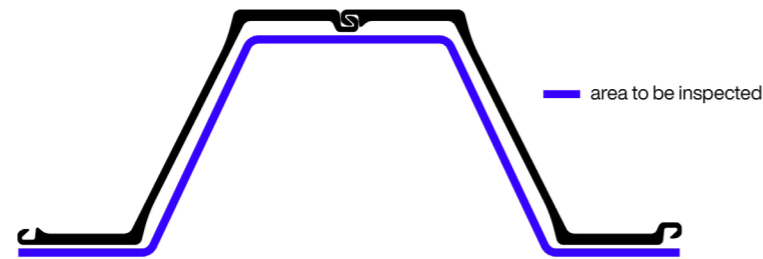
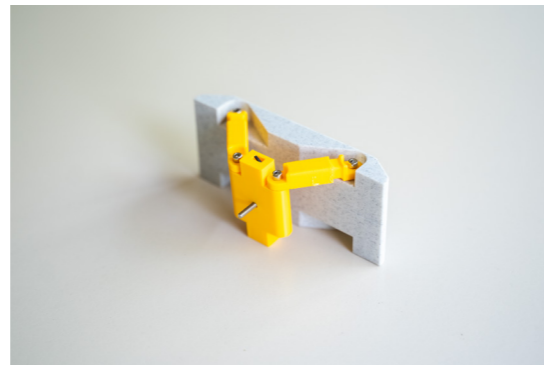


Figure 66 – Area to be inspected

V1 Telescoping Arm

The first version consists of three parts: a large flat main body that follows the outer surface of the sheet pile, two arms that connect at fixed angles, and a smaller flat section that runs parallel to the main body and aligns with the innermost surface of the sheet pile. A screw running between the two flat sections drives the mechanism, pushing the inner section in or out to follow the profile. The arms extend and retract like tripod legs to accommodate this movement. A 3D printed prototype was built to test this concept



The prototype confirmed that the mechanism can adapt to the shape of the sheet pile and move out of the way for obstacles. However it also revealed a practical problem. Because the arms slide over each other like a tripod, there is no stable continuous surface to mount sensors or cleaning tools on. A mechanism that is always shifting and squeezing together underneath them simply cannot provide the reliable attachment point those instruments need.



Figure 67 – Telescoping arm prototype

V2 Door Mechanism

The second version addresses the arm length problem directly. Instead of telescoping, the sections rotate outward like a door opening and closing. When an obstacle appears, the section swings out of the way and returns once it has passed. The length of the arm stays the same, giving a stable surface to mount sensors or cleaning devices on.

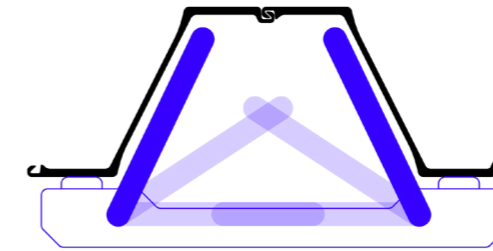


Figure 68 – Door mechanism illustrates that pieces overlap each other.

This solves one problem but introduces two others. As the image shows, when both sections rotate inward to follow a narrower profile, the arms begin to interfere with each other, limiting how far they can move. On top of that, the rotation removes the inner flat section entirely, so the platform no longer has anything following the inner flat surface of the sheet pile. And because the sections rotate rather than extend, the arms can not easily be adapted in length depending on the dimensions of the sheet pile.

V3 Slide and Pivot

The third version takes the best of both previous approaches. The sections are fixed in length, solving the interference problem from V2. But instead of rotating like a door, each section both slides and pivots through the same hinge point. When the mechanism moves in or out, the sections swing and slide at the same time, always staying the same length and never crossing each other.

This keeps a stable surface for instruments at all times, maintains the inner flat section that follows the sheet pile profile, and works across different sheet pile sizes. This is the direction carried forward into the final concept.

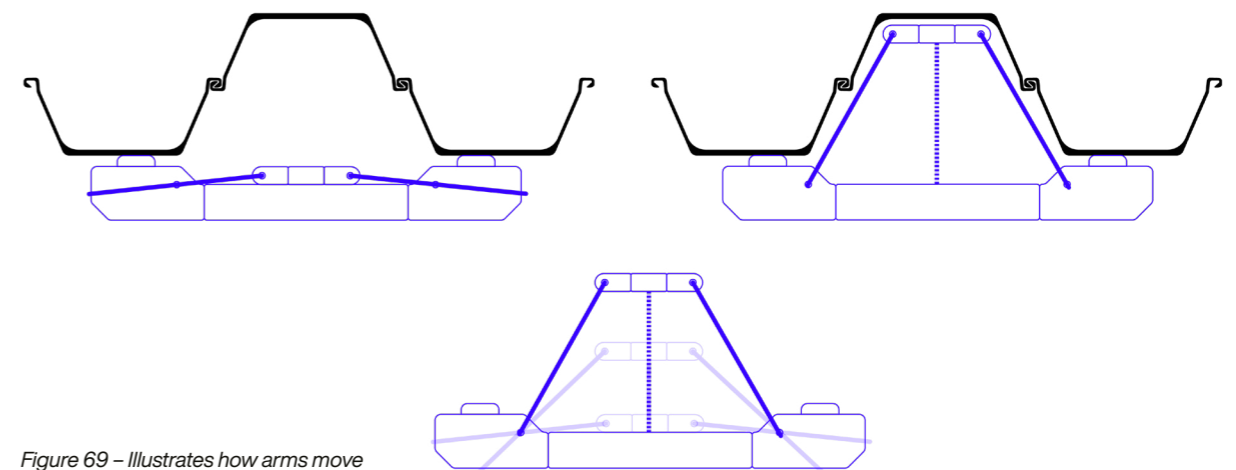


Figure 69 – Illustrates how arms move

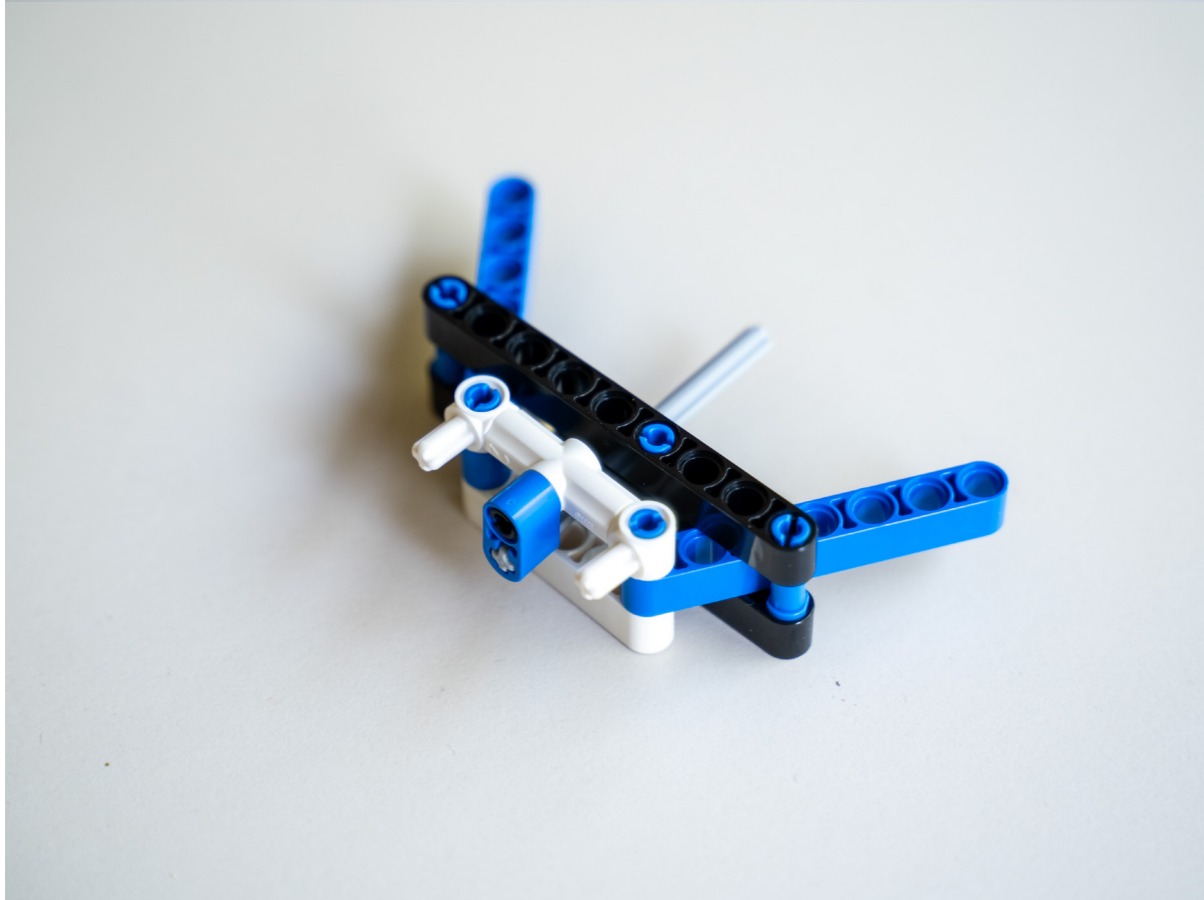
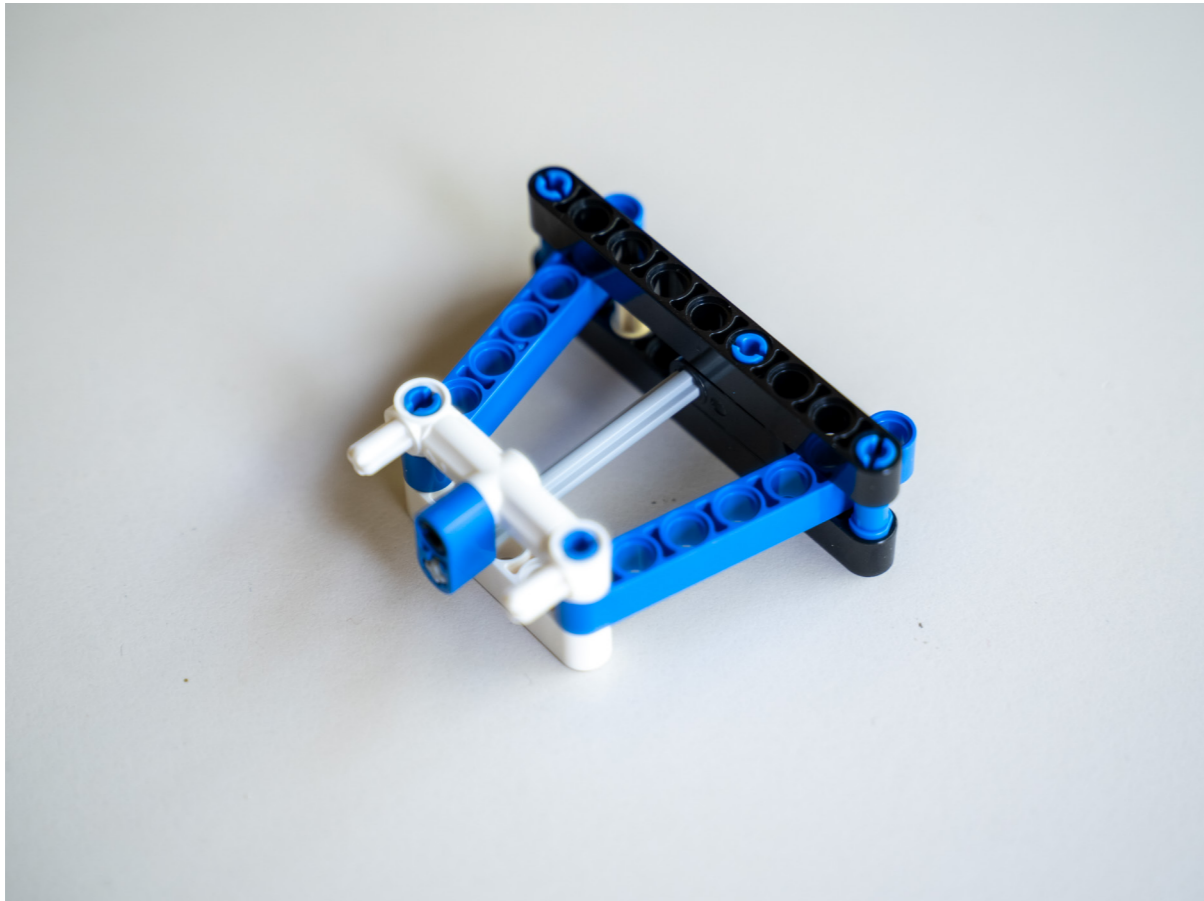


Figure 70 – Slide and Pivot Lego Prototype

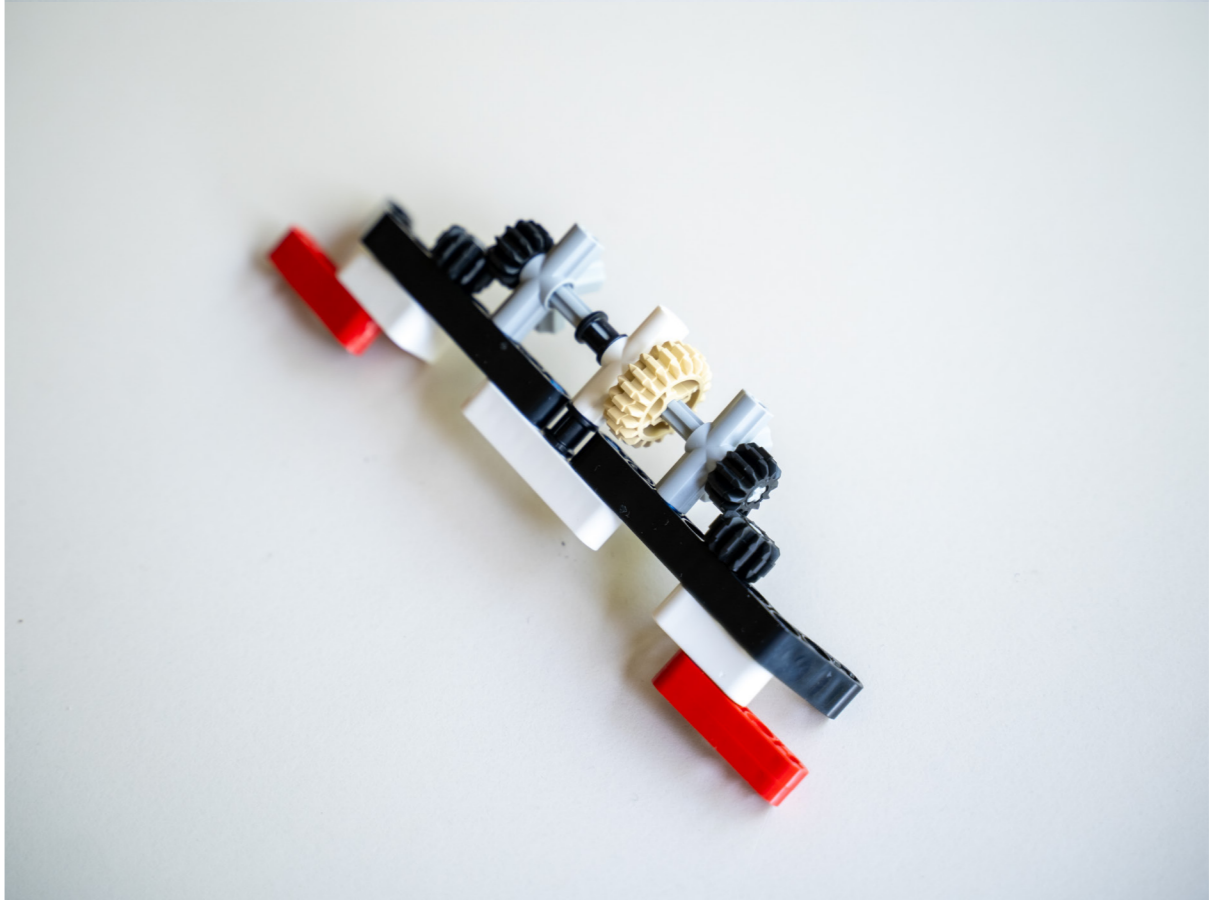
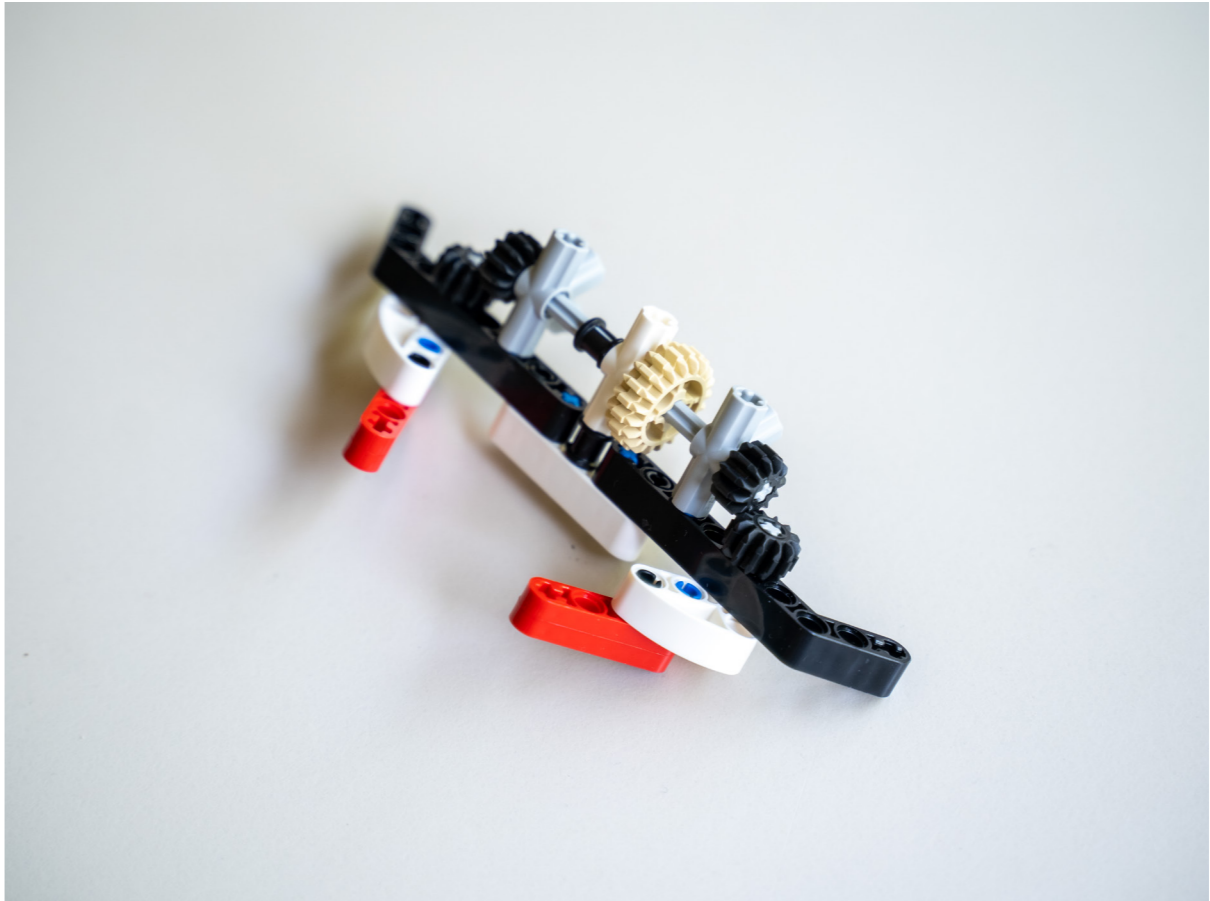


Figure 71 – Door Mechanism Lego Prototype

3.6.3 Size Adapting

Sheet piles come in many different sizes. This raises an immediate design question:

Should a separate platform be built for each size, or is there a smarter way to handle this variety?

The same thinking used to arrive at the flat approach could also work here. Rather than designing around the differences, the goal is to find what stays the same. To do this, the most extreme Z and U profile dimensions are used as a reference. These represent the outer boundaries of the full range. All other profiles fall somewhere in between and gradually transition from one to the other, so if a solution works for the most extreme cases, it will work for everything in between as well.

When these extreme profiles are overlaid, a shared flat section appears at the base of every profile. This area is consistent across all sizes and types. In theory, a single fixed width platform could attach here and work on any sheet pile without any change in size at all.

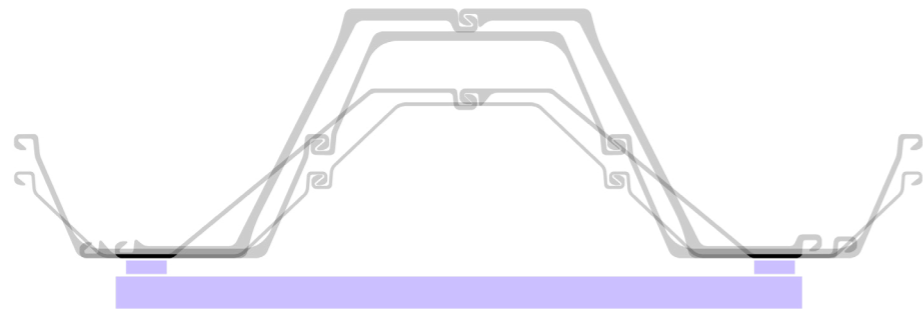


Figure 72 – Single Fixed Width

However a problem emerges. The moment the goal shifts from simply moving up and down to actually inspecting the full shape of the sheet pile as explained earlier, something breaks down. The point where the flat base meets the angled walls is not in the same place on every sheet pile. On wider profiles those corners sit much further out. Arms sized for a small profile fall short on a large one, and sensors or cleaning tools mounted on those arms never get close enough to the surface to be useful. A fixed width leaves too much of the sheet pile out of reach. The platform needs to be adjustable in size.

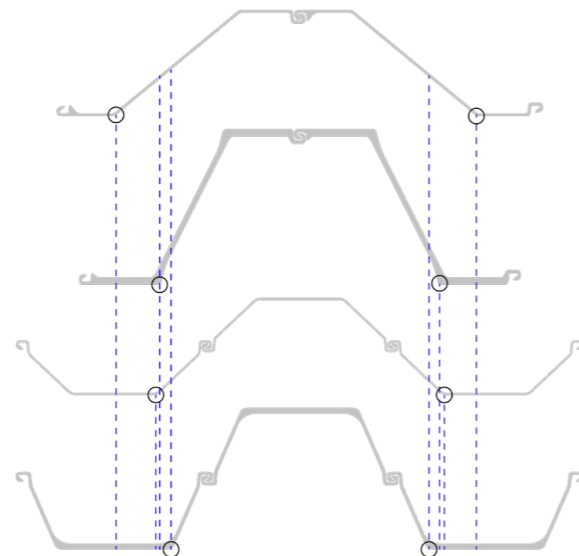


Figure 73 – Illustrates corners being at different distances

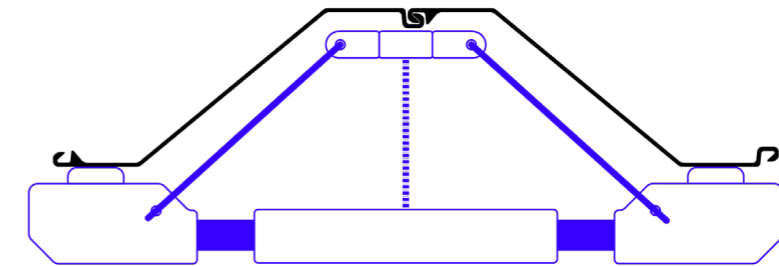


Figure 74 – Size adjusting extended

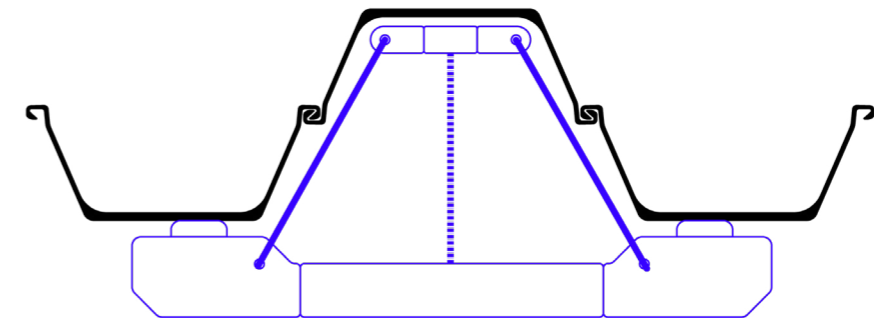


Figure 74 – Size adjusting contracted

Solution

The solution ties both challenges together. The hinge points where the sections slide and pivot are directly linked to the wheel spacing. When the platform is adjusted to fit a different sheet pile size, the hinge positions shift with it automatically. No separate adjustment is needed. The middle section of the platform is deliberately kept clear of any mechanism, leaving a clean mounting point for an actuator to be added later. The image below shows the platform in two configurations, illustrating how the same design adapts to different sheet pile widths without any structural changes apart from the wheel base being moved.

3.6.4 Attachment and Detachment

Attaching to a steel sheet pile using permanent magnets is easy. Detaching is the hard part. The magnetic pulling force acts perpendicular to the surface, which means any mechanism that tries to lift the platform directly away from the wall has to overcome the full magnetic force in one go. In practice this means the platform snaps onto the surface violently on attachment, and requires an enormous force to pull it off. This was experienced firsthand when handling magnets during the prototyping phase. Several mechanisms were sketched out to solve this, including a stroke metal electric pushrod, an eccentric wheel, and a cam clamp (Appendix H).

All of these approaches try to overcome the magnetic force at its strongest point, pulling directly against the full perpendicular attraction. This is the hardest possible way to do it.

The solution is a ramp. Rather than pulling or sliding, the wheel is driven up a gradual slope that slowly increases the distance between the magnets and the steel surface. The further up the ramp the wheel travels, the weaker the magnetic contact becomes, until it releases cleanly. In case of the use of a magnetic wheel rather than a track, to save space, this ramp can be wrapped around the wheel itself, achieving the same gradual separation in a much more compact form. This is the principle behind the separator

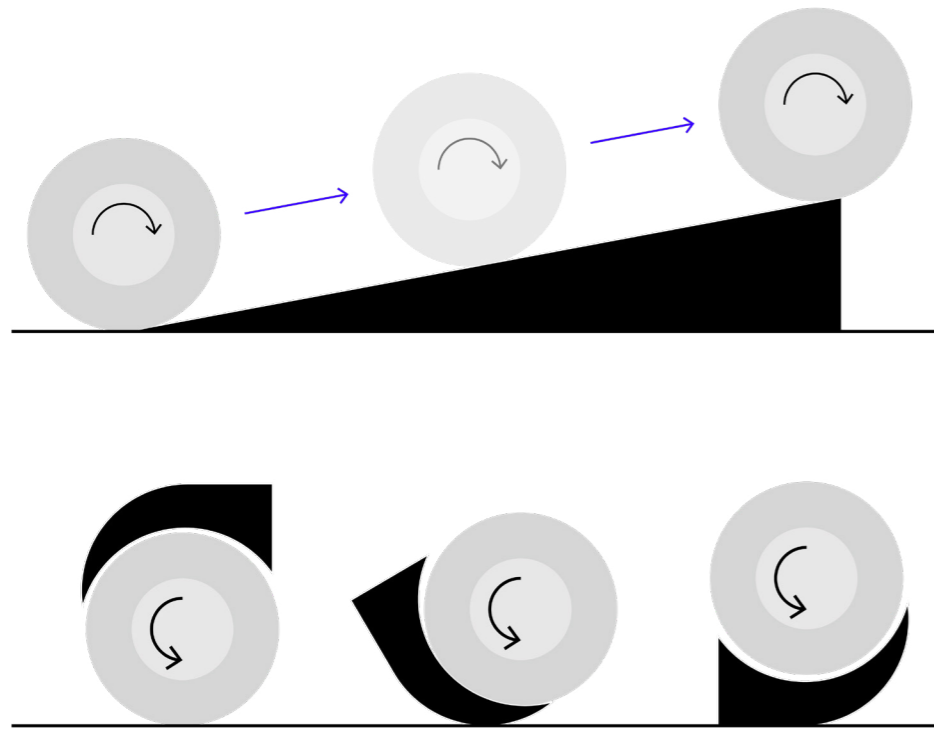


Figure 75 – Separation through slopes

3.6.5 Modularity

Sheet pile inspection is not one thing. The research showed that different clients have very different needs (2.6, 2.8). Some want to know the exact remaining thickness of every sheet pile. Others just want to find out if there is a hole somewhere. Some need a full 3D model of a section. Others do not want the surface cleaned at all, because removing marine growth can actually restart the corrosion process (2.4.1). One tool cannot do all of this, and trying to build one that does makes the platform too complex.

The solution is to treat the platform as a base and keep everything on top of it swappable. The platform handles getting to the wall, staying on it, and moving along it. What it carries depends on the job.

Three categories of modules are identified: cleaning, measuring, and observing.

Cleaning modules remove marine growth to expose the steel underneath. This is not needed for thickness measurement, but it is essential when the goal is to see the surface. Without it, cameras cannot document cracks, holes, or corrosion spots. Brushing, cavitation jet cleaning, and scraping each work better in different conditions depending on how much growth is present.

Measuring modules capture thickness data and do not need a clean surface to do so. UT probing takes point measurements at specific locations. PEC (section 2.4.1) scanning covers a larger area at once and produces a heat map of where material is being lost, all without touching the marine growth on top (2.9).

The observing modules handle visual inspection. Depending on the situation, the client can choose a simple inspection using standard cameras, or go for stereoscopic imaging to create a digital twin.

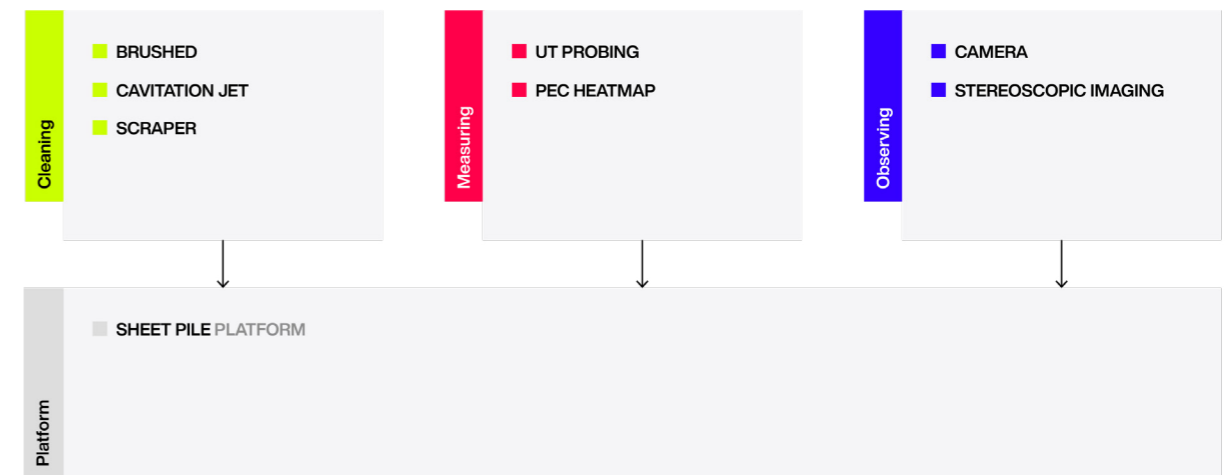


Figure 76 – Modular platform

4

Chapter 4 Deliver

- 4.1 Final Prototype
- 4.2 Final Concept



4.1 Final Prototype

The previous chapters covered a lot of ground. Many approaches were explored and prototypes were built. Magnetic wheels worked reliably on steel surfaces, but only in dry conditions. Thrusters showed real potential, but how they behave in combination with magnetic wheels is still unknown. And while the separator mechanism was designed to solve the attachment and detachment problem, it has not been tested in a working system.

This prototype brings these elements together and tests them where it matters: in the water. It directly addresses two of the four scope areas defined in chapter 3: attachment and detachment, and surface interaction. This is the first real evaluation of whether this direction works. This chapter covers the design of the prototype, the testing, and the results.

4.1.1 Cost and Time Constraints

The design of the final prototype went through many iterations, driven by both time and budget constraints. Originally the plan was to use manufactured magnetic wheels from a supplier in China, with a delivery time of four to eight weeks. That window was too risky given the project timeline, so the decision was made to build new magnetic wheels in-house using stronger magnets than the ones used on the first prototype.

Cost was the other major constraint. Designing for underwater environments is expensive. There are only a handful of suppliers for underwater motors and components, and the prices reflect that. Since this prototype only needs to operate in a water tank at a maximum depth of around two meters, rather than the full operational depth, a cheaper alternative made more sense. At one point the plan was to simply use regular stepper motors and accept that they would be destroyed after testing. A ten euro stepper motor versus an eight hundred euro underwater motor is a hard argument to ignore.

After some searching, IP68 rated stepper motors were found. Fully submersible and significantly cheaper than the dedicated underwater alternatives. Since the goal is to prove the concept rather than deliver a finished product, this was the right call.



Figure 77 – Bluetrail Gearmotor



Figure 78 – Nema17 IP68

4.1.2 Design of the Prototype

The main goal of this prototype is to test the hybrid thruster and magnetic wheel solution in combination with the separator mechanism. To keep things focused, the prototype is stripped down as much as possible.

The Frame

The prototype frame is constructed from aluminium extrusion profiles and has a width of 1300 mm (fits on sheet pile outer edge). To keep the prototype focused on testing the hybrid thruster, magnetic wheel, and separator concepts, the propulsion system has been simplified. Rather than using six thrusters to achieve full underwater maneuverability, only two centrally mounted thrusters are used to generate thrust towards the sheet pile.

The platform is positively buoyant, providing passive control in the vertical axis. Combined with the wide frame geometry, this creates a stable platform that can maintain its orientation without requiring additional thrusters for pitch and roll control.

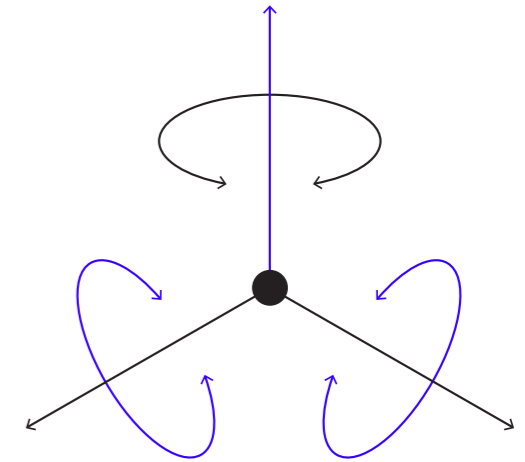


Figure 79 – 6-DOF

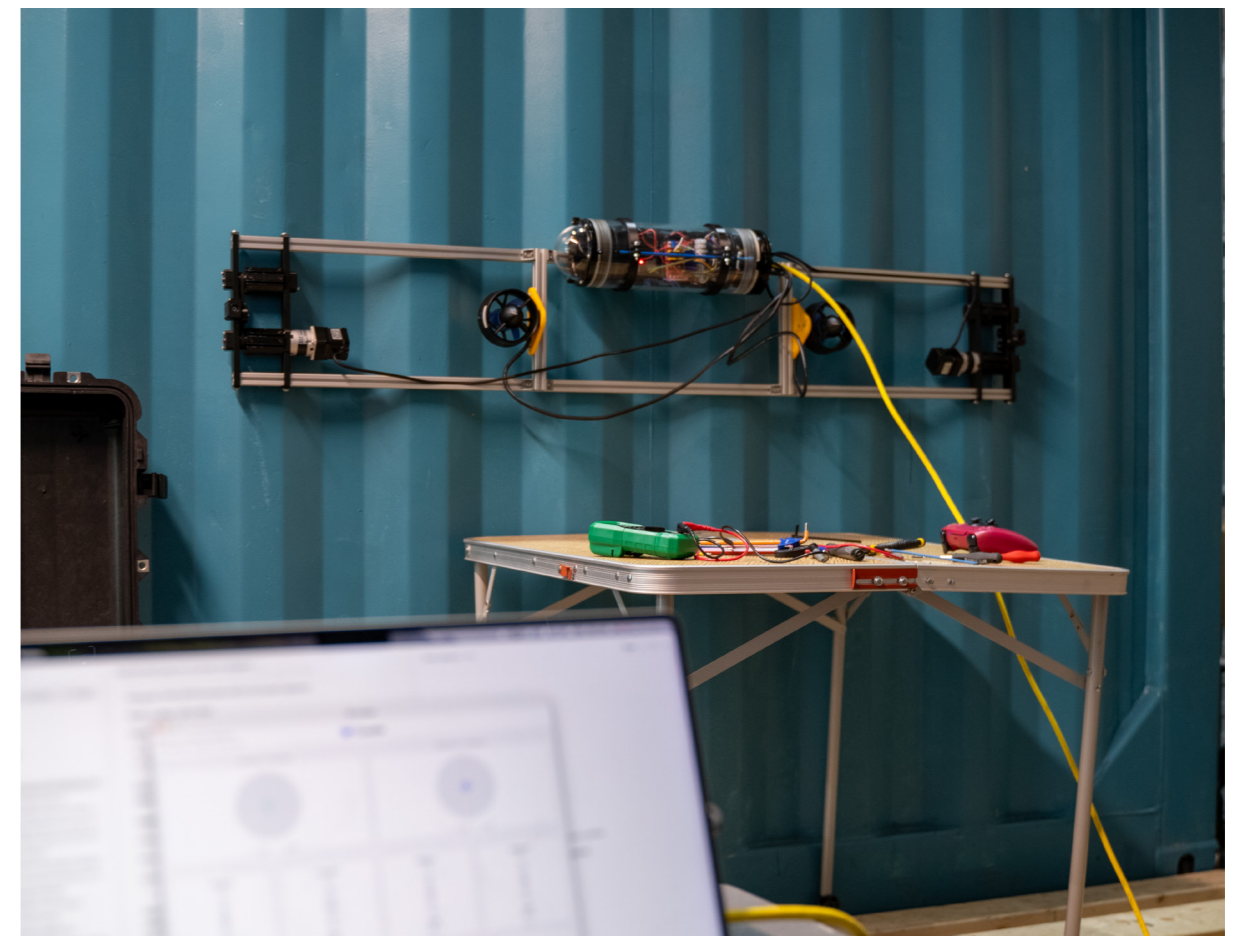


Figure 80 – Dry testing final prototype

The Drive Train

On each end of the frame, two magnetic wheels are mounted. To keep costs down, two NEMA17 IP68 stepper motors are used, one per side, each driving two wheels through a pulley system that can be tensioned. A planetary gearbox with a 20:1 reduction ratio is added to each motor to increase torque. The first magnetic wheel prototype used a 4:1 ratio, but the increased weight of this platform and the stronger magnets required a higher reduction to generate sufficient torque.



Figure 81 – Drive train

The Wheels

Each magnetic wheel consists of eight magnetic plates with a lateral pulling force of 30kgf per wheel, giving 60kgf per side and a total pulling force of 120kgf against the sheet pile. Rubber may be added to the wheels later if grip proves insufficient during testing. The Chinese manufactured wheels include knurling and rubber tracks, but since exact dimensions for the in-house built wheels are hard to match, testing will be done without rubber first

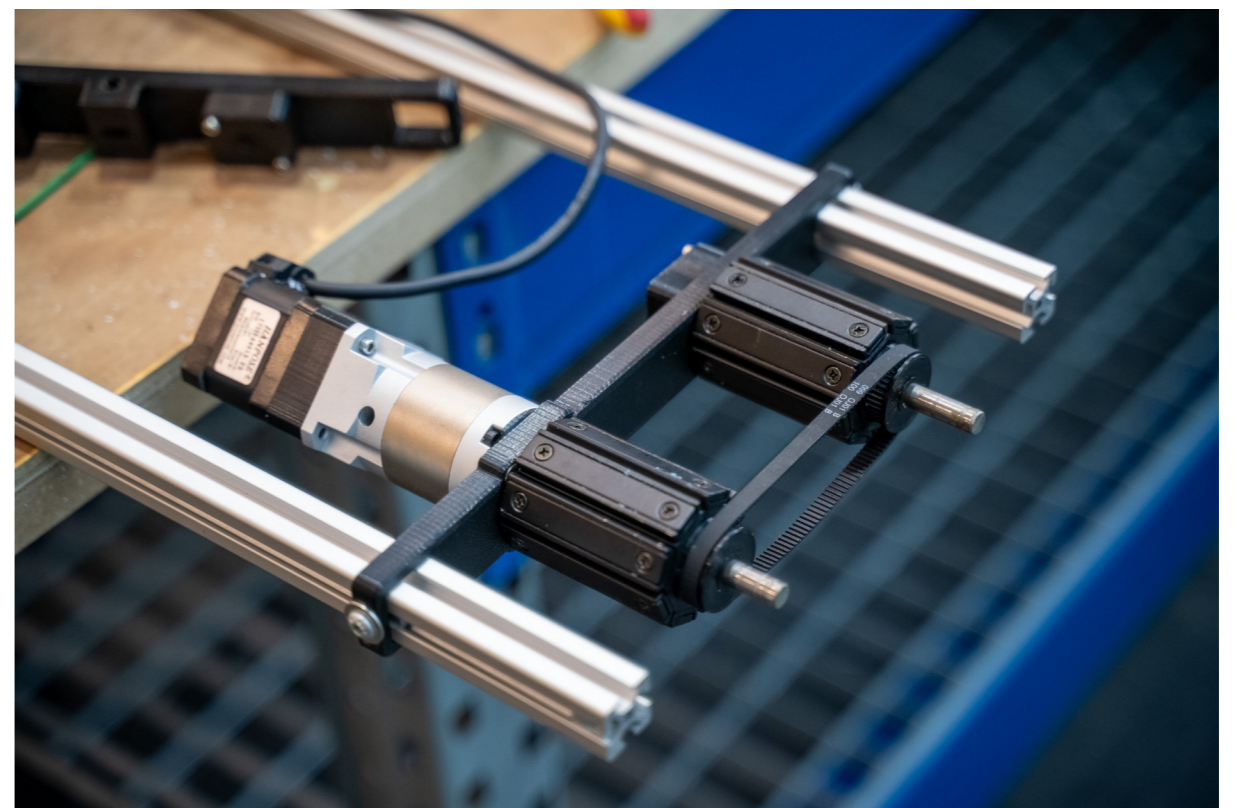


Figure 82 – Magnetic Wheels



Figure 82 – Separator Attached to wheel

The Separator

The original separator concept was designed as an actively actuated mechanism positioned above each magnetic wheel. A rope driven system would move the separator over the wheel when detachment was required. As the wheel rotated, it would climb onto the separator, increasing the distance between the magnets and the steel surface and gradually reducing the magnetic force. (Appendix G - V1)

To keep the prototype focused on validating the separation principle, this actuation mechanism was not included. Instead, a simplified clip-on separator with the same curved geometry was developed. This allowed the prototype to test whether the separator could successfully reduce the magnetic force and enable detachment, without adding unnecessary complexity to the prototype.

Electronics Housing

A central cylindrical housing is mounted on top of the frame and contains the prototype's electronics and battery. The housing also contributes to the platform's buoyancy, although additional foam was added to ensure the prototype remained positively buoyant in the water.

To keep the electronics watertight, five sealed cable ports are integrated into the housing. These provide connections for the Ethernet communication cable, two stepper motors, and two thrusters. The housing was pressure tested by monitoring for air leakage, confirming that the seals remained watertight.

A 4-cell lithium-ion battery is housed inside the cylinder and provides power to the thrusters, ESP32s, and stepper motors. Further details on the electronic system are discussed in the next section.

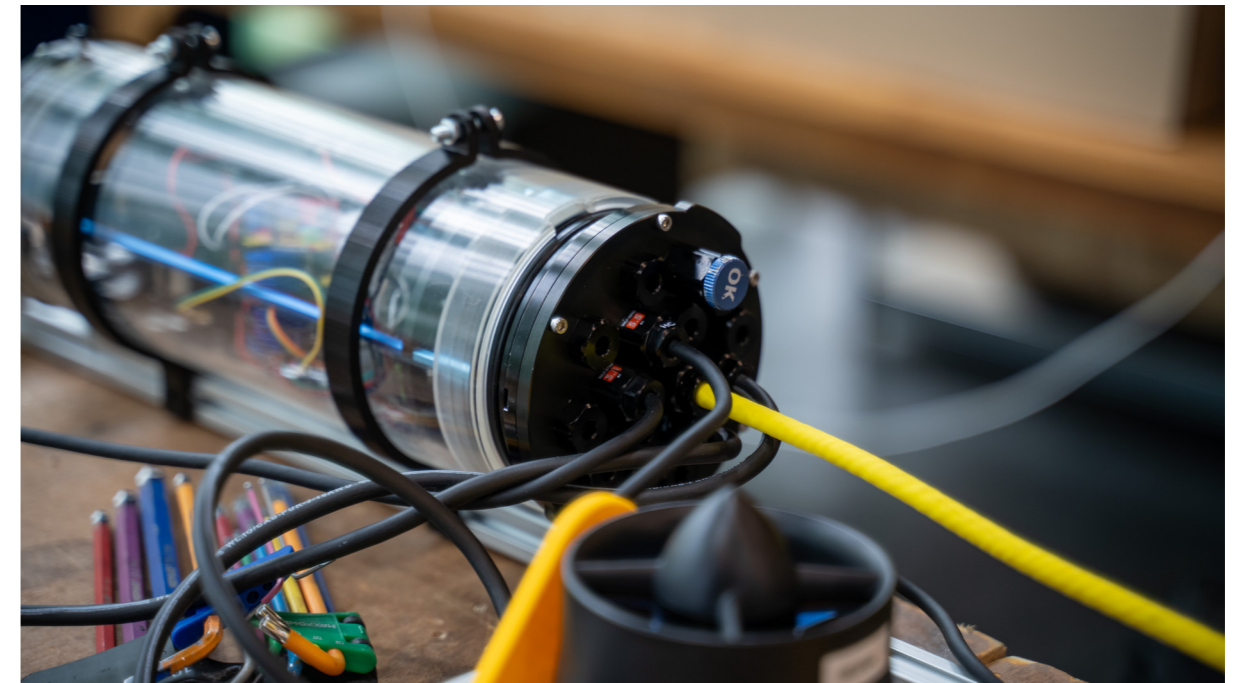


Figure 83 – Cylindrical Housing

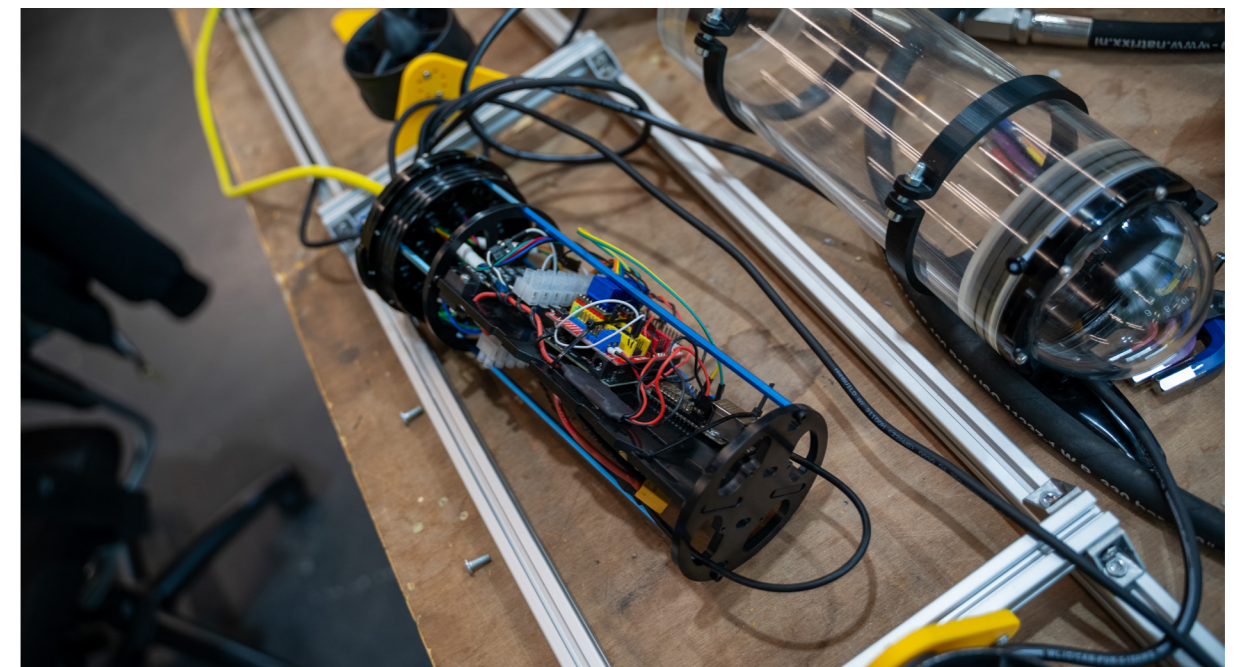


Figure 84 – Electronics in housing

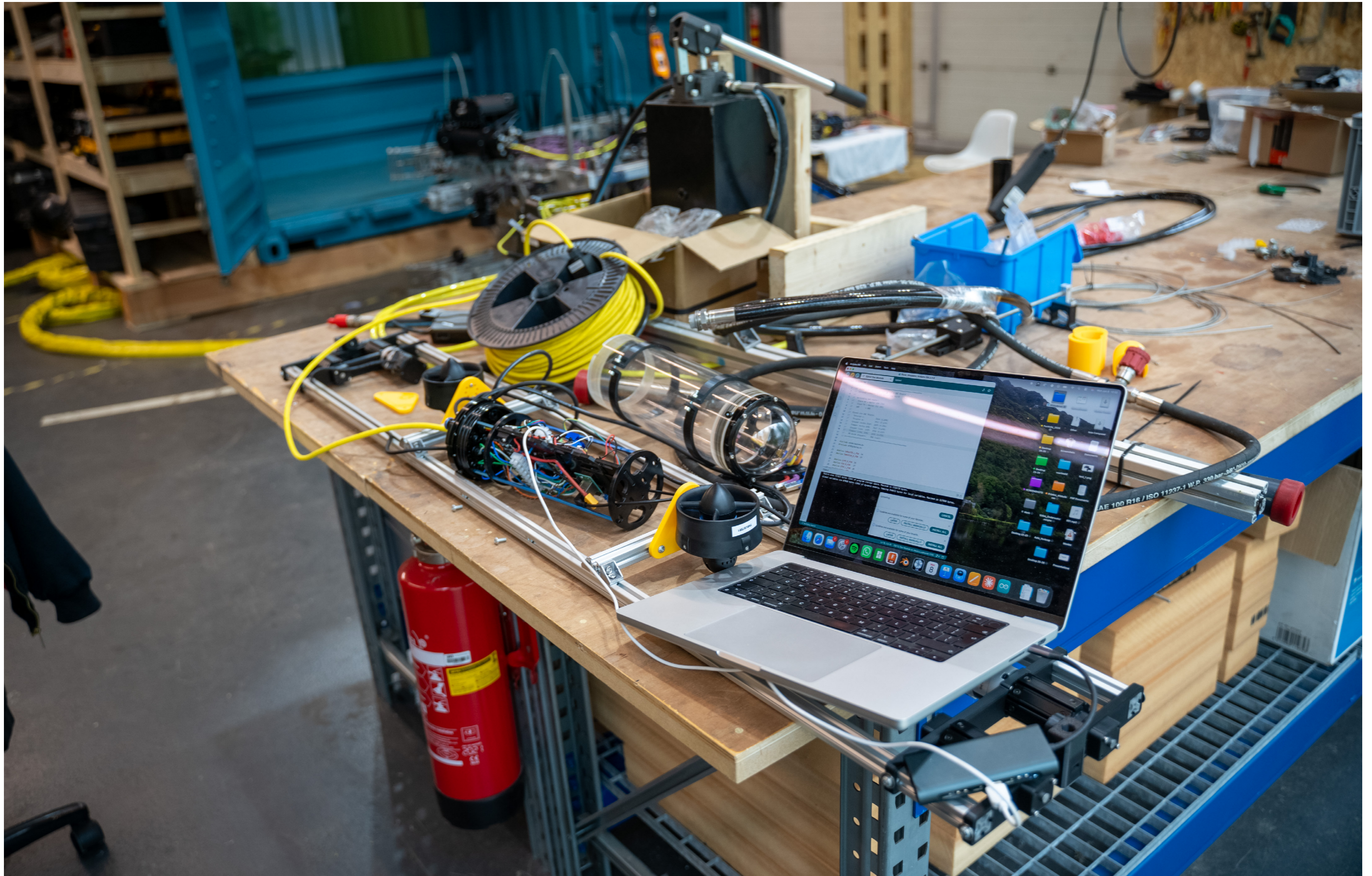


Figure 85 - Uploading code to esp32

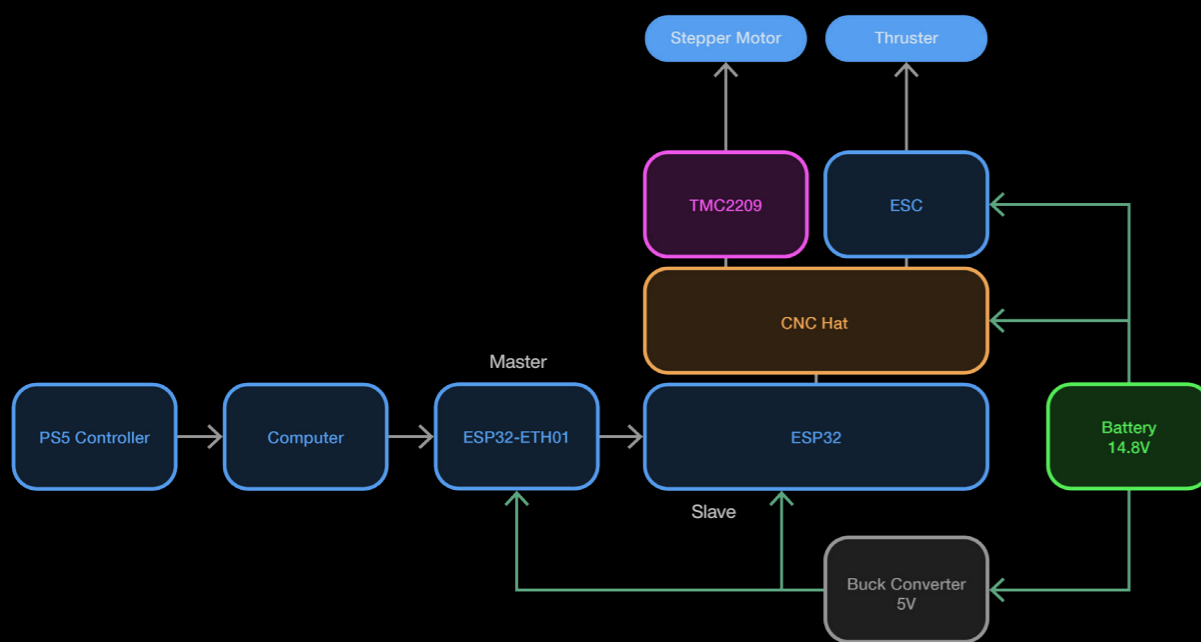


Figure 86 – Illustrates how system is connected

4.1.3 Electronics

The prototype is powered by a 4-cell lithium-ion battery (14.8 V nominal), located inside the watertight electronics housing. Power from the battery is distributed to the different subsystems using buck converters.

A 5 V buck converter supplies power to two ESP32 microcontrollers. The first is an ESP32-ETH01, which receives commands from a computer running a Python control script. The prototype is controlled using a PS5 controller connected to the computer via Bluetooth, while the computer communicates with the ESP32-ETH01 through a long Ethernet cable. This ESP32 acts as the master controller and forwards commands to a second ESP32 over UART communication.

The second ESP32 acts as a slave controller and is connected to a CNC shield equipped with TMC2209 stepper motor drivers. The shield receives power directly from the battery and drives the stepper motors used in the prototype. In addition, the slave ESP32 generates PWM control signals for two Blue Robotics Basic ESCs, which drive the T200 thrusters. Both the ESCs and thrusters are powered directly by the same battery.

The use of two microcontrollers was primarily driven by hardware limitations, as the ESP32-ETH01 did not provide enough available GPIO pins to control all outputs.

4.1.4 User Interface

Since a Python script was required to send the JSON command packets to the prototype, a user interface was developed alongside it. The purpose of this interface was to provide feedback by showing which inputs were being received and how these inputs were translated into commands for the prototype. This made it easier to verify that the communication between the controller, the computer, and the prototype was functioning as intended.

The following sections describe the different elements of the user interface and the design choices that were made during its development.

Actuating

The inputs provided through the PlayStation controller are visualized in the left and right stick cards. These cards display the current position of each joystick, allowing the operator to verify that inputs are being received correctly.

The joystick positions are translated into commands for Thruster L, Thruster R, Stepper L, and Stepper R. The corresponding cards display the percentage of power being sent to each actuator in real time.

Because the prototype uses a skid-steering drive system, steering is achieved by varying the speed of the left and right thrusters. For example, moving the joystick to the left increases the speed of the right thruster while reducing the speed of the left thruster, causing the prototype to turn left. The same principle is applied in the opposite direction when steering right.

Modes

Both the thrusters and the stepper motors can operate in different speed modes. These modes were added to improve control when aligning with the wall of the container. During testing of earlier prototypes, even small steering inputs could cause the thrusters to react quite aggressively, making fine adjustments near the wall difficult. The different speed modes make it possible to switch between precise positioning and faster movement when needed.

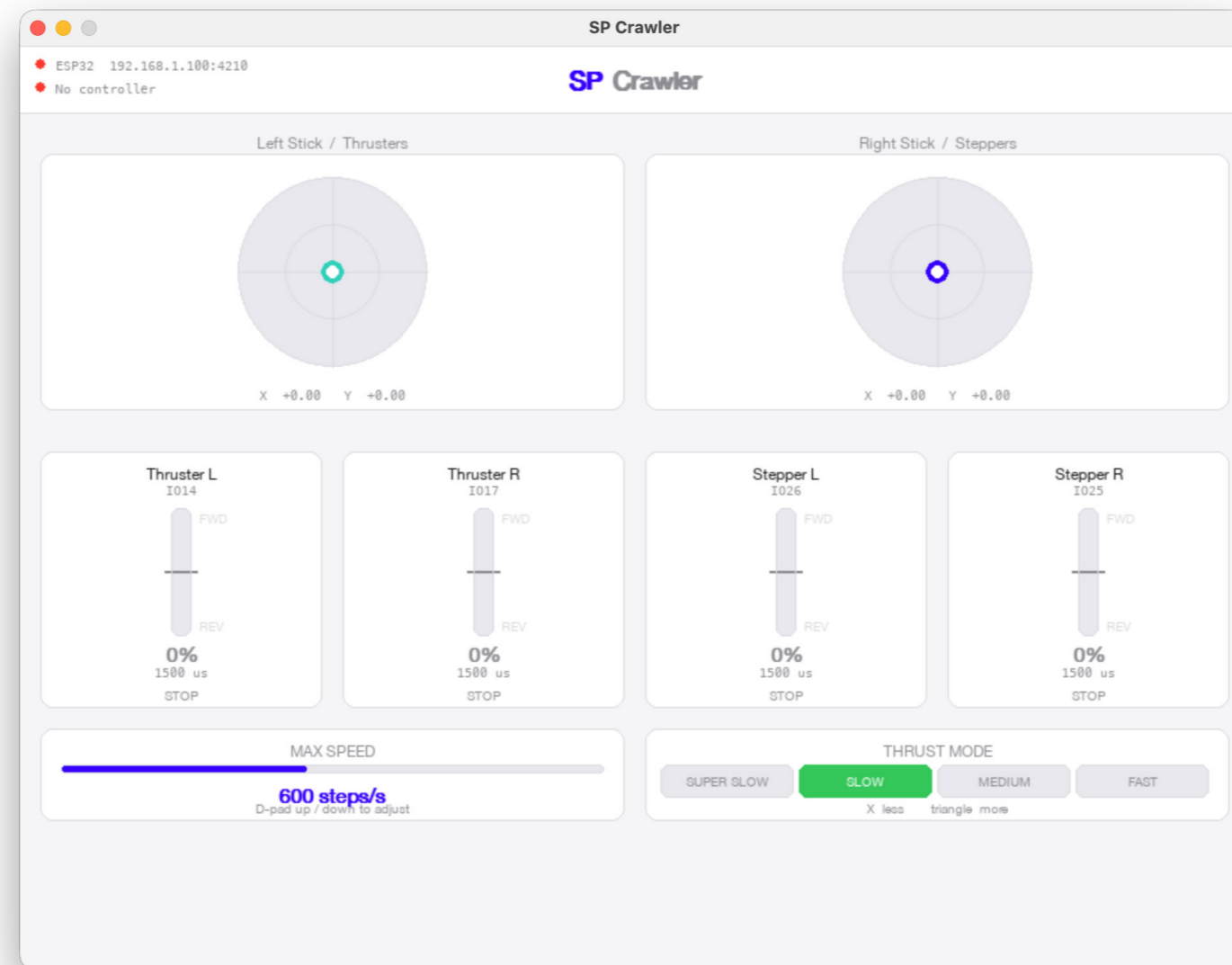


Figure 87 – UI

The placement of the mode controls on the PlayStation controller was also based on observations during testing. The left joystick controls the thrusters, while the right joystick controls the stepper motors. In practice, only one of these subsystems is typically used at a time. This means one thumb is occupied with a joystick, while the other is often free.

For that reason, the speed controls were placed where they can be reached by the thumb that is not actively operating a joystick. This allows the free thumb to adjust the speed mode without letting go of the joystick that is currently being used, making speed changes easier while manoeuvring the prototype.

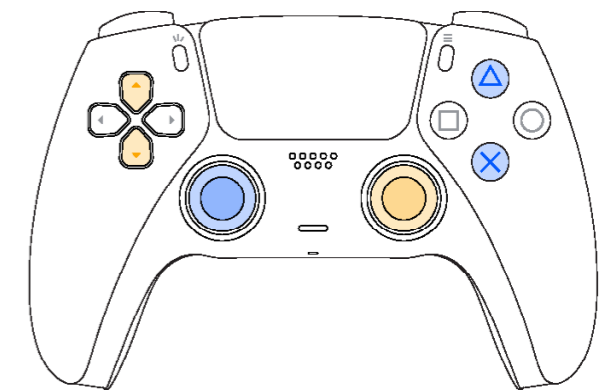


Figure 88 – Button Layout

4.1.5 Testing

Moving

The two thrusters worked reliably and made it easy to move the prototype around and also align it with the wall of the container. Different speed modes were tested and made the alignment process more controllable. By moving back and forth, similar to parking a car, the magnetic wheels could be aligned with the ridges of the container wall. After some practice this became a repeatable process. Two additional side thrusters would likely make this process even easier, as the prototype could then be moved sideways without first having to reposition itself.

The foam caused the prototype to float at a slight angle. While this was not intended, it actually helped during the attachment process. The angled position allowed the magnetic wheels to be aligned with the container ridges before applying more thrust. Once enough force was applied, the wheels snapped onto the wall. This unexpected behavior provided an interesting insight into how attachment could potentially be assisted in future iterations.

Once attached, the magnetic wheels performed well. Even when wet, the magnets provided more than enough grip to climb above the waterline of the container as it never once slipped. Locomotion was relatively slow due to the weaker stepper motors and the 20:1 gear reduction that was used. The belt tensioner proved to be an important component. Because of the strong magnetic attraction, insufficient belt tension caused the belt to skip. Fortunately, the tension could easily be adjusted and the issue was resolved.

The left and right wheel motors also made it possible to steer the prototype using skid steering (like how tanks steer). This was useful when the prototype was not perfectly aligned during attachment. Small steering corrections could be made while driving, helping the magnetic wheels stay aligned with the ridges of the container wall.

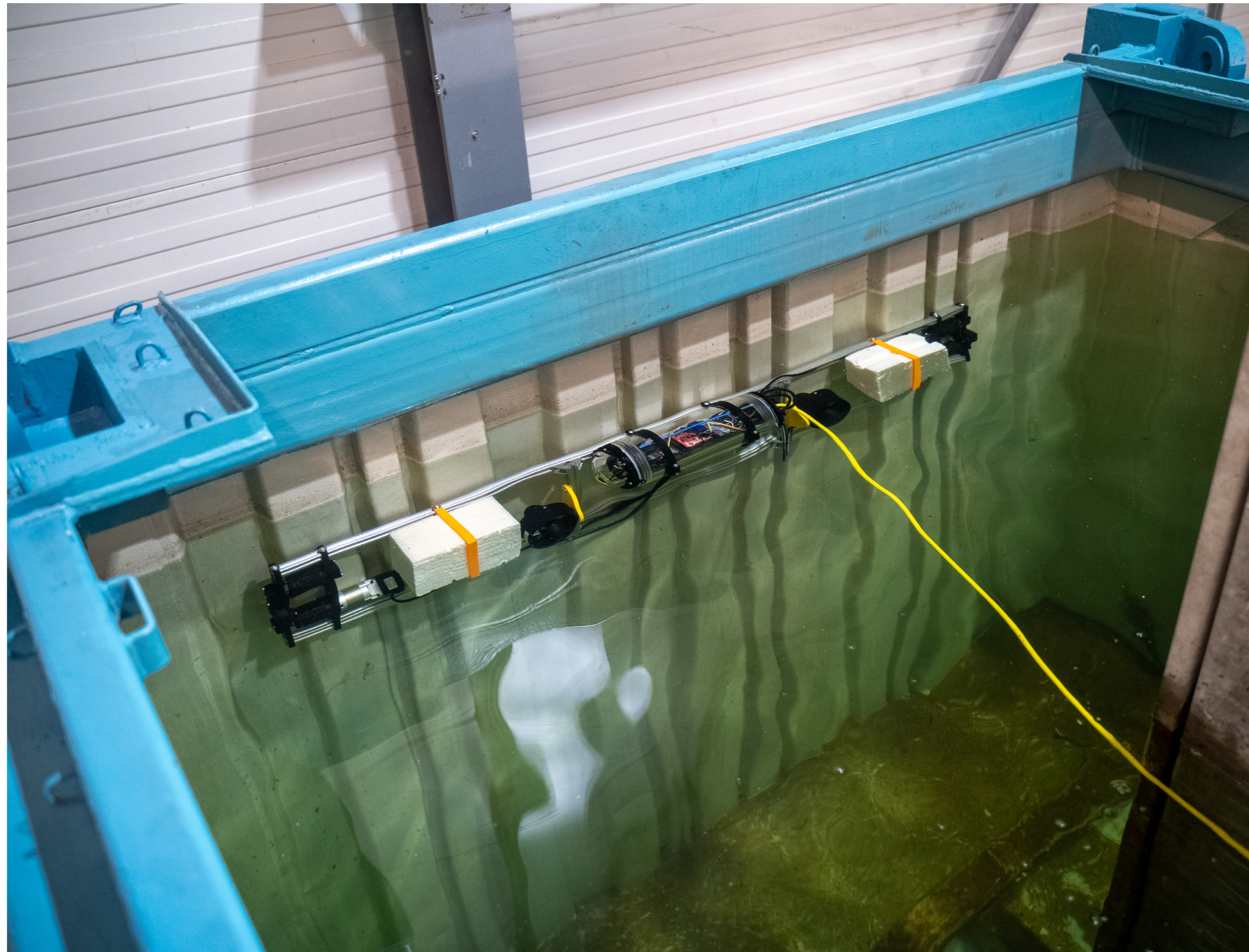


Figure 89 – Testing prototype in container

Attach and Detach

The separator was tested in a separate set of experiments. The goal was to see how it affected both attachment and detachment of the magnetic wheels.

For the attachment test, the prototype was first aligned with the ridges of the sea container wall. Unlike the previous tests, the separator created a small distance between the magnets and the steel surface. As a result, the magnets did not immediately snap onto the wall when approaching it. The prototype was pushed towards the wall using the thrusters while the wheels rotated. As the separator rotated away from the magnets, the distance between the magnets and the steel gradually decreased until the wheels attached to the wall.

The separator was then tested as a detachment mechanism. The question was whether the wheel motors could generate enough torque to rotate the separator while the prototype was attached to the wall. During the tests, the wheels were rotated to increase the separation distance between the magnets and the steel surface. At a certain point, the prototype detached from the wall and floated away.

After each detachment, the wheel rotation was stopped and the separator position was recorded. This made it possible to determine the separator distance at which release occurred (gap is indicated as this distance in mm). The measured values from the different test runs are shown in the table below.

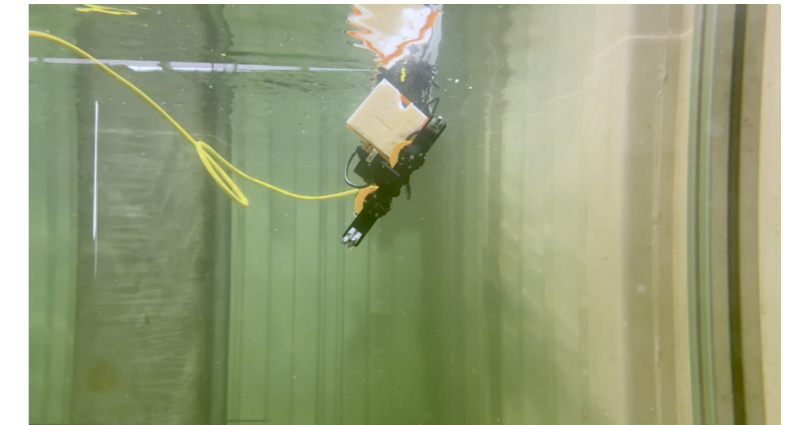
The prototype detached from the wall in every test run. No cases were observed where the separator could not create enough distance for release. The attachment process was also noticeably different from the tests without the separator, as the magnets gradually engaged with the wall instead of snapping directly onto the steel surface.

run	gap (mm)
1	4.89
2	4.83
3	4.98
4	4.95
5	4.89
average	4.91

Figure 90 – Table of measurements

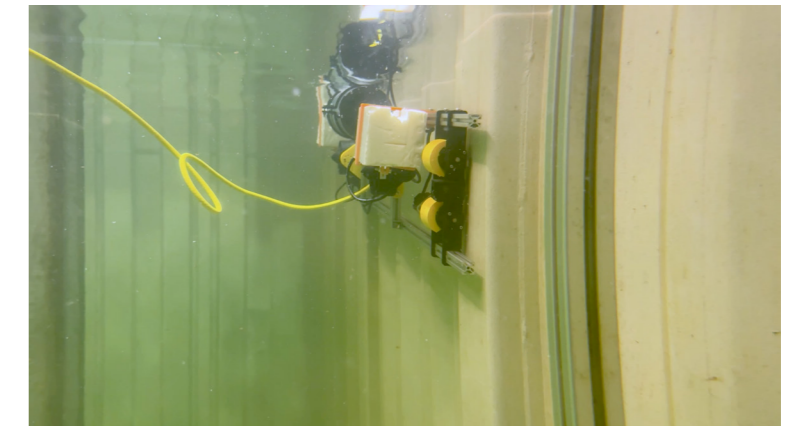
Driving

Drive over to the container wall.



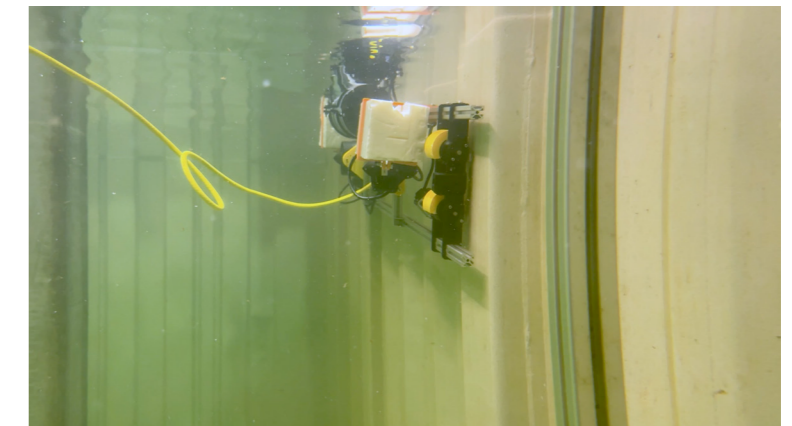
Attach

Attach to the container wall, in this case it snaps on as the separator is not activated.



Activate Separator

Separators start spinning with the wheel and slowly start increasing the gap between the magnet and steel surface



Detach

The separator causes the magnetic wheels to detach from the metal surface, the wheels are stopped and the thickness at that point is recorded.

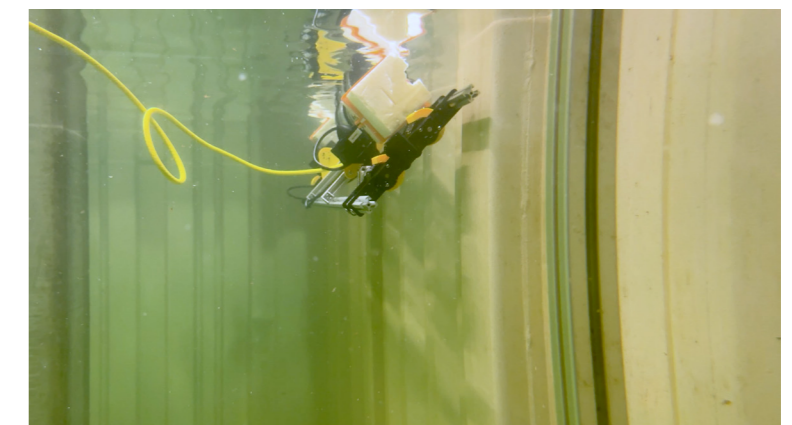


Figure 91 – Different Stages of attachment and separation

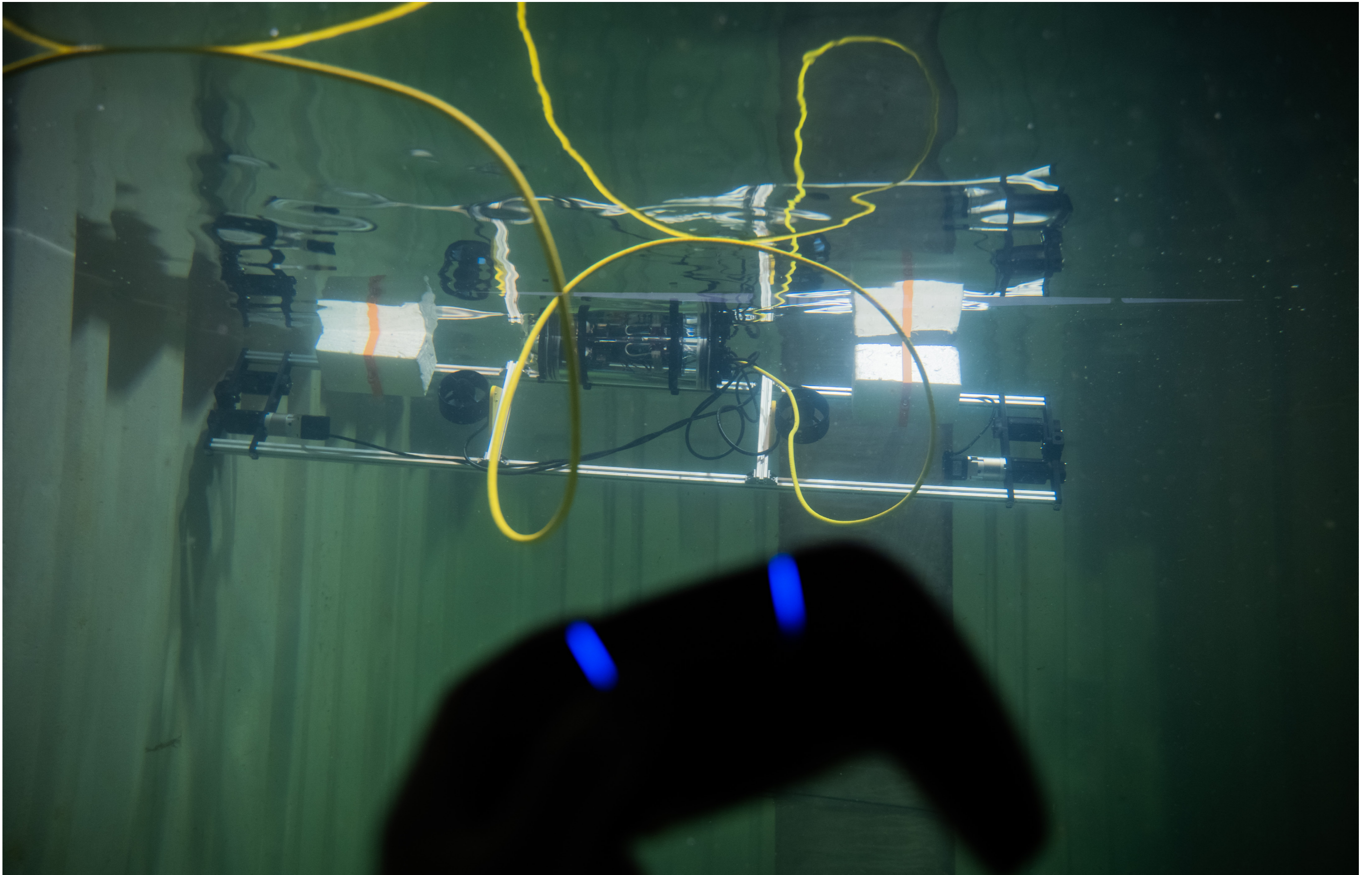


Figure 92 – Prototype in water

Conclusion

The testing showed that the prototype was able to move reliably through the water, align with the container wall, attach to it, and climb along the steel surface. The different speed modes made alignment easier than in earlier prototypes, as small steering corrections could be made without the thrusters reacting too aggressively.

The separator also worked as intended. During all test runs, the prototype was able to detach from the wall. The measured release distance was consistent between tests, with an average separator gap of 4.91 mm. During attachment, the separator caused the magnets to gradually engage with the wall rather than snapping directly onto the steel surface, resulting in a more controlled attachment process.

Several unexpected observations were made during testing. The angled floating position caused by the foam actually helped with attachment, and sufficient belt tension proved important for reliable climbing. These findings will be useful for future iterations of the design.

Overall, the tests demonstrated that the main functions of the prototype could be performed successfully. The prototype was able to move, attach, climb, and detach from the container wall, while also providing valuable insights for further development.

Recommendations

The current prototype was able to successfully move, attach, climb, and detach from the container wall. However, several improvements became apparent during testing.

The addition of two extra thrusters would likely improve manoeuvrability. While the current skid-steering system allowed reliable alignment with the wall, sideways movement was not possible. Additional thrusters would make repositioning easier and reduce the number of alignment corrections required before attachment.

Further testing should also be performed in more realistic conditions. The current tests were conducted inside a controlled container environment. Testing on actual sheet piles, with varying amounts of marine growth, corrosion, and surface irregularities, would provide a better understanding of how the magnetic wheels and separator perform in practice.

Another area worth exploring is the use of magnetic tracks instead of magnetic wheels. Comparing both systems could provide insight into differences in adhesion, climbing performance, and the ability to deal with uneven surfaces.

Finally, the current separator requires power to detach from the wall. A separator mechanism that can still release the prototype during a power failure would increase the reliability of the system and make recovery easier in the event of a malfunction.

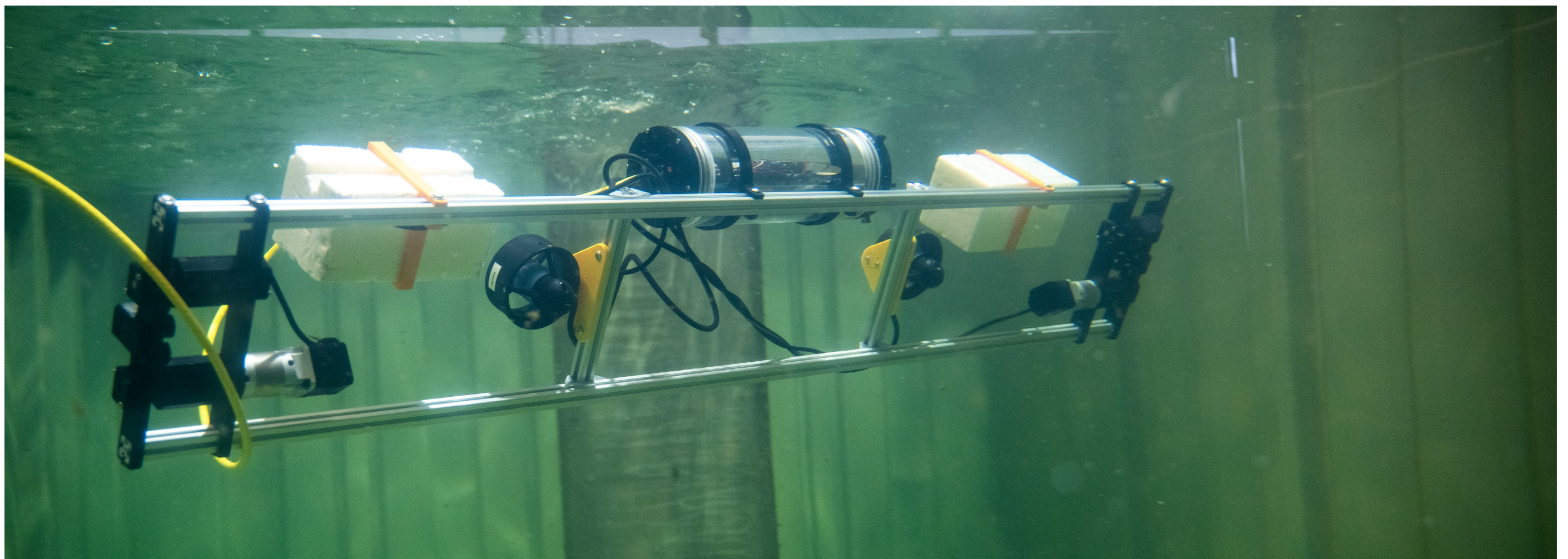


Figure 93 – Prototype in water

4.2 Final Concept



After weeks of research, prototyping, and testing, this is what it all converges into. The Sheet Pile Platform. A system built from the ground up for one thing, inspecting sheet piles in the places no one else can reach.

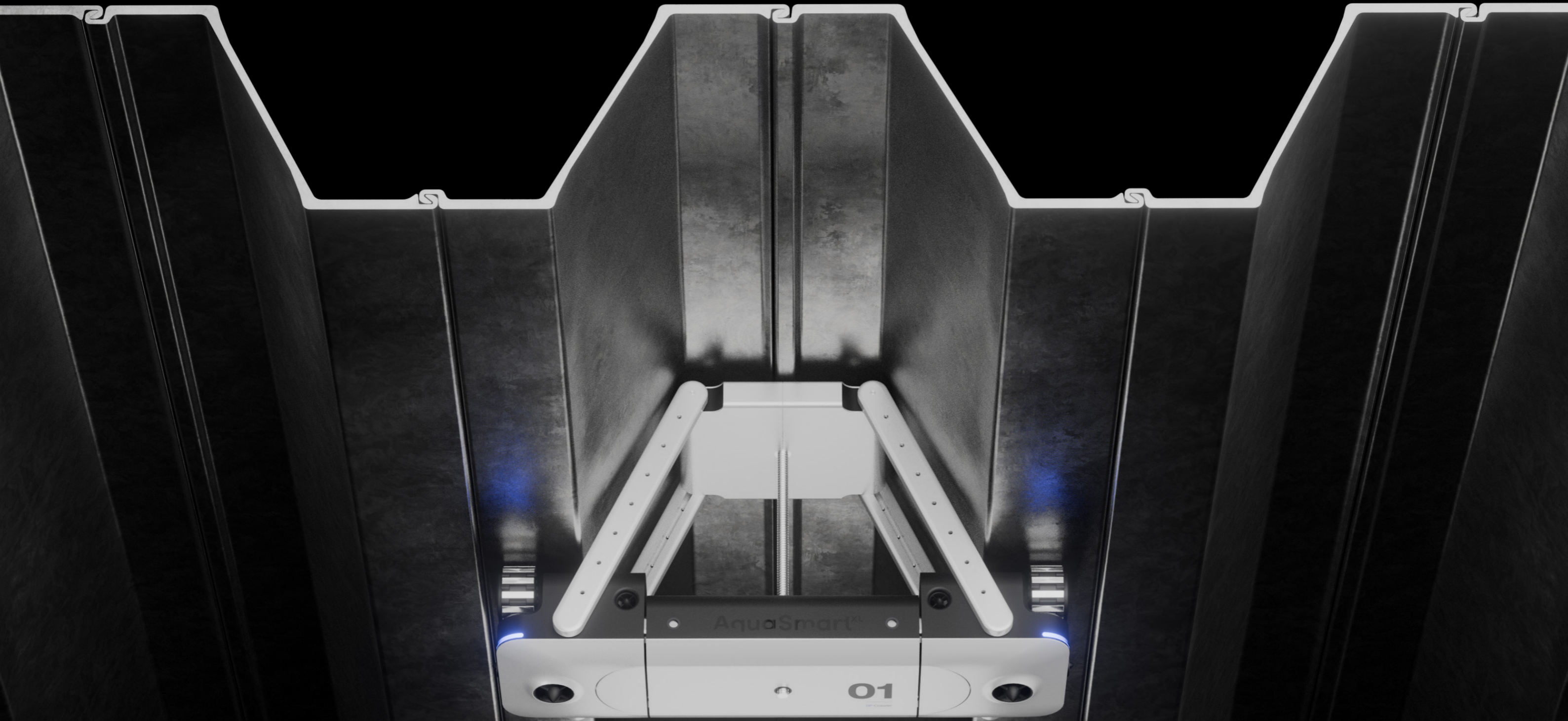
What you see here is meant to spark the imagination. A vision of where this concept is heading, not a finished design. Proportions, mechanisms, and final form will all be worked out further. That is exactly what the prototype in the next chapter is for. But before getting into that, this is the idea made visual.



THE DESIGN

SP Crawler

The Sheet Pile Platform is called the SP Crawler. A neutrally buoyant, magnetically driven inspection platform. It navigates to sheet pile walls using thrusters, attaches to the steel using magnetic tracks, and moves vertically along the surface for inspection both above and below the waterline. The design is modular allowing the SP Crawler to do all the jobs it needs to do.



The extendable middle section and arms adapt to different sheet pile geometries, while the main platform remains attached to the outer surface. This allows the crawler to operate on both U- and Z-profile sheet piles with a simple and adaptable design.



THE DESIGN

Size Adjustment

The SP Crawler can be adjusted to fit different sheet pile dimensions. A simple size indicator shows the current setting, making adjustments quick, precise, and easy to repeat.



THE DESIGN

Obstacle Avoidance

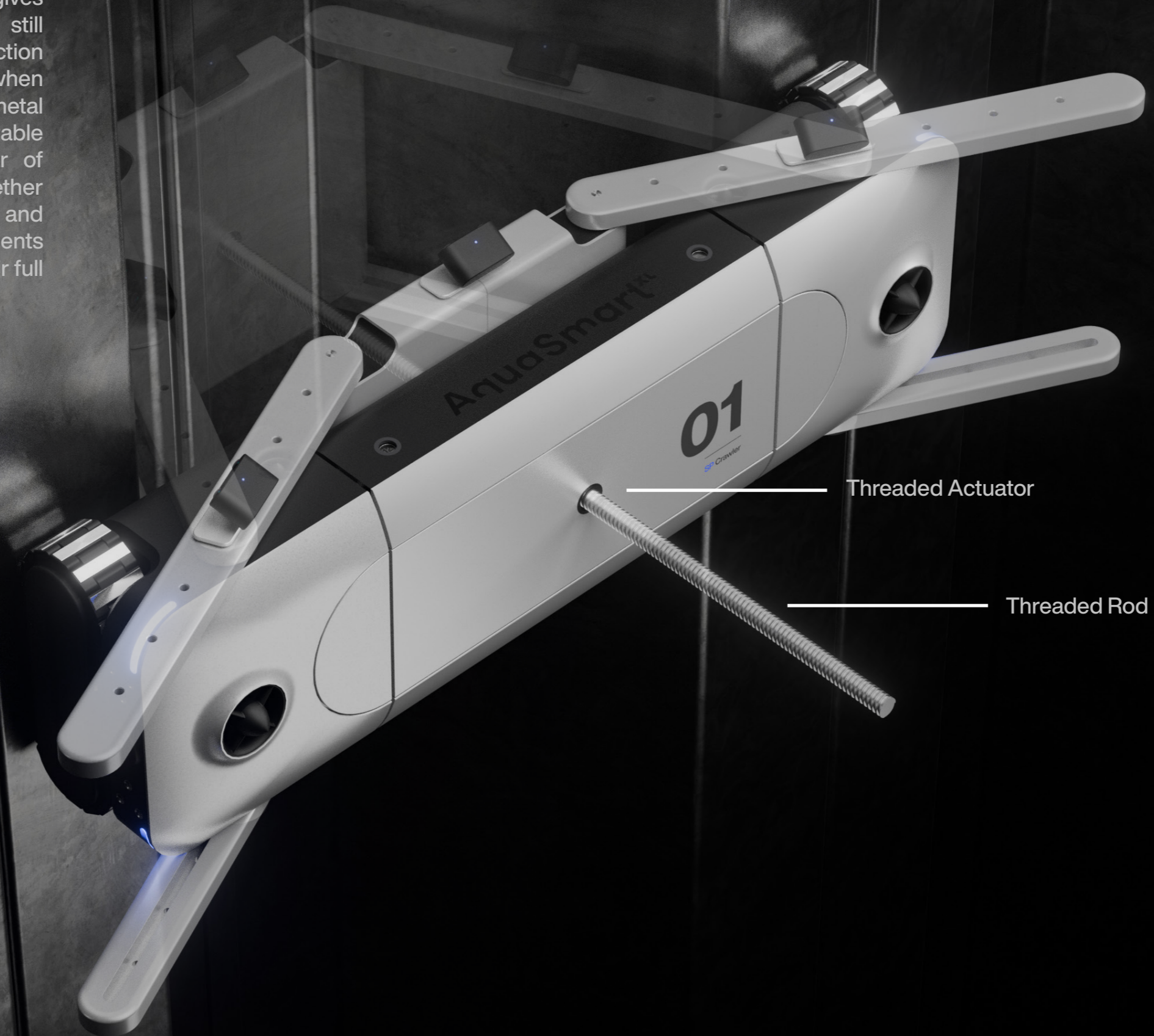
The middle section extends and retracts to handle obstacles like anchor heads and sacrificial anodes.

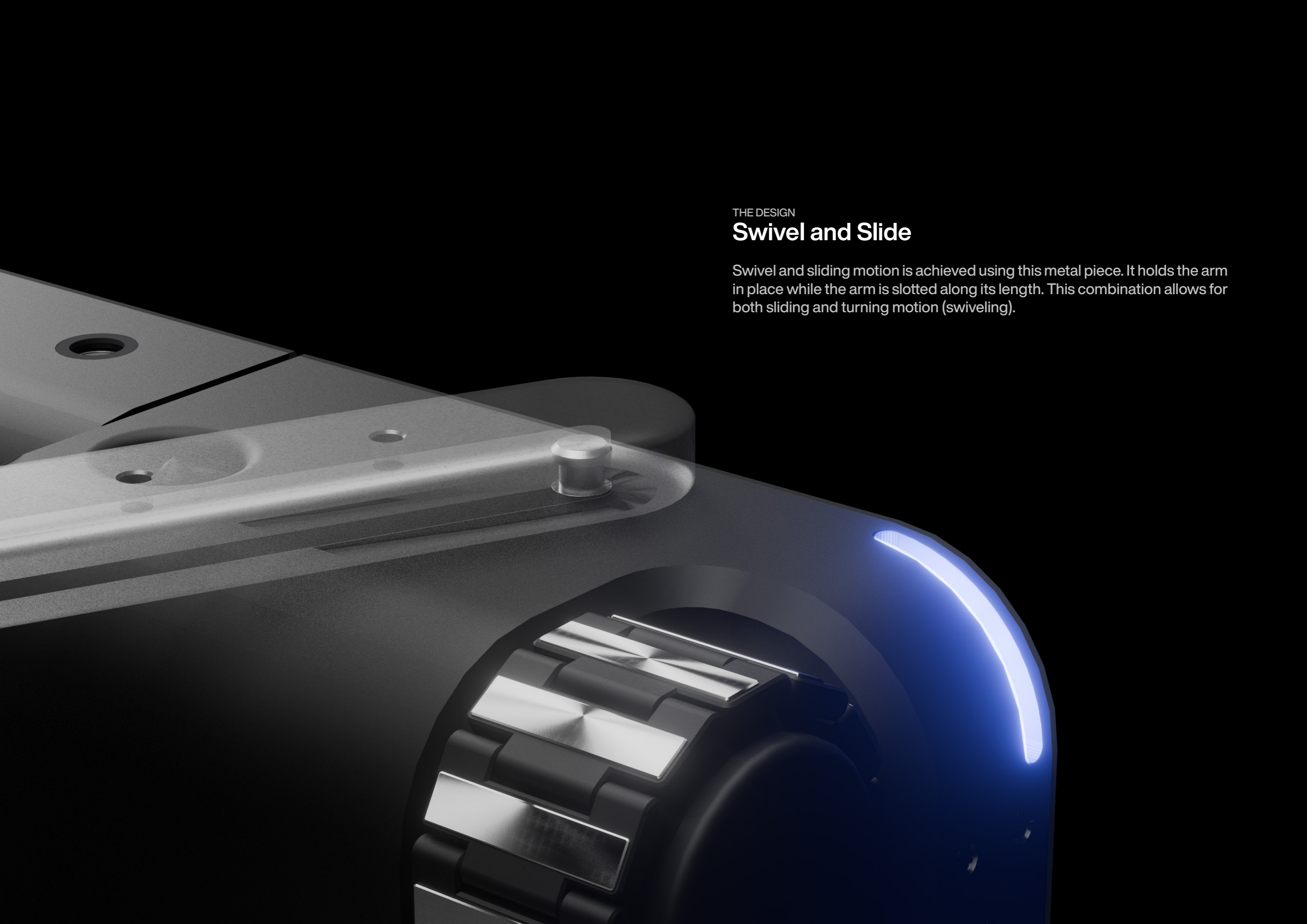


THE DESIGN

Obstacle Avoidance

The middle section extends and retracts via a long threaded rod. The black portion of the main body is itself threaded and motor-driven, actuating the rod inward or outward. This gives a greater range of motion while still allowing the extended middle section to sit flush against the main body when retracted. The trade-off is that the metal rod is exposed, which is acceptable here since this area stays clear of obstructions. The arms move together with the middle section, swiveling and sliding out of the way so attachments remain free to operate through their full range of motion. (See 3.6.2)





THE DESIGN

Swivel and Slide

Swivel and sliding motion is achieved using this metal piece. It holds the arm in place while the arm is slotted along its length. This combination allows for both sliding and turning motion (swiveling).



MOVING
Thrusters

The SP Crawler is placed in the water from either the shore or a boat. It can then be driven towards the sheet piles. When a sheet pile is difficult to reach from the surface, the combination of thrusters allows the crawler to dive underwater and attach to a section of the sheet pile where attachment is possible. This creates a stable platform in a six-degree-of-freedom (6-DoF) underwater environment.

The crawler uses eight thrusters to maintain stability and control underwater. Some of these thrusters play an important role in the crawler's operation. The two large thrusters at the rear provide most of the thrust. They help maintain contact with the sheet pile when marine growth prevents the magnetic wheels from attaching properly.

The two thrusters on the left and right sides allow the crawler to move sideways, similar to a crab. This makes it easier to align the crawler with a sheet pile and move between adjacent sheet piles when needed.



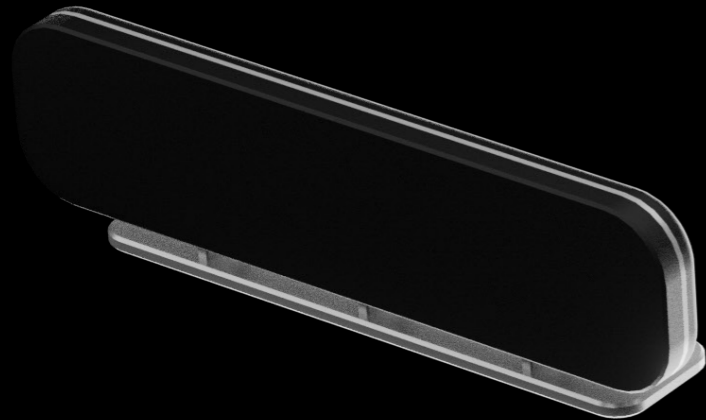
MOVING

Tracks

The SP Crawler attaches to the sheet pile using magnetic tracks. Tracks offer more contact area and handle uneven surfaces more easily than wheels.

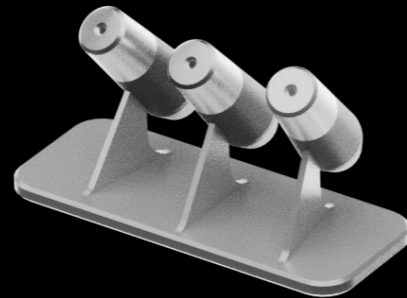
PEC Sensor

Allows for thickness measurement



Cavitation Jet

Cleaning method



Stereoscopic Camera

3D reconstruction



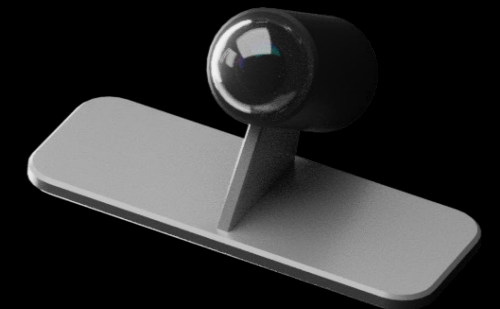
Light

Enhance visibility



Camera

Standard Visual Inspection



MODULARITY

Inspection Modules

As discussed in Section 3.6.5, sheet pile inspections require different approaches depending on the client's needs and site conditions. The SP Crawler acts as a modular platform that can be equipped with different inspection modules. Examples include a PEC sensor for large-area thickness measurements, a cavitation jet for surface cleaning, stereoscopic cameras for 3D reconstruction, and standard cameras for visual inspection.

By selecting only the modules required for a specific inspection, the crawler can be adapted to different situations without increasing the complexity of the base platform.

MODULARITY

Attachment

Universal attachment points allow different tools and sensor modules to be mounted depending on the task. This makes the crawler adaptable to various situations while keeping attachments quick and easy to install. The standardized interface also supports future upgrades and new modules.



MODULARITY

Side Attachment

Attachment points on the sides of the SP Crawler provide additional flexibility for mounting tools and sensors. In this example, a scraper is used to remove marine growth and improve contact with the sheet pile. Depending on the inspection, other cleaning tools, cameras, lights, or sensor modules can be mounted instead.

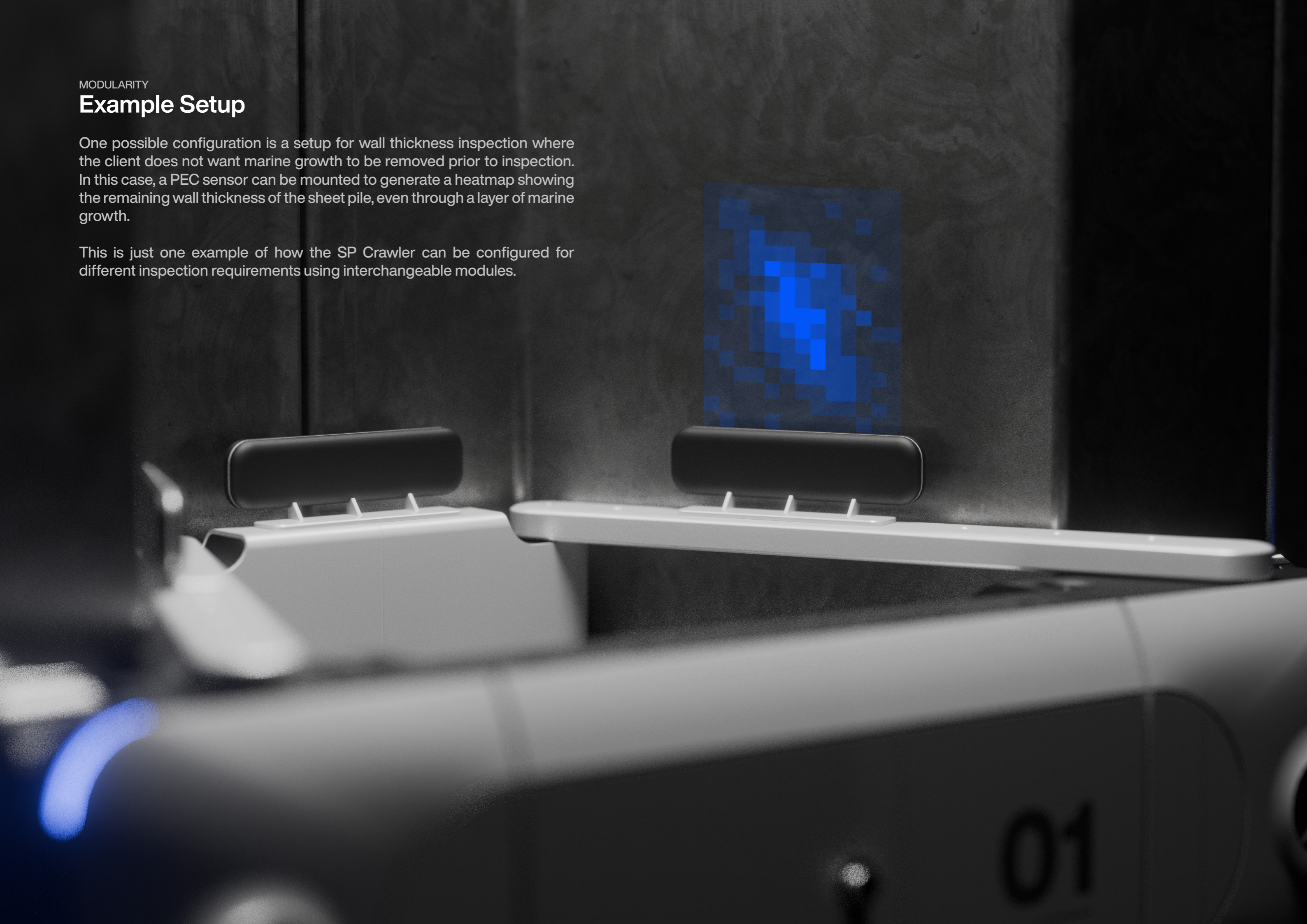


MODULARITY

Example Setup

One possible configuration is a setup for wall thickness inspection where the client does not want marine growth to be removed prior to inspection. In this case, a PEC sensor can be mounted to generate a heatmap showing the remaining wall thickness of the sheet pile, even through a layer of marine growth.

This is just one example of how the SP Crawler can be configured for different inspection requirements using interchangeable modules.



DETACH

Separator

Just like the magnetic wheel separator, the magnetic track separator follows the same principle. When inactive, the separator is stored alongside the tracks. When separation is needed, the separator is activated and the tracks drive over it, creating distance between the magnets and the steel surface.

The ability to remotely attach to and detach from the sheet pile is a valuable feature of the SP Crawler and contributes to what makes the solution unique.



Figure 94 - Separator inactive



Figure 95 - Separator activated



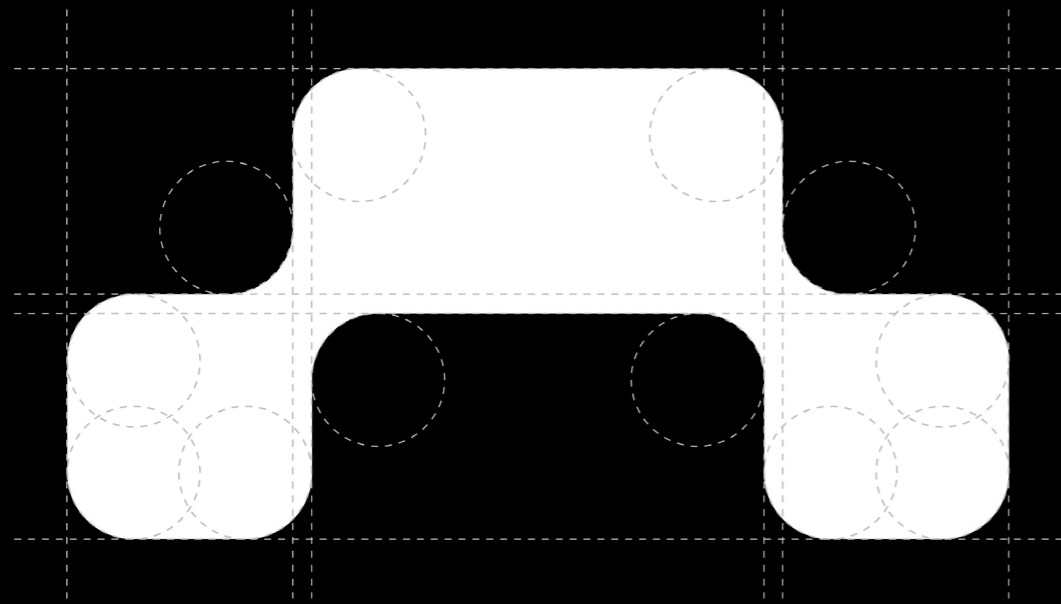
Figure 96 - Separated



Figure 97 – Flowchart for picking attachments

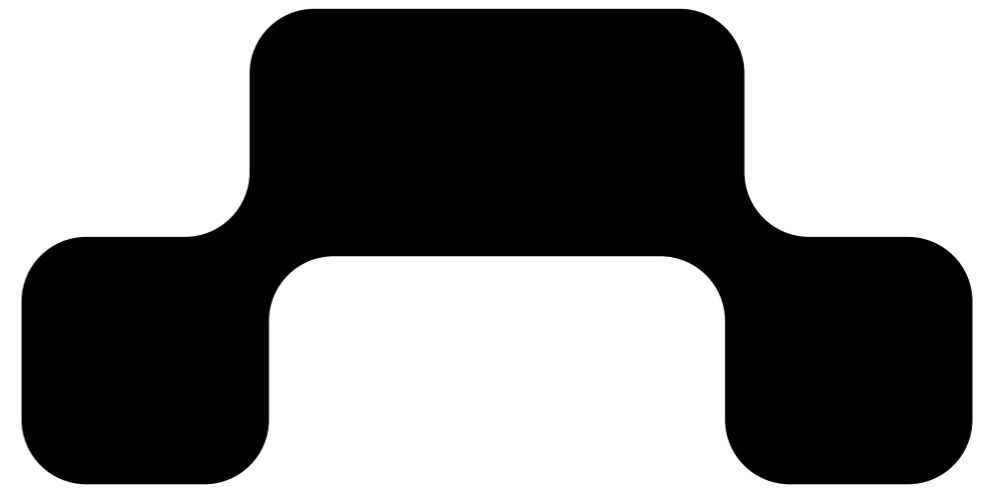
MODULARITY Flowchart

As described in Section 3.6.5, the SP Crawler acts as a base platform that can be equipped with different modules depending on the inspection requirements. This flowchart illustrates one possible decision-making process, showing how cleaning, measuring, and observing modules can be combined to create a suitable inspection setup for a specific situation.



Logo Design

The logo was designed as an abstract representation of a sheet pile profile. Depending on the interpretation, the shape can be seen as either a U-shaped sheet pile or two interlocking Z-shaped sheet piles.



5

Chapter 5 Discussion

Conclusion
Recommendations



Conclusion

The research revealed a clear gap in current sheet pile inspection practices. While existing methods such as divers, cofferdams, and elevated platforms can provide valuable information, they all rely heavily on human intervention and can have a significant impact on port operations. Furthermore, there is currently no dedicated platform capable of travelling along a sheet pile wall and performing inspections in a controlled and repeatable manner. As a result, collecting consistent inspection data over time remains a challenge.

Because of this, the scope of the project was narrowed down. Rather than designing a complete inspection system, the focus shifted towards the development of a platform that could support future inspection equipment. A reliable platform capable of moving to a sheet pile wall, attaching to it, moving along its surface, and detaching again was identified as a valuable first step towards future robotic sheet pile inspection systems.

The resulting SP Crawler concept combines thrusters, magnetic wheels, and a separator mechanism to achieve these functions. Testing showed that the prototype was able to reliably move through the water, align with the wall, attach

to the steel surface, climb the wall, and detach again. In doing so, the project demonstrated that robotic wall crawling inspection of submerged sheet piles is a feasible direction for future development.

The goal of this project was not to create a finished inspection robot, but to explore and validate a possible solution for the subsystems involved. Within that scope, the project successfully demonstrated a foundation on which future sheet pile inspection systems can be built.

Recommendations

The prototype recommendations described several possible improvements to the current platform. Building on these findings, future work should focus on turning the SP Crawler from a mobility platform into a complete inspection system.

A logical next step is testing the platform on actual sheet pile walls. The controlled test environment was useful for evaluating the main functions of the prototype, but real sheet piles introduce additional challenges such as marine growth, corrosion, currents, waves, and obstacles. Testing in these conditions would provide a better understanding of how the platform performs in practice and which parts of the design need further development.

Another interesting direction is further investigation into magnetic locomotion systems. During concept development, both magnetic wheels and magnetic tracks were considered. Tracks offer a larger contact area and may deal better with uneven surfaces, while wheels provide a simpler and lighter solution. Future work should compare both approaches on actual sheet piles. Different ways of integrating magnets into a track system could also be explored. For example, not every track segment has to contain a magnet. Some sections could use other materials to improve traction while reducing weight and complexity.

Future iterations should also focus on improving platform awareness and control. The current prototype mainly sends commands to the platform, but receives very little information back. Adding sensors to monitor battery status, orientation, depth, and other system information would give the operator a better understanding of what is happening underwater. This information could also be used for active stabilization, allowing the platform to automatically maintain its orientation and improve control in moving water.

Finally, future work should investigate what a minimum viable inspection product could look like. The long-term vision includes advanced inspection equipment, but the current prototype already demonstrates controlled movement and alignment with a sheet pile wall. Even in its current form, this could already improve visual inspections by providing a more consistent inspection path. A possible next step would be adapting the geometry of the platform so it naturally follows the profile of a sheet pile wall, combined with cameras and lighting. Rather than trying to solve every inspection challenge at once, an MVP should focus on doing a limited number of inspection tasks reliably. This would provide a realistic first step towards practical robotic sheet pile inspections.

6

Chapter 6
References



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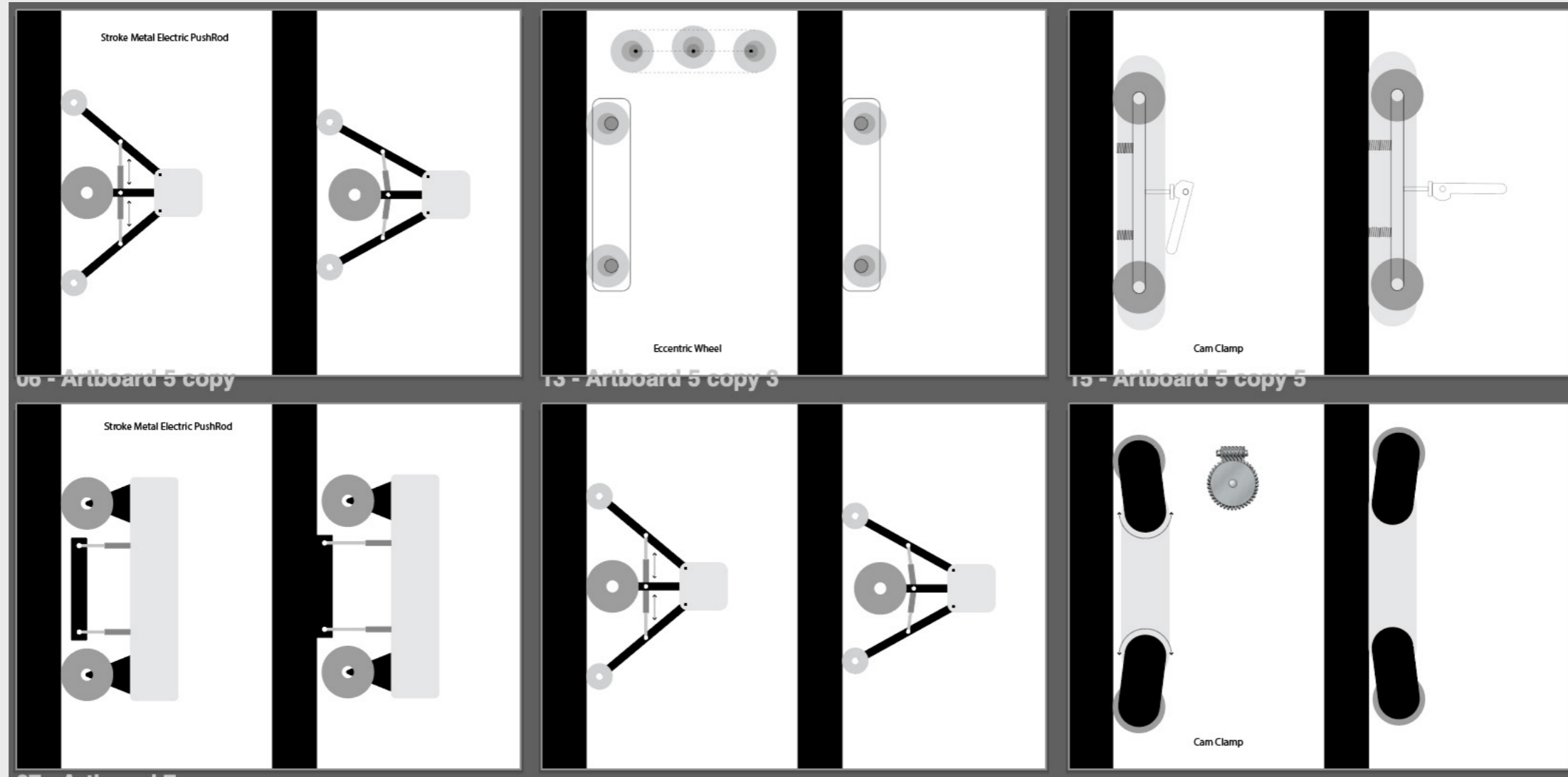
7

Chapter 7 Appendix

- 2.1 Sheet Piles
- 2.2 Mechanics
- 2.3 Corrosion
- 2.4 Visibility
- 2.5 Accessibility
- 2.6 Inspection
- 2.7 Current Inspection Methods
- 2.8 Inspection Strategy and Segmentation
- 2.9 Key Findings



Appendix A - Attach and Detach Magnetic Wheels



Appendix B - Dummy Inspection

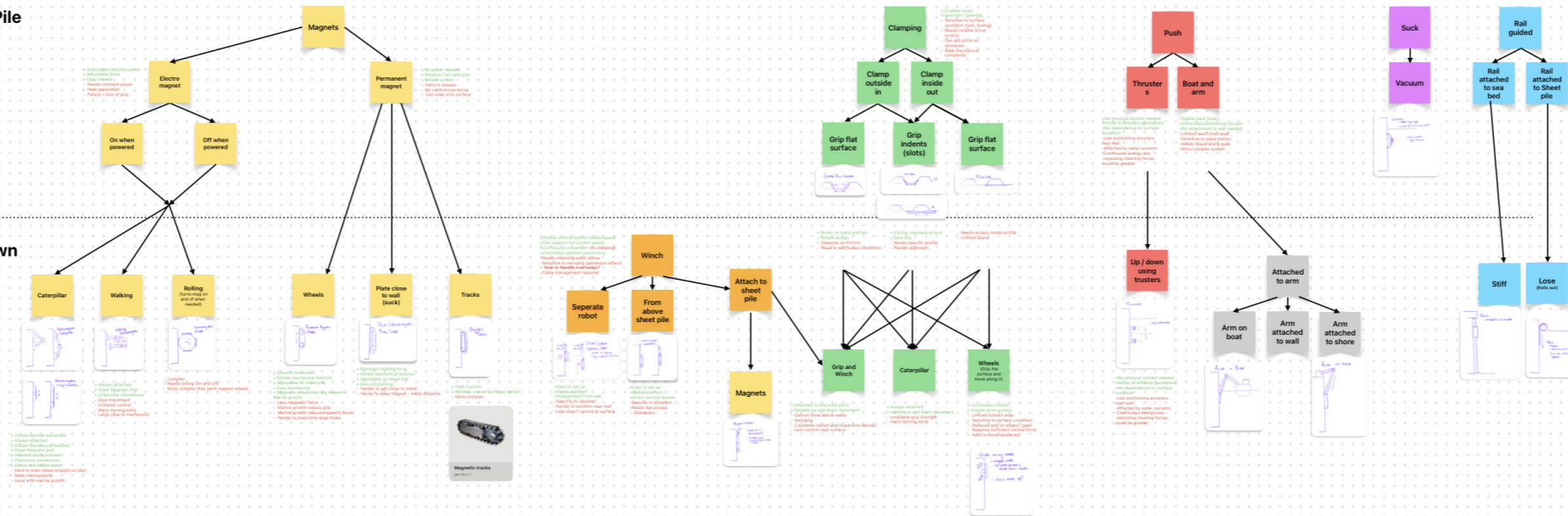


Appendix C - Miro

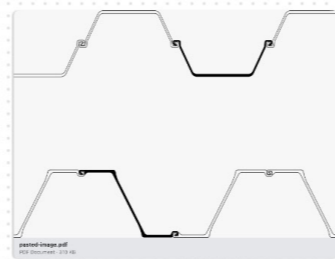
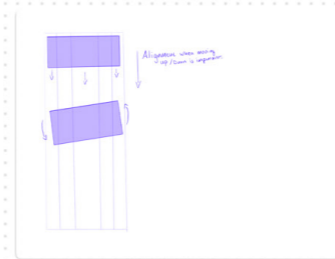
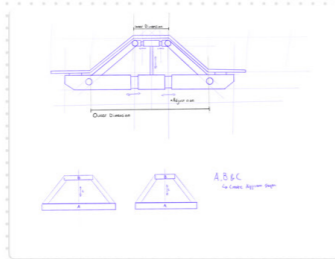
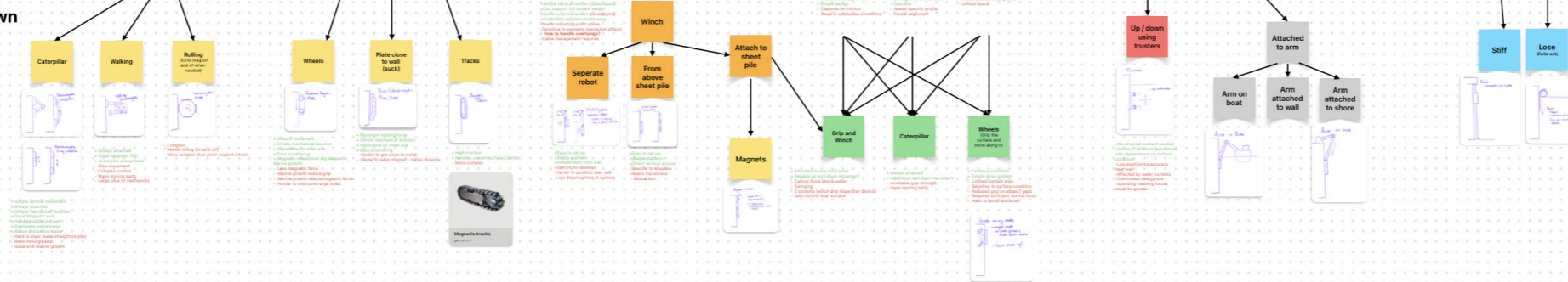
Sheet Pile Design Solution

Stick to wall and move up and down

Attach to Sheet Pile

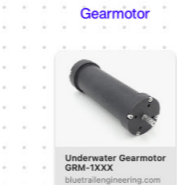
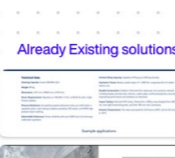
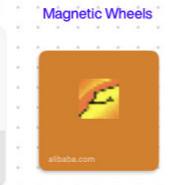
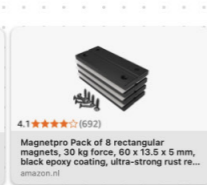


Move up and down



Magnetische rupsbanden bestaan niet PreFab

Final Design



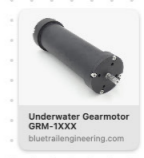
- 1. Adhesion**
Permanent magnets, not electromagnets as the main system.
Reason: simpler, safer, lower power, keeps holding if power dips.
- 2. Coarification**
Two vertical drive tracks or wheel-track modules.
Reason: better obstacle tolerance and more contact area than small rigid wheels.
- 3. Compliance**
Each side should have passive suspension / rocker / spring-loaded module.
Reason: keeps more magnets close to the steel when one part rides over interlocks, rust lumps, or marine growth.
- 4. Surface preparation**
A final loading scraper, brush, or wiper before the sensing/contact zone.
Reason: you do not need to clean the whole wall, only the strip where the magnets and sensor need reliable contact.
- 5. Safety and load management**
Use a tether for power/data and also to offload some weight.
Reason: reduces the adhesion force you need and gives a recovery method.

"There are so many different situation and variables. It's important that the device is modular to adapt to those situations"

- Calm / Turbulent water -> first go 2m deep
- Easy to scrape of marine growth / though -> different ways of cleaning
- Sheet Pile dimensions -> adapt to dimensions
- Marine growth can vary both at depth and time -> must find place to attach to sheet pile.

Prototype

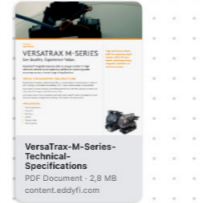
- Hoe control ik alles? (Wiring diagram)
- Kies magneet wiel (moet passen bij kloppende gewicht)
- Kies de motor (wss die ene van bluetrail)
- Kies een worm gear (moet een hold hebben)
- Kies een extrusie profiel waar ik mee ga werken
- Release mechanisme maken



Verslag

- Midterm verwerken in nieuwe format (max 2 dagen)
- Bronnen toevoegen (max 1 dag)
- Verder schrijven voor resterende fase

ONDERZOEK NAAR MAGNETISCH KLIMMEN



Profile 80x80L I-Type slot 8	Profile 40x40L I-Type slot 8	GRM-1XXX Underwater Gearmotor																												
<table border="1"> <tr><th colspan="2">Profile 80x80L I-Type slot 8</th></tr> <tr><td>Slot</td><td>8 mm</td></tr> <tr><td>Slot</td><td>14 mm</td></tr> <tr><td>Width of flange</td><td>41 mm</td></tr> <tr><td>Width of flange</td><td>41 mm</td></tr> <tr><td>Section modulus</td><td>80 mm³</td></tr> <tr><td>Surface</td><td>1175 mm²</td></tr> </table>	Profile 80x80L I-Type slot 8		Slot	8 mm	Slot	14 mm	Width of flange	41 mm	Width of flange	41 mm	Section modulus	80 mm ³	Surface	1175 mm ²	<table border="1"> <tr><th colspan="2">Profile 40x40L I-Type slot 8</th></tr> <tr><td>Slot</td><td>8 mm</td></tr> <tr><td>Slot</td><td>14 mm</td></tr> <tr><td>Width of flange</td><td>21 mm</td></tr> <tr><td>Width of flange</td><td>21 mm</td></tr> <tr><td>Section modulus</td><td>40 mm³</td></tr> <tr><td>Surface</td><td>587.5 mm²</td></tr> </table>	Profile 40x40L I-Type slot 8		Slot	8 mm	Slot	14 mm	Width of flange	21 mm	Width of flange	21 mm	Section modulus	40 mm ³	Surface	587.5 mm ²	<p>Gearmotor Datasheet GRM-1XXX_REV_1_1-2 PDF Document - 853 KB</p>
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Surface	587.5 mm ²																													
3x heavier per meter. Probably need 2/3 meters 10 - 15KG	Probably need 2/3 meters 3 - 5KG																													





ANODES!!!

Week To-Do

Week To-Do content area

ALLES OVER DAMWANDEN



AquaSmartXL

Sheet Pile

What is a sheet pile?

Main functions

- Retain water
- Retain earth
- Retain structures
- Retain traffic
- Retain temporary and permanent walls

Material types

- Steel
- Aluminum
- Concrete
- Composite
- FRP

Shapes

- U-Profile
- Z-Profile
- Omega-Profile

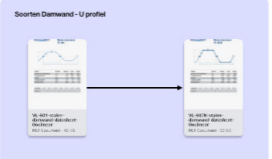
Water Tightening

- Water-tightening in sheet pile walls
- Water-tightening in sheet pile walls
- Water-tightening in sheet pile walls

Permanent Sheet Piles

- Retain water
- Retain earth
- Retain structures
- Retain traffic
- Retain temporary and permanent walls

Comb Damwand



Interesting

Interesting content area

Random Gedachten

Random Gedachten content area

Stakeholders

Stakeholders content area

Interview Matrix

Interview Matrix content area



Inspection

Inspection content area

Maintenance

Maintenance content area

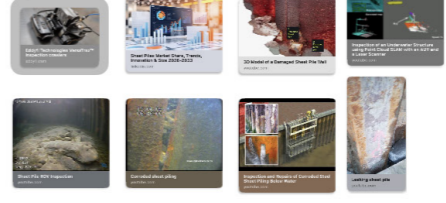
Corrosion

Corrosion content area

Material selection

Material selection content area

Eddyfi / Mechanics



Brushless Motor for underwater use

Brushless Motor for underwater use content area

Magnetic Wheel

Magnetic Wheel content area

You want to use as little as possible Mechanical!

Appendix E - Project Proposal

Project Proposal form IDE Master Graduation Project

In this proposal the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document needs to be prepared for the Kick-off meeting and should be submitted in MyCase.

Name student Thomas van Leeuwen Student number 5055008

Project title Design of an Inspection Device for Steel Sheet Pile Structures

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

MSc programme Design for Interaction Integrated Product Design Strategic Product Design
 Other (in case of a double degree outside IDE): _____

Introduction

Describe the context of your project in the box below; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Sheet pile structures are a critical component of waterfront infrastructure, forming quay walls, embankments, and retaining systems in ports, rivers, and industrial waterways. Many of these structures are aging and experience continuous degradation from corrosion, marine growth, mechanical impacts, and fluctuating water conditions. As a result, operators increasingly rely on periodic inspections to assess remaining wall thickness, structural integrity, and potential safety risks. However, current inspection methods are slow, costly, and often inconsistent, especially in underwater environments where visibility is low and heavy marine growth prevents effective measurement.

This project takes place in the domain of maritime infrastructure inspection, focusing specifically on permanent steel sheet pile walls. The main stakeholders include AquaSmartXL (the commissioning company), port authorities, municipalities, and contractors responsible for maintenance and safety. Their shared interest lies in obtaining reliable, efficient, and repeatable inspection data that supports maintenance decisions, lifecycle planning, and risk mitigation. For these stakeholders, reducing inspection time and cost while improving data accuracy can have substantial operational and financial advantages.

At the same time, the domain presents clear limitations. Underwater sheet piles are difficult to access, marine growth blocks visual inspection and measurement, and currently there are no existing robotic solutions to this specific problem. These challenges create a clear opportunity for a new inspection tool that can navigate the underwater environment, handle marine growth, and deliver accurate structural information with minimal operational burden.

→ space available for images / figures on next page

Introduction (continued): space for images



Figure 1: Example of a maritime sheet pile use case

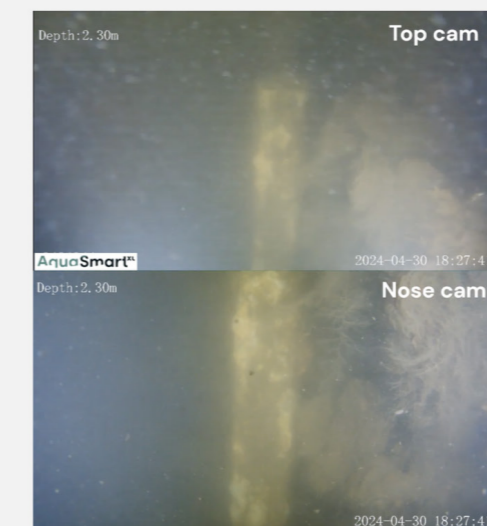


Figure 2: Underwater view of a sheet pile covered with marine growth

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice. (max 200 words)

This project focuses on the conceptual design and development of key subsystems for inspecting sheet pile structures, including access, attachment, vertical movement, and surface preparation for measurement. Instead of trying to build a fully finished, commercial product, the focus is on solving the main technical challenges that make reliable inspection possible in the first place.

To keep the project realistic within 100 working days, the system will be broken down into clear subfunctions such as access, attachment, vertical movement, and surface interaction. These parts will be tackled step by step, with the aim of developing and validating at least one or two of these subsystems to a high level of maturity. This way, the project delivers solid results, clear insights, and useful recommendations to the client, instead of a broad but shallow prototype.

The value of this project lies in making inspections faster, cheaper, and more consistent for infrastructure owners. The main contribution is the development and testing of concrete mechanical solutions for critical functions such as attachment, vertical movement, and surface interaction, supported by prototypes and experiments. This gives the client not only working concepts, but also clear insight into what approaches work, what does not, and where further development effort should be invested.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project (1 sentence). As you graduate as an industrial design engineer, your assignment will start with a verb (Investigate/Design/Validate/Create), and you may use the format: *(Investigate/Design/Validate/Create) a (what will be the deliverable → prototype/roadmap/process/intervention /approach/guideline/strategy/...) to (what should it do → (create/understand/evaluate/validate/improve/execute/analyse/...)) (the objective → experience/value/process/product/...) for (whom → target group/client/...) in (what context).*

“Design an inspection system for steel sheet piles, with prototyping and validation focused on the most critical subsystems for maritime environments.”

Explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words).

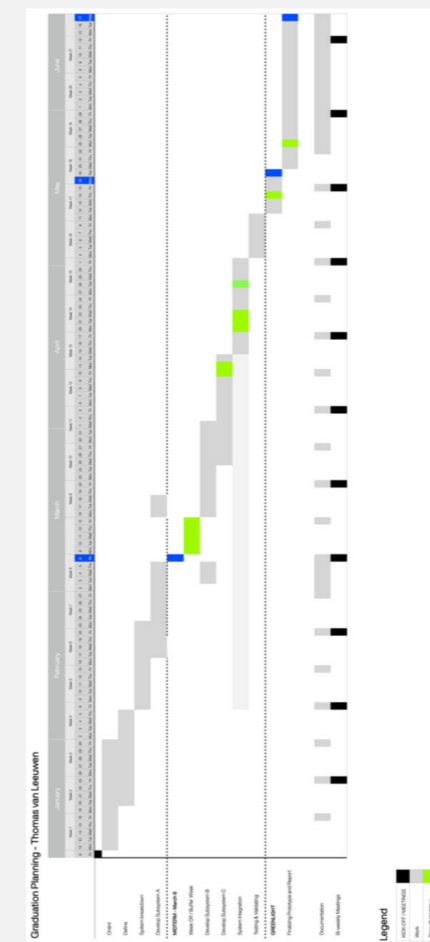
The project will follow an iterative design process that starts with building a solid understanding of the inspection context through field visits, discussions with stakeholders such as port owners, engineers, and inspection professionals, and studying existing methods and relevant literature. These inputs will be used to define a clear set of requirements and design criteria.

Based on this, the inspection task will be broken down into clear subfunctions such as access, attachment, vertical and possibly horizontal movement, and surface interaction. To explore solutions, different approaches will be used, including but not limited to tools from the Delft Design Guide. This includes morphological charts, SCAMPER, and brainstorming sessions with Spark Design & Innovation (a design agency acting as a sparring partner), as well as basic simulations where useful.

Rapid prototyping will be used throughout to test ideas, validate assumptions, and support design decisions. Promising ideas will be built and tested, improved through several iterations, and used to create demonstrable prototypes, together with clear recommendations for further development.

Project planning

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include the **Kick-off, Midterm Evaluation, Green Light** and **Finalisation (ceremony)**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities). Add (an image of) the planning in the box below. If it is not readable, you can add the planning as an attachment to My Case along with this Proposal.



Oriënt

- Kick-off and align scope, expectations, and planning with supervisors and AquaSmartXL.
- Identify and map key stakeholders (port owners, inspectors, engineers, contractors).
- Prepare interviews (list of questions and topics)
- Go into the field to interview port owners, engineers, and inspectors.
- Observe how inspections are currently done in practice where possible.
- Collect and structure insights about workflows, tools, bottlenecks, risks, and constraints.
- Study relevant background: sheet pile structures, degradation mechanisms, and current inspection methods.
- Synthesize findings into a clear problem understanding, including constraints, opportunities, and design space boundaries.

Define

- Sharpen the problem, scope, and list of requirements.
- Do a first brainstorming session with Spark.

System breakdown

- Break the problem into a few key functions the device needs to perform.
- Explore possible ways of solving these using sketches, references, and idea-generation methods.
- Decide which parts are worth developing and testing in depth.

Develop subsystems

- Work on the main parts of the system one by one (fixation, movement, surface interaction).
- Build and test rough prototypes.
- Improve the ideas based on what works and what doesn't.

Integrate & validate

- Combine the best parts into one system.
- Build and test an integrated prototype.
- Check if it actually meets the requirements and improve it

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some (max 5) personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology (200 words max).

I chose this graduation project because I enjoy working on tangible, technical problems that exist in the real world and that actually need a practical solution. I like designing and building things that have to work in difficult conditions, and this project combines mechanical design, prototyping, and fieldwork in a context that is new to me and technically challenging. The maritime inspection world is something I did not know much about before, which makes it a great opportunity to learn.

Working together with AquaSmartXL gives me the chance to be close to real inspection practice and real constraints, instead of designing something in isolation. In addition, collaborating with Spark Design & Innovation allows me to learn from a more design driven and creative way of working and to challenge my ideas early on through discussions and brainstorming sessions.

With this project, I want to further develop myself as a designer who can translate complex, real-world problems into concrete technical solutions. I want to get better at breaking systems into sub functions, building and testing prototypes, and improving them based on what actually works in practice.

My personal learning goals are:

- Improving my mechanical design skills through hands on prototyping and testing.
- Learning to work with real users, constraints, and environments.
- Structuring and managing a large technical design project.
- Becoming more confident in making and defending technical design choices.
- Better documenting my design process, decisions, and iterations.

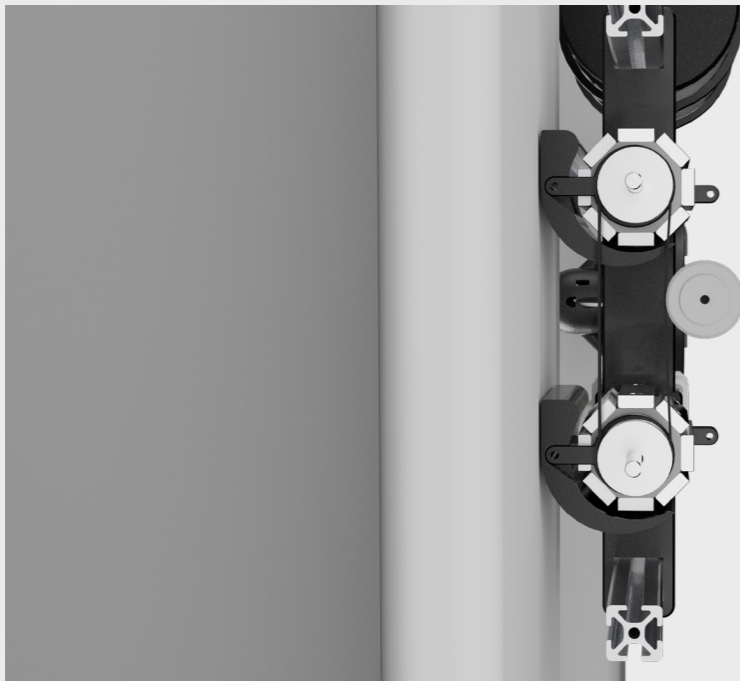
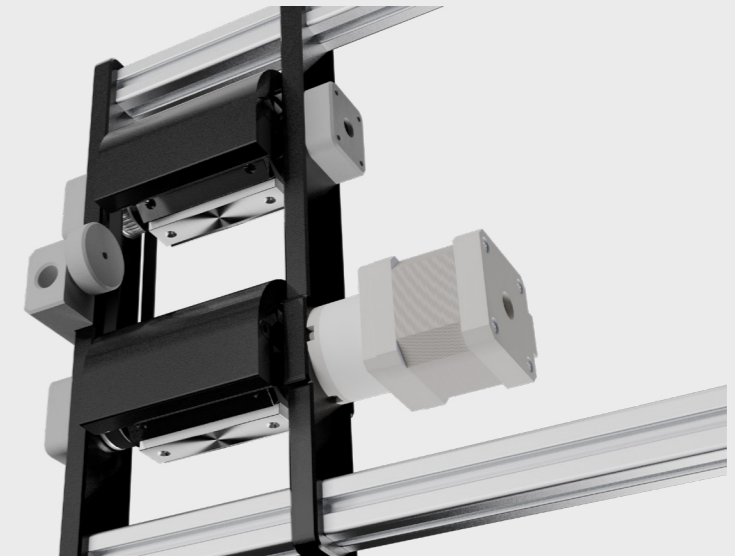
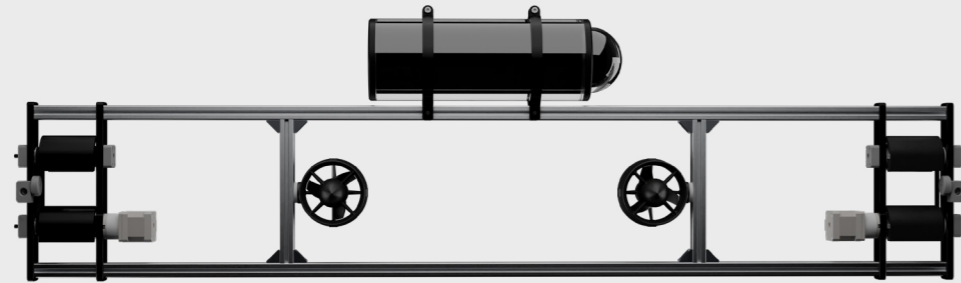
Appendix F - Clamping Prototype



Appendix G - Separator Prototype



Appendix H - V1 Separator



Statement on AI use:

Artificial Intelligence (AI) tools were used during this project as supporting tools. AI was primarily used to assist with programming tasks, such as writing and debugging code, and to help review parts of the report for clarity and language corrections. All final design decisions, analyses, interpretations, and conclusions were made by the author.

Thomas van Leeuwen
5055008

MSc. Graduation Thesis
July, 2026