Hull-cleaner

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Abstract

Biofouling, the growth of organisms on submerged ship hulls, has economic and environmental repercussions. The accumulation of organisms on ship hulls increases drag, requiring more propulsive power. Extended idle periods exacerbate fouling conditions, leading to negative consequences such as increased fuel consumption and potential structural damage due to corrosion. Periodic hull cleaning is crucial for cost reduction, fuel efficiency, and environmental benefits. Our research proposes an innovative solution: a robot utilising biomimicry in the form of suction cups and a rotary brush to clean submerged ship hulls. A prototype of this solution was created by 3D printing the parts for making a body and legs to serve locomotion powered by a Raspberry Pi and using ClingTech Bionics' suction cups to adhere to the rough surfaces these biofouled hulls come with. This prototype, although unfinished, provides insight on how the versatile approach addresses the diverse challenges of biofouling across different ship sizes.

Keywords: 3D printing, biofouling, biomimicry, ClingTech Bionics, hull, Raspberry Pi, robot, suction cup

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Introduction

Marine fouling is described by Evans (1981) as: ‘the result of settlement and growth of algae and invertebrate animals on the surfaces of submerged objects’. The accumulation of these organisms on immersed surfaces leads to economic, environmental and safety-related negative effects (Bressy & Lejars, 2014). Biological biofouling affects the hydrodynamics of a ship's hull by increasing drag and therefore increasing the required propulsive power (Dennington 2010). Long idle periods or low activity, such as frequent stays in port, of the vessel can exacerbate fouling conditions (Ådland et al., 2018), leading to several undesirable consequential effects.

For one, hull fouling leads to excess fuel use at a maintained speed or speed loss at a maintained engine power (Ådland et al., 2018). Fuel is a major cost driver for the international shipping industry, accounting for 50% to 70% of a ship’s total running costs (Rehmatulla & Smith, 2015). Periodic hull cleaning could diminish these expenses as it leads to a significant reduction in the daily fuel consumption of oil tankers (Ådland et al., 2018).

As a secondary effect, hull fouling might damage the structural integrity of a ship due to corrosion induced by the fouling (Ådland et al., 2018). Settlement of fouling deteriorates coatings (Bressy & Lejars, 2014) and it can be the primary cause of decay in the lifetime of ships (Kizor et al., 2021).

Besides, hull cleaning can be beneficial to the environment for several reasons. Looking into hydrodynamic optimization of hulls can aid carbon reduction and improve the energy efficiency of the world fleet (Ådland et al., 2018). Even though ocean transport was found to be the most energy-efficient transport mode compared to road, rail and air (IMO, 2009), the cumulative carbon dioxide emissions from international shipping are estimated to be responsible for 2.2% of global emissions (IMO, 2009). This share will probably even increase in the coming years due to a slower rate of decarbonisation than in land-based transportation and growth in international trade (Energy Transitions Commission (ETC), 2017). Fouling on a vessel’s hull is a substantial contributor to increased CO_2 emissions, which is illustrated by the fixed 9% yearly increase in fuel consumption across the world fleet that the third IMO greenhouse gas study (IMO, 2014) applies to account for the resulting loss in energy efficiency.

An additional environmental benefit of regular hull cleaning is the removal of potential invasive species that house in the barnacles and seaweed (Ådland et al., 2018). Transfer of these species could pose a major threat to the conservation of biodiversity and the world’s oceans by changing ecosystem processes and increasing trophic levels (Bressy & Lejars, 2014). Ships have been recognised as a major vector for the introduction of harmful and non-native organisms for a long time (Gollasch, 2002), and removing the biofouling on a ship can significantly reduce this effect.

Hull fouling is the only main driver of decreased hydrodynamics over which a ship owner has a large degree of control (Ådland et al., 2018). While a ship owner cannot influence the rate of marine growth on the hull, he can decide the frequency and quality of the periodic maintenance of the underwater hull. Based on this principle, the International Maritime

Organization (IMO) introduced a formal system in 2011, called the Ship Energy Efficiency Management Plan (SEEMP), mandating every ship owner to optimise and manage ship and fleet performance (Jensen et al., 2018). The periodical cleaning of the vessel's hull and propeller were mentioned amongst the key operational measures in the plan.

The current methods for hull cleaning can roughly be divided in two approaches: (1) the removal of the vessel from the water to land for defouling (e.g. dry-docking), or (2) in-water cleaning (Hopkins & Forrest, 2008). Removing the vessel from the water is usually an expensive procedure (Wilson, 2017), and alternatives are needed for large vessels outside of their dry-docking schedule (Hopkins & Forrest, 2008). On the other hand, in-water cleaning techniques are usually not designed to clean the entire hull of the vessel, and niche areas mostly remain untreated between dry-docking periods (Hopkins & Forrest, 2008). Besides, this method is typically implemented as a reactive measure when biofouling reaches a critical level and requires powerful machinery (Swain et al., 2022). This machinery damages coatings and creates unwanted discharge, which will require capture and disposal in many locations (Swain et al., 2022). Additionally, current methods for external inspection or cleaning of in-water ships use divers, which can be a hazardous operation (Wilson, 2017). Therefore, the Hull Inspection Techniques and Strategy (HITS) joint-industry project (JIP) called for alternative methods to be developed that minimise or eliminate diving (Wilson, 2017). In summary, current hull cleaning procedures allow for better solutions to be proposed, and innovations in fouling prevention techniques are important to address this problem and optimise treatment.

In our research, we propose a new solution for the maintenance of submerged ships' hulls to prevent biofouling. Our robot adheres to the underside of ships using suction cups and employs a rotary brush to effectively clean away algae and barnacles. This project was motivated by the need for a versatile solution that could be applied across various ship sizes and cater to the diverse stakeholders facing biofouling challenges. To achieve this, we adopted a systematic approach, segmenting the problem into distinct aspects and developing individual solutions that were subsequently integrated into a single, user-friendly robot. We believe this innovative approach has the potential to significantly impact the maritime industry by reducing maintenance costs, enhancing fuel efficiency, and minimising the environmental harm caused by biofouling.

Theoretical Framework

Oliveira en Granhag (2020) posit that hull cleaning should target the early stages of biofouling, using minimal forces, and our proposed solution operationalizes this concept by using a method called 'grooming'. This is a proactive approach to keep a ship's hull free of biofouling by gently and frequently wiping the hull surface to prevent the recruitment of fouling organisms (Hunsucker et al., 2018). Groomed biofilm was found to be associated with significantly less drag forces compared to ungroomed biofilm (Hunsucker et al., 2018). Grooming by using a rotating brush system reduces fouling on many surfaces and it can prevent fouling when done periodically (Tribou & Swain, 2015). A rotating brush system for underwater cleaning robots was also advised by Song en Cui (2020), after extensively comparing multiple underwater ship hull cleaning technologies. They suggest to select a suitable cleaning brush according to the construction material of the hull: metal brushes are used on ships constructed of aluminium or steel, while nylon or nonmetallic brushes are used on ships constructed of wood, fibreglass, aluminium, and steel (Song & Cui, 2020).

The solution proposed in this research paper will use this grooming mechanism in combination with a suction-based attachment to the underwater hull. Effective suction on submerged and fouled surfaces is inspired by the Gobiesox Maeandricus, also known as the Northern Clingfish. The Northern Clingfish (living along the rocky shores of the American Pacific coast) is known for its adhesive strength while attaching to a substrate: their ventral suction disc was found to hold up to 150 times the body weight of the fish when attached to fouled surfaces (Ditsche et al., 2014). The saltwater fish uses its elastic disc margin to adapt to surface irregularities and attaches to the fouling organisms without making direct contact with the primary substrate (Ditsche et al., 2014). It can attach to surfaces with a roughness between two and nine percent of the suction disc width (Ditsche et al., 2014).

In order to mimic the adhesiveness of this suction disc, Ditsche and Summers (2019) transferred its biomechanical principles to develop a bioinspired suction cup. The functioning of this suction cup is based on three biomimetic principles:

1. The bones underlying the suction disc of the Northern Clingfish were mimicked using a harder and stiffer outer layer in the suction cup prototype, which provides stability and resistance against sliding centrally of the soft suction disc when the suction cup is pulled in a normal direction.
2. The elasticity and softness of the biological disc rim and its hierarchical structures in the Northern Clingfish enable adaptation to surface irregularities of the substrate. This principle is mimicked in the very soft layer of the suction cup.
3. The Northern Clingfish uses enhanced friction at the rim of its suction disc to delay failure and increase attachment forces and tenacity. This enhanced friction was also introduced in the rim of the suction cup using layers of micro-sized, hairlike structures, in many different hierarchical sizes, which provide resistance to the cup edge slipping inwards (Ditsche & Summers, 2019).

Dr. Petra Ditsche and her team developed the biomimetic clingfish suction cup based on their research on the Northern Clingfish. They discovered a way to combine different materials to give the artificial suction cups a rigid and stiff structure that was strong enough to hold tension, while also flexible and soft enough to stick and conform to rough surfaces (ClingTech Bionics, 2023). ClingTech Bionics (2023) currently manufactures this suction cup in serial production for its first applications.

In order to be able to move, the proposed robot prototype would need multiple suction cups that can alternately attach and detach. This would require some form of a robotic leg design. Deshmukh (2006) states that multiple subjects are important to study for optimal leg design: joint placement, actuator placement, torque, sensors and the grounding impact. (1) The locations of the leg joints determine the kinematic and dynamic properties as well as the reach of the legs. (2)

An actuator that is placed at the knee joint adds complexity to the control algorithms that are needed to move the leg, and it requires more powerful motors at the hip joint to move the extra mass on the leg. Locating the actuators at the base of the leg (also called remote actuation) could eliminate these problems but increases the complexity of the mechanism. (3) The actuators should be powerful enough to provide the required torque. (4) Deshmukh (2006) also posits that sensors could help the robotic system to grasp the leg movement when walking, and (5) detect the impact force imposed on the leg during the walking. If these subjects form the basis of decision-making during the leg design process, effective joint design and control will lead to proper walking gaits and optimal leg usage (Deshmukh, 2006). However, a lack of reliable, compact, simple and cost-effective actuator packages is also a major problem in current leg designs (Deshmukh, 2006).

Evolution of Prototype Design

Step-by-step evolution

To address the problem of biofouling on ship hulls, our approach involved contemplating the realisation of a robot designed to resolve the existing issues associated with the accumulation of barnacles and algae on ships. Our objective was to develop a solution applicable across various scales, catering to different stakeholders encountering similar challenges with biofouling. This necessitated a systematic breakdown of the problem into distinct aspects, each warranting individual solutions that could be integrated into a single robot, subsequently delivered to stakeholders.

This project underwent several stages. Each will be explored and the state of the design will be noted and its changes throughout the phase will be discussed.

Phase 1 - Brainstorm

The initial phase of our project involved a thorough examination of the biofouling issue, encompassing an exploration of potential solutions and identification of inherent challenges. Focused on mitigating biofouling on ship hulls, conceptualising a robot for this purpose introduced several critical considerations. This also involved validating the significance of the problem, ensuring it lacked an existing solution or identifying areas for improvement in existing solutions. Through extensive literature research and stakeholder interviews, we found the relevance of biofouling as a prevalent issue. This investigative process served as a foundation for our project.

First and foremost, addressing the removal of barnacles and algae necessitates the implementation of an efficient cleaning apparatus. Additionally, the robot must have the capability to adhere to or closely navigate the ship's hull for effective removal of the biofouling. Furthermore, the robot must be equipped with a propulsion system to traverse the entire surface area of the hull. Lastly, a key concern is ensuring the robot is waterproof, allowing operational functionality while submerged, thereby eliminating the need for watercraft extraction during cleaning.

With these core aspects in mind, the brainstorming phase was initiated. The primary focus was on developing a robot capable of adhering to the boat's hull. This led to the idea of an starfish-like structure with legs or tentacles featuring suction cups for attachment, along with additional legs equipped with rotating brushes for cleaning purposes. This starfish design was our initial idea of integrating biomimicry into the design of our solution. As previously mentioned, our strategy involves the utilisation of suction cups to attach the legs to the boat's hull. In the pursuit of self-made suction cups, inspired by insights from Bas Overvelde's class, the team initially considered crafting silicone suction cups.

At this time, using soft robotics at the tip of the leg besides the self made suction cups was considered, because of Bas Overvelde's class. Unfortunately, this did not offer any promising prospects for practical application.

Phase 2 - Concept and Initiation

After the brainstorming phase, the conceptualization of the robot commenced. At this point the envisioned design involves rigid legs equipped with suction cups at their ends, utilising hydraulics for attachment to the surface of the hull.

Addressing the challenge of waterproofing, a decision was made to centralise all electronic components, requiring only a central section of the robot to be waterproofed, as waterproofing the whole structure would be hard and require a great deal of resources. Consequently, the design necessitated limbs controllable from the centre of the body, possessing enough degrees of freedom for versatile movement following the ideas of Deshmukh (2006) that were discussed earlier. This centralization extended to the placement of the cleaning tool, resulting in the integration of a centrally located cleaning brush and legs with joints supported by gears.

To achieve the centralization of electronics, research was conducted to determine the required leg design. Because of the interview with Martin van Vliet, the imperative was to minimise moving parts in the non-waterproofed section of the robot, ensuring smooth operation without jamming in water, because any accumulation of hindrance like erosion or small particles getting stuck in between the parts could be detrimental for prolonged use of the robot. Consequently, the goal was to identify or develop a design featuring gears at the base of the leg, facilitating movement of the suction cup at the end with two degrees of freedom to accommodate a broad range of motion. Given the varied and contoured surfaces of ships' hulls, a sufficient range of motion was crucial. A suitable design was discovered, meeting these criteria, providing a foundation for further refinement and adaptation to meet our specific design requirements.

Upon further examining the idea of crafting our own silicone suction cups it became evident that this approach was going to be a challenge because of the precision it would require to make these. For this reason this idea was kept as a second option and a new approach had to be thought of. After sidelining this idea of moulding our own suction cups, we opted for commercially available suction cups. These suction cups operate by employing a dome-shaped structure impermeable to air, which is pressed against a flat surface. This action expels the air, creating a low-pressure environment within the cup. The material of the cup seeks to revert to its original shape, and the contact ring with the surface establishes a seal (Smith, 2018). However, given our intention to utilise suction cups underwater, the conventional suction cup concept becomes impractical due to the limited deformability of water compared to air. Consequently, our alternative approach involves the incorporation of hydraulics to generate a low-pressure environment within the cup, facilitating effective attachment to the hull.

With the leg design in place, the focus shifted to sourcing the necessary materials and electronics for the robot's construction. This involved researching servos capable of maintaining a stable angle, withstanding water-induced forces, and exerting sufficient strength to affix suction cups securely to surfaces. After acquiring the identified components, the quest continued to determine the most suitable suction cups. In addition to having hydraulics work with the suction cup, the suction cup would have to be able to attach to moderately rough surfaces. A research discovery from Petra Ditsche at ClingTech Bionics, who designed a suction cup inspired by the Northern Clingfish, prompted us to request an interview with this company to gain deeper insights. The interview revealed an opportunity to acquire these specialised suction cups from ClingTech Bionics at a significantly discounted rate for the use of this project. These suction cups proved resilient in withstanding forces both above and below water without requiring hydraulics, and with the useful ability to attach to very rough surfaces (figure 1). The Northern Clingfish-inspired suction cup operates conventionally by pressing down to adhere to a surface and easily releasing the vacuum by lifting a designated corner. Petra Ditsche strongly influenced our decision to completely discard the notion of crafting our own suction cups. The considerable time, extensive research, and the intricacies involved in working with diverse materials ClingTech Bionics put into crafting their suction cup, would not be feasible for our project given the time, which deterred us from pursuing this idea altogether.

At this time, the team familiarised themselves with the machines, 3D printers, and corresponding software in the Makerspace. The 3D printing process for the leg design commenced, leading to the identification of flaws that were promptly addressed through iterative tweaks. One early improvement involved realigning gears to enhance interlocking and create a more rigid system, ensuring optimal power transmission from the servo to the leg and enabling optimal locomotion. To bolster servo stability in relation to the gears, additional support was created. The original design did not offer this support since it was designed for DC motors, while our project made use of servo motors. Servo motors can be controlled more precisely than DC motors can and therefore offer better use for this project.

By the conclusion of this phase, the robot's design had undergone a significant transformation. Originally incorporating hydraulic suction cups, the design transitioned to utilising specialised suction cups inspired by the Northern Clingfish, procured from ClingTech Bionics. Simultaneously, progress was made in the 3D printing of the legs, with ongoing refinements to the design to better align with our project requirements.

Phase 3 - Definition and Planning

With a clearer understanding of how the suction would operate, we embarked on defining every facet of the robot and combining already defined components. The initial focus was on making the legs compatible with the suction cups. To achieve this, a 3D printed part with dual functionalities was introduced. The first function involved securing the suction cup in place, while the second provided a pivot for the suction cup. The rationale behind the pivot was to accommodate variations in surface levels when the robot's body pressed down the leg for movement on the boat's hull. Opting for a ball and socket joint allowed the suction cups to move freely in a circular motion, like an arcade joystick. Pressing down on the joint enabled the suction cup to adjust to the surface level.

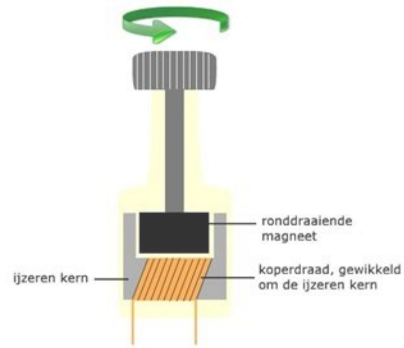
***Figure 1**: Suction cups received from ClingTech Bionics which are able to stick to rough and uneven surfaces.*

Note. Images retrieved from the official website of ClingTech Bionics (ClingTech, 2023)

Moreover, we needed to devise a mechanism for releasing the vacuum in the suction cup. As previously noted, in the suction cup provided by ClingTech Bionics, this was accomplished by lifting a specific corner to break the vacuum and release the suction cup. To achieve this mechanically, we incorporated a mechanism to lift this corner. The suction cup was designed with a dedicated hole in this corner, which we utilised to attach nylon thread. This thread was then threaded through the leg and into the body, where a pulley system would be integrated.

Addressing the placement of the cleaning brush in the centre of the robot's body, an alternative mechanism was sought to power the brush without relying on a motor (see Figure 2). Initially considering a magnet mechanism where the brush's rotation would be induced by the attracting and repelling forces of magnets, this idea proved challenging to implement consistently. Consequently, a servo motor was chosen as this when placed inside the body, can be waterproofed this way. The motor would drive the brush via a bevel gear to relay power from the vertical to horizontal axis. The brush would be attached to the body with a ball bearing to allow for smooth rotations.

Figure 2 : *Simplified model of the concept of magnetic rotation.*



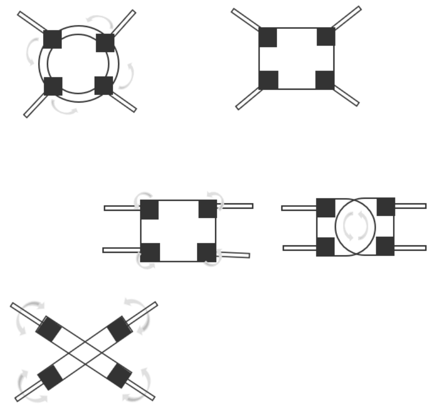
Note. Image retrieved from Google Images.

Consultations with experts from the UvA Technology Centre influenced the evolution of the robot's body design. Originally contemplating a starfish-like configuration with five limbs, this concept was deemed impractical for locomotion, leading to the adoption of a more manageable structure with four legs. This decision prompted further considerations about the body's shape and the implementation of multidirectional locomotion, especially given that the legs had only two degrees of freedom in the vertical axis.

To achieve multidirectional locomotion, the team explored various body design options (see Figure 3). Initially, a round body with a motor facilitating rotation between two halves of the robot, combining the front two legs and the back legs, was considered. This configuration would enable two legs to twist simultaneously. Another concept involved two straight components that could pivot around each other in a scissor-like fashion. Additionally, a design featuring a solid body with added rotation bases for the legs, providing an extra degree of freedom, was also contemplated. However, these designs were ultimately rejected in favour of a rigid cross design.

The decision to opt for the rigid cross design was influenced by the challenges associated with waterproofing around pivot areas in designs where the body would rotate around itself. Additionally, minimising moving parts was a priority. A design was created for laser-cutting plexiglass to attach the printed legs and the Raspberry Pi. Subsequently, holes were cut to accommodate the brush and bearing mount. This initial body design allowed the team to test coordinated movement patterns of the four legs, enabling the robot to move forward with a fixed pattern.

Figure 3: *Robot's body design sketches.*



Note. Sketches created using Microsoft Office 365.

Concluding this stage, the design of the robot had largely taken shape, paving the way for the development of a functional prototype. The legs were attached to the body enabling testing of the code. Suction cups were secured to the tips of each leg, and a nylon thread was fastened to the dedicated corner holes of the suction cups, where the vacuum would be broken to release the suction. Also the cleaning brush was added with a ball bearing to ensure smooth rotations.

The code written for the servo control was based on the pca9865 library. The documentation for the Adafruit PCA9685 16-Channel Servo Driver that was used allowed for 16 independent servo motors to be controlled simultaneously using multiprocessing. The code written manipulated the pulse width of the servos in order to set the angle in which the motors turn. Since each leg had two degrees of freedom, and the prototype has four legs, we control eight motor angles, in order to freely move the legs. With this library the initial movement system was developed. The system identified the four legs as 'North', 'East', 'South', and 'West'. The pattern of movement for a step in the northern direction is as follows; starting from a position where all legs are firmly attached to the surface on which the movement is intended, the eastern and western legs initially from the surface to a neutral position leaving only the northern and southern legs attached (by the suction cups) to the surface. Following this the southern leg extends, while the northern one retracts, whilst continuing to stick to the surface, after this step a displacement of the centre of mass of the prototype has taken place in the northern direction of approximately 0.05 metres, however the pattern is yet to be completed. The final two stages of the pattern are reattaching the eastern, western legs to the surface and detaching the northern and southern legs from the surface in order to reset them into a neutral position. Concluding this pattern we have arrived back at the starting position, and are ready to repeat it, or 'rotate' it in order to move in a different direction.

Phase 4 - Execution and Iteration

After concluding the last phase, existing components were undertaken to identify areas for improvement in creating a stable prototype.

Upon printing and testing the legs with a 30 percent filling, it was observed that the parts were excessively flexible, resulting in a deviation in the position of the leg tips. To enhance rigidity, a 90 percent filling was adopted. This additionally gave the parts more durability. The bevel gear designed for the cleaning brush, also underwent some revisions since the teeth of the gear were not attached to itself very strongly. Initially, various printers available in the Makerspace were utilised for printing the robot parts. However, prints from the Prusa MK3 printer were found to be less smooth and detailed for certain moving parts. As a solution, the Prusa MK4 printer and later the Bambu Lab printer were used for finalising all 3D prints.

During the leg assembly phase, it was discovered that the initial batch of servos exhibited a tendency to fail or experience twitching. The twitching phenomenon can be attributed to low amperage, and when these servo motors started twitching, some failed to recover, compromising their effective use and precision. Consequently, a second batch of servo motors was procured, and replacements were made as required to ensure optimal functionality. The base of the legs had to be reprinted in order to align the gears and bring them closer together.

To accommodate the placement of servos and other integrated parts in the robot, adjustments to the screw holes were necessary. Calibration of the legs involved positioning the servos at zero and manually adjusting the legs to the correct position with the servo at a specific angle state of zero degrees. Numerous issues with movements arose, primarily stemming from misalignments between servo angles and the actual angles of the legs. This misalignment was attributed to improper printing and gear setup, allowing for deviations that disrupted alignment.

Besides the legs, the pulley system mentioned in the earlier stage, had to be integrated. The nylon thread was added to the suction cup and threaded through the legs, but was not yet mechanised. For this we made a spool for each opposite pair of legs, resulting in two spools. These spools attached to a servo motor are able to reel in the corner of the suction cups. In combination with the legs moving, this enables them to remove the suction and lift the legs.

The testing process became challenging, prompting the team to explore various solutions. Initial attempts involved code revisions for finer adjustments to servo angles. Upon the failure of this solution, a decision was made to redesign and reprint the leg parts and focus on precise fastening of the screws. While this step improved movement, the imperfections were present, yet at a smaller scale, which hindered the development process.

Phase 5 - Testing and Finalization

Testing the current prototype after the improvements we made in the previous phase resulted in some findings. In this late stage we opted for a 3D printed body with additional space for everything. For the power we thought about having battery packs or making our own battery pack. Though this was a decent solution, we chose a power bank, since this would be enough power as long as the power bank can deliver 5 volts and 3 ampère and was easy to implement. For this power bank a slot in the centre of the body was added to distribute the weight evenly.

The second stage of programming the robot's movement revolved around revising the code to be more object-oriented. The hard coded initial movement was separated into modules that can be stringed together to form a loopable movement pattern. This greatly improved the readability and adaptability of the code. The multiprocessing aspect of the code was also revisited, due to an interesting property of the Python Multiprocessing library. The aforementioned property is that two (or more) processes only run in parallel until one of them finishes their task. In our case the relevance of this is immense because not all angles in each leg need to be rotated by an equal angle. Leading to an issue, where a smaller rotation finishes faster, than a larger one. This led to unequal strain on parts of the legs, where we did not expect it. To solve this issue we started to develop a method for them to finish at the same time, by adjusting the tick-rate of the angle change by the ratio of the angles to be rotated simultaneously. The created method worked in many, but not all cases, during longer periods of movement the internal memory of a servo angle shifted from time to time which caused the algorithm to fail.

In this stage we also did tests regarding the strength of the robot and the power needed to push the suction cups on and pull them off. These tests will be discussed later in this paper.

Stakeholder insights

Throughout the course of our six-month project, we consulted with several stakeholders to gain more insights into the scope of the problem, the design of our robot, and the possibilities for our process. Summarised below are six interviews with stakeholders that were interviewed at several stages during the project.

Richard Breurken

Richard Breurken is the owner of shipyard Stella Maris. Iannis and Kiki conducted an in-person interview with him on the third of October 2023. The interview mostly covered his methods of cleaning the normally submerged underside of houseboats that are located in the canals of Amsterdam. He removes the boats from the water and uses a 240 bars high pressure sprayer (1000 litres of water per minute) for about six hours (€65 per hour for manual labour, excluding materials such as paint or coatings) to remove the fouling off a 25-metre boat (total costs would be around €4000,-). This procedure needs to be repeated every five years. Breurken explained that fouling is slower when a boat is often in motion, but once there, greatly increases drag and fuel costs. He therefore advised us to market our product for commercial shipping (such as Fairship yachts). Breurken explained that most antifouling coatings are banned from 2024 onwards, which will be a big problem for the shipping industry. He also told us that the pressure needed to get rid of algae is very hard to quantify since it depends on a lot of factors.

Dr. Petra Ditsche

Dr. Petra Ditsche is the Managing Director at ClingTech Bionics, whom we first contacted via LinkedIn. Mathieu and Kiki conducted an online interview on the 30th of October 2023. We spoke to Ditsche about the process of creating her artificial suction cups inspired by the Northern Clingfish. The product is patented, so Ditsche could not explain the development or functioning in very precise detail. She warned us that mimicking the suction disc of the Northern Clingfish would not be possible in a few months, considering that it took her and her team about three years to come up with the prototype. Ditsche demonstrated the use of the suction cup on an anti-slip mat (with a rough surface), explained its possible applications and offered to collaborate with us and sell us her suction cups.

Dr. Mazi Jalaal

Dr. Mazi Jalaal is Professor at the Faculty of Science at the University of Amsterdam. Kiki and Iannis conducted a short online interview with him on the 25th of September 2023. We discussed the possibilities and challenges of our ideas and design. Jalaal told us to focus on the underwater suction first, considering that this (and the waterproofing) might be our biggest challenge. He suggested taking a closer look at the operational aspect by doing more literature research, and quantifying the power needed to be able to decide on the feasibility of our project. Jalaal also thought that our project could benefit from soft robotics and he suggested that we looked into swimming pool cleaning methods first.

Mihaly Lorincz

Ex Robotics Engineer at MYTHRONICS, an Agro-Tech start-up based in Delft. The interview was conducted by Aron and it revolved around robotics development in a professional environment, costs and development techniques. Mr Lőrincz had experience in building navigation systems in a two dimensional space with the help of quaternions. He described this process as initially difficult to understand, however very helpful in the long run. Mihály with respect to the deadline we have, assured us that it is more reasonable to create a first moving system with hard coded servo-angles, continuing on creating a solution using inverse-kinematics, then finally using quaternions for a comprehensive navigation system. The costs he outlined were above and beyond the scope of the minor.

Bas Overvelde

Bas Overvelde is an Associate Professor at Eindhoven University of Technology and works as the Principal Investigator at the Soft Robotic Matter Group at AMOLF. Iannis conducted an online interview with him on the 16th of October 2023. In the early stages of the design process we consulted Overvelde about the sort of suction cup and pneumatic system that was suitable for our prototype. He advised against a pneumatic system under water. It is very hard to keep it waterproof. He showed us various types of suction cups with different sizes of hollow chambers. With a one-way valve they can be pushed into a vacuum on the wall. We brainstormed how to then control the valve to release the vacuum. He suggested a spot where the water could slowly flow back to break the vacuum. He said he was willing to help us make the suction cups.After this interview we solved this problem with the Clingtech Bionics suction cups. They aren't pneumatically controlled. They can be pushed on a surface and detached by pulling on the edge where a hole is. After this interview we knew this was the best option for our prototype. At this moment in the design process we were considering using soft robotics to adjust to the form of the hull. After the interview we chose the design of the ball and socket joint because of the complications of using soft robotics like the attachment to the rest of the body.

Martin van Vliet

Martin van Vliet is Chief (Mechanical) Engineer at RollDock and is an acquaintance of Kiki. Mathieu and Kiki conducted an online interview with him on the 18th of October 2023. Van Vliet provided us with an extensive explanation of the problem and current underwater hull cleaning procedures. Currently, ships that are in between their dry-docking schedules can be cleaned in Singapore, where divers clean the hull using powerful brushes with magnets and waterjets. This costs about $27,000 per tanker and is a great risk for the divers. Van Vliet also mentioned that Australia requires arriving ships to be completely clean before entering their waters to prevent invasive species from transferring to their seas. Antifouling coatings sometimes use electrical anodes to prevent algae from sticking onto the hull, but they often deteriorate over time and leave ships very prone to fouling.

Besides, Van Vliet spoke to us about the mechanical properties of our design. He advised us to minimise the amount of moving parts, since they erode quicker underwater. To waterproof our robot, he suggested coating our main body in special wax or investing in a waterproof electronic control unit and waterproof electricity cables. He also said that it would be possible to mimic screw seals where the depth determines the air pressure inside the body, preventing water from going in (even when there is a leak). This is a non-polluting way to waterproof a robot compared to using oil seals.

Testing

Testing Method

To test the functioning of the prototype we decided to test using several different measures. First, we performed several different Newton tests to check some factors of the prototype before assembly. The first Newton test that was performed was a suction cup pulling test. The measurement was done using a calibrated analogue force gauge that was attached to the suction cup and then vertically pulled up (see figure 4). This same force gauge was used in the second Newton test, which was a suction cup detachment force measurement.

Second, the prototype was tested on some of its functions once fully assembled. The first function that we tested was the leg movement once we assembled the legs. For this test, the goal was to check whether the leg had the range of motion that was desired for its movement. The servo-motors were not yet attached, because they would prevent an unlimited range of motion. To perform this test properly, the leg had to be attached to the body (in this phase, the body still consisted of plexiglass). We would push the leg in all its possible angles and check where motion was limited or distorted.

The second function that we tested was the vertical weight test on the suction cups and legs. Once the robot was fully assembled, we stuck it to a window using the suction cups. The goal of this test was to check if the suction cups were in fact strong enough to hold the weight of the whole robot, and if the legs of the robot could deal with that much strain on them. Prior to sticking the prototype to the window, we weighed it and made a theoretical possibility prediction based on our Newton tests.

Third, we had to do a lot of code testing to assure that the output matched our expectations. The tests related to code, mainly focused on assuring that the movement patterns we discussed in the sections above could be smoothly implemented, that the suction cups could attach by the forces produced by the servos.

Testing the correct angles in each substep of the movement process was a qualitative endeavour due to the difficulty of measuring the stresses on the joints. The tests had the goal of finding the optimal angular setups for the four states that each leg should be in according to our movement model; *'up', 'down', 'extended', 'retracted'*.

By incremental editing of the angles corresponding to each servo in these states, while running the walking loop and carefully examining the stability of the robot; taking into account the tilts in either direction or visible strain on a specific part of the prototype the current angles for the states mentioned were found. Qualitative testing is not the ideal methodology for such a search, however it seemed like the only feasible option with a search space for the problem as expansive as the one parsed. Even though there are limitations to what are reasonable configurations in the search space, (i.e up should not have a larger bottom servo angle, than down, so on) the optimising the angle organisation still consists of at least 3600 cases to be examined. This number comes from the possible reasonable angles for up down falling into a 20 angle range for both the bottom and the top servos in case of the 'down' state, both the *'extended'* and the *'retracted'* have 40 reasonable angles for the bottom and top servos, and lastly the the *'up'* state can be pretty safely ignored due to the fact that a leg in this position is disjoint from the others, it does not produce strain on the other legs.

Results

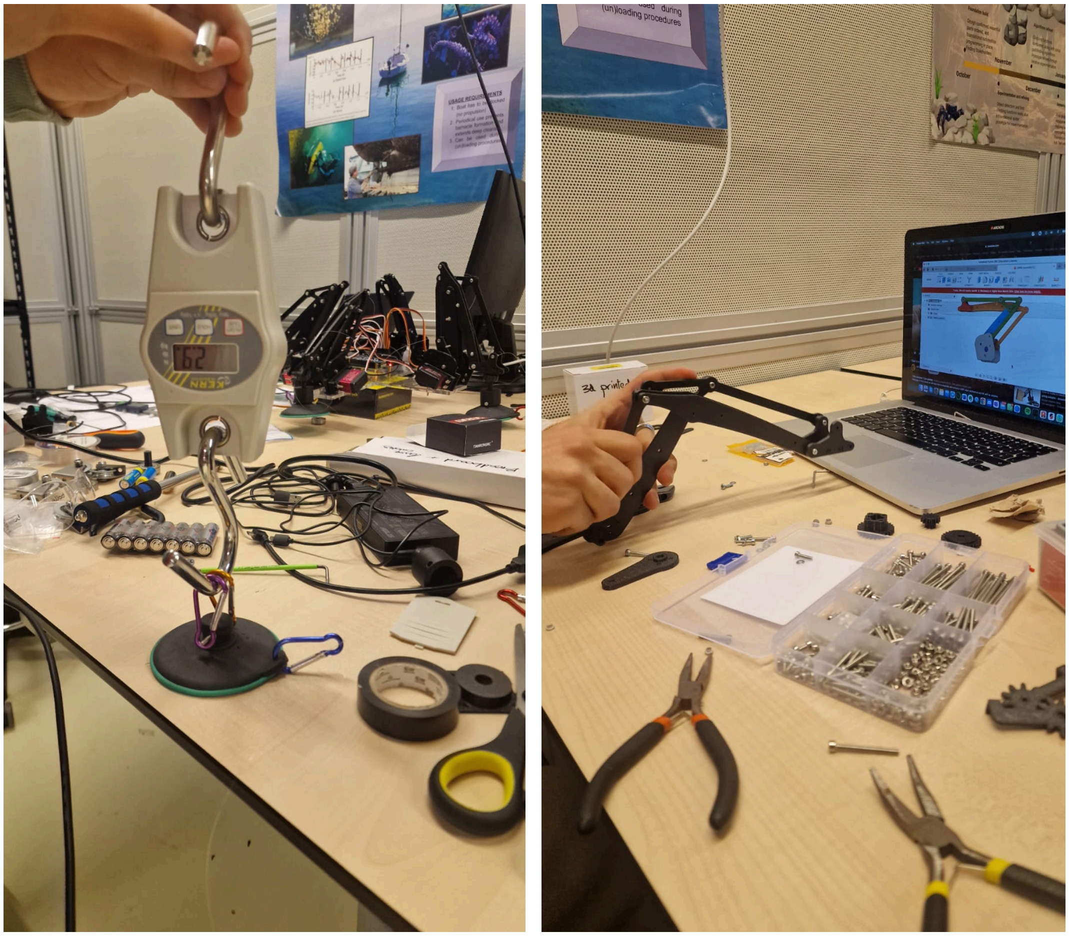
The suction cup pulling test showed that the force that could be applied on the suction cup was greater than the measurement device that was used. It confidently showed that the suction cup could withstand at least 33 kg of pulling weight, which is equal to about 320N of force. However, the detachment force that was measured during the suction cup detachment force measurement was found to equal just 0.32 kg of pulling weight. This would equal about 3.1N of force necessary to detach the suction cups, if pulled at the detachment pull tab.

The results of the function tests were as follows. The leg functioning test showed us that our range of motion was limited by the back-end of our longest lever. This part would touch the body and prevent the leg from moving further up. Besides, at a certain combination of angles, the 'wrist joint' could flip over and prevent the arm from moving altogether. This led us to check at which combination of angles this was a risk. We could do so by attaching the servo-motors and limiting the range of possible angles of the leg.

The vertical weight test on the suction cups and legs showed significant results. The weight of the assembled prototype was found to be approximately 3.4 kilograms. Since our Newton tests showed that one suction cup could hold at least 320 Newtons worth of force (this equals approximately 33 kilograms of weight), we were confident enough to try the actual vertical weight test. The robot was able to stick to the window, which means that the suction cups are strong enough for the weight of the prototype and the legs can handle that much strain.

The result of the qualitative study regarding the angles of each position defined in the testing methods section are the following: 'up' - (45, 45), 'down' - (90, 0), 'extended' - (120, 60), and 'rectracted' - (120, 0), where (x, y) and x is the angle of the bottom servo, while y is the angle of the top servo at a given position.

***Figure 4**: The suction cup pulling test using a force gauge (left) and a short leg movement test after assembly (right).*



Note. Images retrieved from personal documentation.

Analysis

The Newton tests were in line with the minimum expectations that we had for the suction cups, based on the information that was presented to us by ClingFish Bionics (a minimum of 250 N normal forces and up to 95 N of sheer force). This made us confident enough to decide to stick to our decision of using these suction cups for the prototype. Also, the detachment turned out to need a relatively low pulling force, which makes it very suitable for our prototype.

The leg functioning test initiated some changes to the code of the robot. The back-end of the longest lever touching the base of the body could not be changed by re-assembling this differently. The code was therefore adapted to prevent the servo-motors from getting the leg that far up. Besides, to prevent the 'wrist joint' from flipping over, we limited the range of angles of the legs so that this risk was minimised.

The vertical weight test confirmed that the suction cups were strong enough for their function and that the legs were good enough in their initial design. This is in line with the consistent pattern that the suction cups were expected to easily be strong enough for our design purpose. This was for instance already suggested by the tests that were performed by ClingFish Bionics themselves, where the suction cups were found to hold more than 250 N of normal force and up to 95 N of sheer force.

Conclusion and discussion

Design Evaluation:

The final design has many attractive features, such as flawlessly working adhesion to surfaces, and a compact design, however is lacking in many ways. Some issues that keep it from effectively tackling the problem statement include; the lack of waterproofing, unstable movement, not tackling the autonomous navigation, poor battery life. The mechanism to pull the suction cups off is not functioning properly. The fishing lines are not attached to the rotational motors. The suction cups are a suitable mechanism of adhesion but the force is not yet proven to be enough to perform cleaning on the hull. The compact design is suitable for waterproofing. But that is still a big challenge. This is because of all the moving parts and motors.

Comparison with stakeholder input:

To conclude the four primary design considerations - suction, locomotion, cleaning, and waterproofing - only waterproofing remained unaddressed. Waterproofing was not taken into consideration throughout the entire process due to the inherent challenges it posed. Unfortunately, given time constraints, the project did not allow for any attempts at waterproofing. Nevertheless, the concept of waterproofing was consistently considered at as many steps as possible.

Each stakeholder interview gave us insight into a field which we had little experience in, this allowed us to revise practical design aspects such as the body design, suction method, and coding methodology. In the interview with Richard Breurken we learned more about the market for this type of device. There is a market for boats that need to be cleaned regularly and are sensitive to damage. We did learn that houseboats are not economically viable because they do not function less because of biofouling, which is why we decided to shift our target group focus to ships with an economic function. In the interview with Dr. Petra Ditsche, she told us her suction cups would be suitable for our prototype. She did not elaborate on the material and method of how these suction cups were made, but we learned a lot about the suction method of the clingfish. She inspired us to change our initial plans and order the suction cup (instead of creating it ourselves).

Evaluation of biomimicry:

There is a comparison to be made between sharks and oil tankers that travel vast distances in the ocean, restlessly swimming across thousands of nautical miles. This image inspired us to create the Hull Cleaner. Large ships being continuously cleaned by small robots that travel alongside it, have a close resemblance to sharks travelling through the ocean with remoras attached to them.

Northern Clingfish attach to slippery rocks staying in place and withstanding powerful forces using their suction disc. We chose the attachment solution of the clingfish because it prevents damage to the host and provides a stable state in which the cleaning can take place.

The locomotion aspect of our design, however, was not inspired by this clingfish, nor by remoras. The Northern Clingfish has one suction cup with which it attaches itself to its host, and when not attached, it travels using its fins, leveraging the currents around it to manoeuvre.

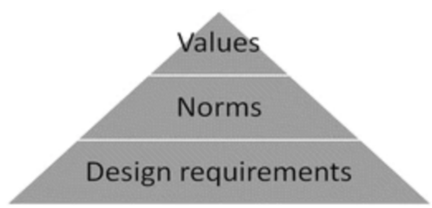
To avoid problems while not attached to the ship (e.g. buoyancy), we decided to remain attached to the ship at all times using multiple suction cups. This choice is not based on the features of the Northern Clingfish. We opted to use multiple suction cups, settling on the use of multiple ‘legs’, which roughly mimic a starfish or octopus. We settled on centralised control to ease operation and waterproofing, though implementing intelligent limbs could be a future enhancement to our design.

Ethical Considerations:

Previous solutions for the problem of bio-fouling included either dangerous human labour while operating heavy machinery under water or coating ships with toxic chemicals that harm the environment. Even though the most obviously toxic Antifouling (AF) agent has been banned, many companies still use AF agents that have unknown, and possibly detrimental effects on marine environments. “Most AF agents had Tributyltin (TBT), and has been phased out by IMO since 2008 due to harmful effects on the environment. However, use of TBT in AF paints is not prohibited, though it has been restricted in several countries. ” (Vol. 10 (2022): Special Issue. International Conference on Innovative Trends in Engineering for Sustainability (ICITES-2021))

We have developed our prototype considering the shortcomings of current solutions. Opting for a solution that will provide a positive impact by cleaning hulls without the use of Antifouling coats or hazardous human labour.

Figure C.D.1: *Values hierarchy outlined by (van de Poel 2013)*



Our solution is one that adheres to ethical principles, more so than towards profitability. The importance of an eco-friendly and safe solution trumps the amount of money that could be made by using unethical practices that would harm natural habitats or continuing traditional methods (norms) that result in people working in dangerous circumstances. It can be said that the project respects the “highest level in the values hierarchy are therefore intrinsic or final values, which are defined as values that are strived for for their own sake (Zimmerman 2004).”

Future Plans:

We believe that there is a market, and a future for this solution, and hope that this prototype is continued and upgraded. Future plans could include a more robust design for the legs and an updated mechanism for locomotion. A more thorough testing of the method of cleaning could improve how easy the robot would clean the hull. We hope our design inspires more people to create more solutions to tackle the problem of biofouling in order to save fuel to push for a greener and more sustainable way to ship goods across the world.

Improvements to the design could include analysing the structure of the body, and the kinetics of the entire prototype compared to animals that dwell underwater, their buoyancy and morphology as described by the book, (The Biokinetics of Flying and Swimming). This could be a promising area for future research, possibly resulting in a new design more suited to its environment.

Aside from the body there are many enhancements that can be made to the script controlling the gate of the robot. Firstly from a software engineering perspective, the code that controls the substeps of each movement iteration should be given a variable input. Continuing, the precise angles for these substeps should be refined in order to create a smoother walking pattern. This could be achieved via many routes, it is up to succeeding developers to decide on a path. A possible methodology for uncovering the optimal system of angles, is the use of evolutionary algorithms. Simulating the robot in a virtual environment, instantiating a population of robots with certain angles for each servo motor at every substep, then analysing the strain on the joints of the legs. Searching the state space of angles finding the minimum for the strain, while moving cyclically in one direction.

Another crucial future upgrade is implementing a manual control functionality, allowing the developers to test movements in either direction via an interface controlling the robot. This functionality would allow for experimentation with different manoeuvres, and getting closer to the final goal of autonomous navigation.

The cleaning portion of the prototype needs to be improved immensely, creating a faster rotary brush by using a servo motor is a great first step in this direction. Alongside this, alternative cleaning methods, their benefits and downsides for example removing algae with electrical shocks could be examined in greater detail.

Another critical aspect for the success of this prototype is waterproofing. As discussed in the interview with Martin van Vliet: there are many different ways that mechanics waterproof units (e.g. oil sealing or air pressurisation). It is up to future innovators to decide on the best method for waterproofing.

Reflective Insights:

This project has been a long up and down journey, it contained my beautiful moments, when something finally came together, however it also had its fair share of moments where nothing seemed to work. Finding a way to get through the tough times and remember, cherish the good ones is a skill that everyone needs to have and the team believes that this project developed this ability for each of us immensely. We have learnt that communicating beats ruminating in a project, and for all future projects we shall prioritise it.

Throughout this experience we were exposed to many outstanding biological solutions. Furthermore we gained practical experience in coding, design, 3d modelling and printing, and much much more. For all of us this was the first time designing and implementing a physical product from scratch. Despite the team's lack of experience we managed to create something that moved, and even though that is a low bar to tackle, we did it and for that we are proud. With the help of the workshops and assistance from each other, every team member developed a valuable skill set in this domain.

Documentation

Github:
https://github.com/A-lamo/HullCleaners
This public repository stands as the documentation for the prototype, the manual defined below alongside the repository itself serves as the user guide. The code is commented and the instructions for use are outlined.

However, to absolve any confusion for use or further development, please reach out to Aron Ferencz at the email address: a.r.ferencz@student.vu.nl.

References

Ådland, R., Cariou, P., Jia, H., & Wolff, F. (2018). The energy efficiency effects of periodic ship hull cleaning. Journal of Cleaner Production, 178, 1–13. https://doi.org/10.1016/j.jclepro.2017.12.247

Bressy, C., & Lejars, M. (2014). Marine Fouling: An Overview. *The Journal of Ocean Technology*, *9*(4). https://www.researchgate.net/profile/Marlene-Lejars/publication/271179593_Marine_Fouling_An_Overview/links/54bf69850cf28ce68e6b4e8d/Marine-Fouling-An-Overview.pdf

ClingTech Bionics. (2023, 3 March). ClingTech Bionics. ClingTech Bionics |. https://clingtech-bionics.com/

Dennington, S. (2010). Understanding marine fouling and assessing antifouling approaches. National Centre for Advanced Tribology at Southampton (nCATS), Engineering Sciences, University of Southampton, Southampton, UK,(2101), via https://scholar.google.com/scholar_lookup?title=Understanding%20Marine%20Fouling%20and%20Assessing%20Antifouling%20Approaches&publication_year=2010&author=Simon%20Dennington .

Deshmukh, A. (2006). Robot Leg Mechanisms. DEPARTMENT OF MECHANICAL ENGINEERING INDIAN INSTITUTE OF TECHNOLOGY, BOMBAY. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=5321603db69e2e4dc0f8e975d20752afbcb304a2

Ditsche, P., & Summers, A. (2019). Learning from Northern clingfish (Gobiesox maeandricus): bioinspired suction cups attach to rough surfaces. *Philosophical Transactions of the Royal Society B, 374*(1784), 20190204. https://doi.org/10.1098/rstb.2019.0204

Ditsche, P., Wainwright, D. K., & Summers, A. (2014). Attachment to challenging substrates – fouling, roughness and limits of adhesion in the northern clingfish (Gobiesox maeandricus). *The Journal of Experimental Biology, 217*(14), 2548–2554. https://doi.org/10.1242/jeb.100149

Energy Transitions Commission (ETC). (2017, 25 april). Better energy, Greater prosperity: Achievable pathways to low-carbon energy systems. https://apo.org.au/node/76074

Evans, L. V. (1981). Marine Algae and Fouling: A review, with particular reference to Ship-Fouling. *Botanica Marina*, *24*(4). https://doi.org/10.1515/botm.1981.24.4.167

Gollasch, S. (2002). The importance of ship hull fouling as a vector of species introductions into the North Sea. *Biofouling*, *18*(2), 105–121. https://doi.org/10.1080/08927010290011361

Hopkins, G. A., & Forrest, B. M. (2008). Management Options for vessel hull fouling: An Overview of risks posed by in-water cleaning. *Ices Journal of Marine Science*, *65*(5), 811–815. https://doi.org/10.1093/icesjms/fsn026

Hunsucker, K. Z., Vora, G. J., Hunsucker, J. T., Gardner, H., Leary, D. H., Kim, S., Lin, B., & Swain, G. (2018). Biofilm community structure and the associated drag penalties of a groomed fouling release ship hull coating. *Biofouling*, *34*(2), 162–172. https://doi.org/10.1080/08927014.2017.1417395

IMO 2009 Second IMO GHG Study 2009: International Maritime Organization (IMO) London, UK, April 2009; Buhaug, Ø.; Corbett, J.J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; Mjelde, A.; Nelissen, D.; Nilsen, J.; Pålsson, C.; Winebrake, J.J.; Wu, W.–Q.; Yoshida, K..

IMO, I. (2014). Third imo ghg study 2014. International Maritime Organization (IMO). Available online: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Greenhouse-Gas-Studies-2014.aspx.

Jensen, S., Lützen, M., Mikkelsen, L. L., Rasmussen, H. B., Pedersen, P. V., & Schamby, P. (2018). Energy-efficient operational training in a ship bridge simulator. *Journal of Cleaner Production, 171*, 175–183. https://doi.org/10.1016/j.jclepro.2017.10.026

Kizor, N., Shirose, B., Adak, M., Kumar, M., J, S. J., Srinivasan, A. K., & Muhammad, R. S. (2021). Design of a Remotely Operated Vehicle (ROV) for Biofoul Cleaning and Inspection of Variety of Underwater Structures. *9th RSI International Conference on Robotics and Mechatronics (ICRoM)*. https://doi.org/10.1109/icrom54204.2021.9663518

Oliveira, D., & Granhag, L. (2020). Ship Hull in-water cleaning and its effects on fouling-control coatings. *Biofouling*, *36*(3), 332–350. https://doi.org/10.1080/08927014.2020.1762079

Rehmatulla, N., & Smith, T. (2015). Barriers to energy efficient and low carbon shipping. Ocean Engineering, 110, 102–112. https://doi.org/10.1016/j.oceaneng.2015.09.030

Smith, Steve. (2018). How Does a Suction Cup Work?. sciencing.com. Retrieved from https://sciencing.com/how-does-4896154-suction-cup-work.html

Song, C., & Cui, W. (2020). Review of Underwater ship hull cleaning Technologies. *Journal of Marine Science and Application, 19*(3), 415–429. https://doi.org/10.1007/s11804-020-00157-z

Swain, G., Erdogan, C., Foy, L., Gardner, H., Harper, M. S., Hearin, J., Hunsucker, K. Z., Hunsucker, J. T., Lieberman, K., Nanney, M., Ralston, E., Stephens, A., Tribou, M., Walker, B., & Wassick, A. (2022). Proactive In-Water Ship hull grooming as a method to reduce the environmental footprint of ships. *Frontiers in Marine Science, 8*. https://doi.org/10.3389/fmars.2021.808549

Tribou, M., & Swain, G. (2015). Grooming using rotating brushes as a proactive method to control ship hull fouling. *Biofouling*, *31*(4), 309–319. https://doi.org/10.1080/08927014.2015.1041021

Wilson, A. (2017). In-Service hull inspections for avoiding dry docking safely. *Journal of Petroleum Technology, 69*(02), 58–59. https://doi.org/10.2118/0217-0058-jpt

Sadan, N. E., Akash, P. S., & PG, S. K. (2022). Biofouling impacts and toxicity of Antifouling agents on marine environment: a qualitative study. *Sustainability, Agri, Food and Environmental Research*, *10*.

Michelfelder, D. P., McCarthy, N., & Goldberg, D. E. (Eds.). (2014). *Philosophy and engineering: Reflections on practice, principles and process* (Vol. 15). Springer Science & Business Media.

https://learn.adafruit.com/16-channel-pwm-servo-driver/library-reference

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Manual for operating the prototype

Operating the prototype is currently quite technical, and requires some programming knowledge (PYTHON). All files are gathered in a repository publicly available on github, at the link specified above, in the documentation section.

Hardware:

The prototype uses an adafruit 16-channel servo driver, which needs to be connected to both the RPI and the servos, it is already attached to the RPI, however the servos need to be wired to the board.

IMPORTANT: The wires should be attached in accordance with the figures below.

Figure M.1: Connecting a Servo Motor to a Raspberry Pi via the GPIO Pins.

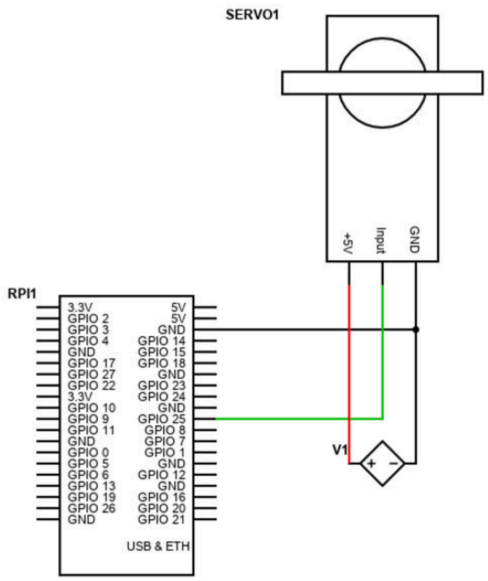
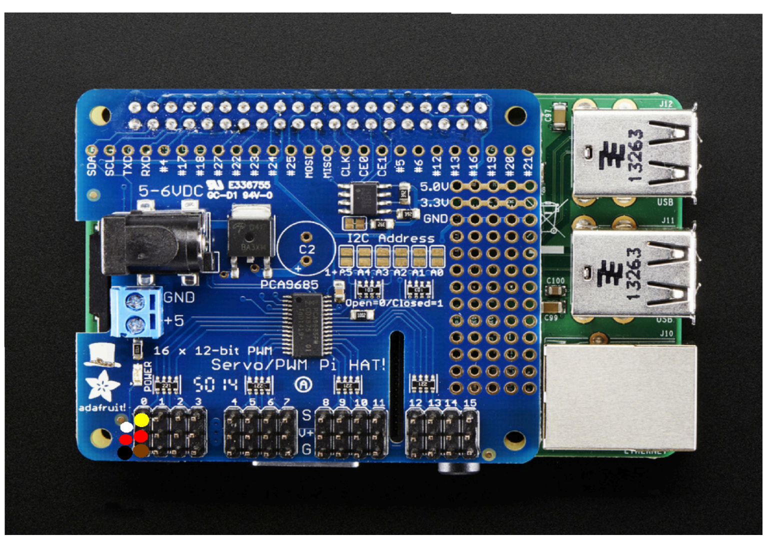


Figure M.2: Demonstration of the Colour Coded Wiring for the Servo Driver.



It is crucial to attach the ground cable, (brown or black) to the outer edge of the board, if incorrectly attached the servo motor's input signal will be overloaded, the servo will get fried.

Initialising the hardware therefore consists of plugging in each servo you want to use, to access the full functionality of the code nine servo motors need to be attached to the board. This allows for the movement of four legs (two servos each), and the brush (one servo).
In the case of the legs, we recommend attaching the servo pairs next to each other. This is optional, however it will lead to a more understandable coding interface.

Top and Base Servos:

In the previous section we discussed the hardware setup, attaching the servo motors to the machine, now in order to actually control they need to be addressed by the program. This is done at a higher level, meaning that each leg should be initialised with the two servo motors that control it; base servo and top servo as seen in the , as in the servo that controls the lower part of the leg's angle, highlighted in blue in Figure 3, and the the top part of the leg coloured orange.

Figure M.3: Side view of the leg structure

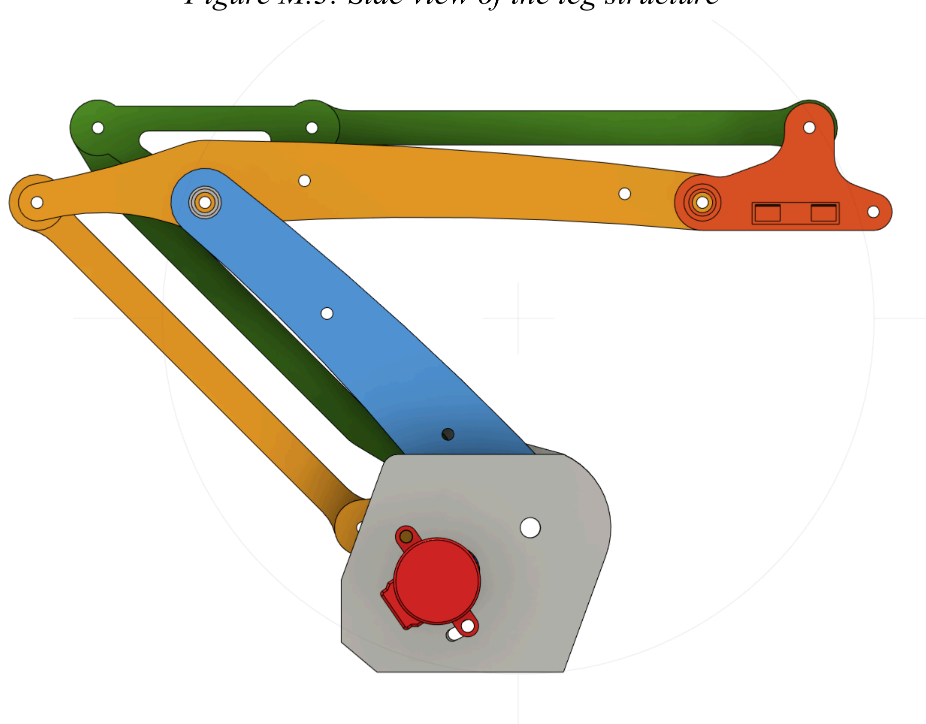
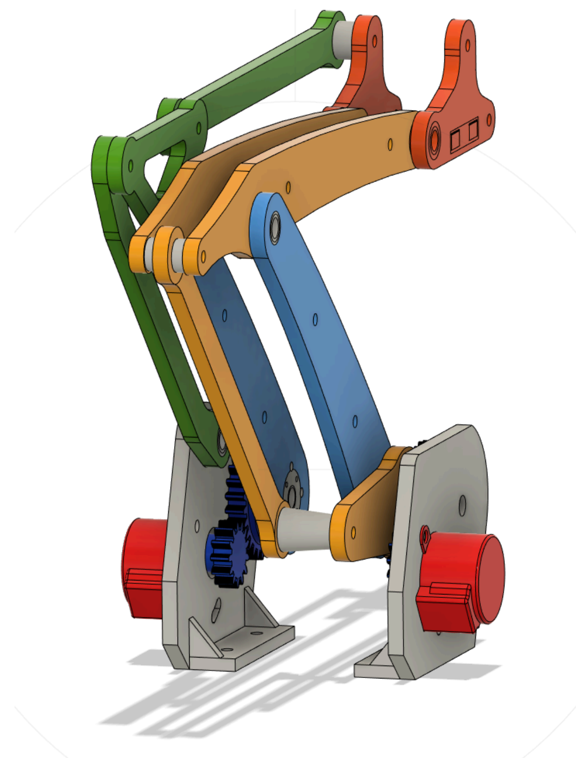


Figure M.4: Rotated view of the leg, showcasing the top(left)- and base(right) servos



Software:

I recommend going through the three most influential files of the repository mentioned above. Starting with servo_control.py, then legs.py and then main.py. Every important piece of code's purpose and methodology is explained through comments beside the code.

Running the prototype:

You can run the script controlling the robot's walk by:

- **Opening a terminal** (alt+t on linux),
- Navigating to the directory where the downloaded files are located : **cd 'directorypath'**
- Running the command : **python main.py**

In the robot's current state (02/2024) this will start a walk pattern moving all legs of the prototype according to the steps elaborated on in this manual.

Further software explanations:

Aside from the wiring it may occur that one of the leg's gears gets miscalibrated, leading to a misalignment between the actual angle of the leg and the perceived value by the software. This can be checked by viewing the script's output in the terminal, which continually displays the angle changes after each movement function call. During the run the terminal will print each servo motor's internal angle updating.

The precise instantiation of each leg is done by the main.py file, creating Leg objects with arguments bottom servo and top servo, these arguments are passed as a tuple, as depicted by the figure below.

Figure M.5: Initialization of brush and leg objects

```
init()
brush = Brush(15, 2) #Brush, servo = pin15,  rotation speed = 2
north = Leg([0, 1])  #North, bottom servo = pin0, top servo = pin1
east = Leg([2, 3])   #East,  bottom servo = pin2, top servo = pin3
south = Leg([4, 5])  #South, bottom servo = pin4, top servo = pin5
west = Leg([6, 7])   #West,  bottom servo = pin6, top servo = pin7
```

As discussed the gate of the robot is controlled through the changing angles of the servo motors. The locomotion process requires many steps, precisely seven. Each of these steps represent simultaneous movement of (at least) two legs. The steps defined in the main file, call upon many functionalities that do not need to be fully understood in order to operate the robot. However to gain a deeper understanding please read the comments in the servo_control.py and the legs.py files. These files contain all information regarding the manipulation of all variables.

Editing the movement pattern can be done by tweaking the step functions; these currently don't have angular inputs, meaning that changing the movements can be done by changing the actual angles in the step functions, i.e. the functions one(), two(), …, seven(). This is shown in Figure 6.

Figure M.6: Step function, calling all substeps, with their angles showed by comments

```
def step(num_steps):
    # (1) north : down,    east : down,       west : down,    south : down
    # (2) north : down,    east : up(r),      west : up(r),   south : down
    # (3) north : extend,  east : up(r),      west : up(r),   south : in
    # (4) north : in,      east : up(r),      west : up(r),   south : extend
    # (5) north : in,      east : down,       west : down,    south : extend
    # (6) north : in,      east : down,       west : down,    south : extend
    # (7) north : up(r),   east : down,       west : down,    south : up(r)

    for i in range(num_steps):
        first()     # (90, 0), (90, 0), (90, 0), (90, 0)
        second()  # (90, 0), (45, 45), (45, 45), (90, 0)
        third()  # (120, 60), (45, 45), (45, 45), (120, 0)
        fourth()  # (120, 0), (45, 45), (45, 45), (120, 60)
        fifth()  # (120, 0), (90, 0), (90, 0), (120, 60)
        sixth()     # (120, 0), (90, 0), (90, 0), (120, 60)
        seventh()    # (45, 45), (90, 0), (90, 0), (45, 45)
```

As mentioned, each substep moves at least one pair of legs, simultaneously. The parallel movement is achieved using the built-in multiprocessing library of Python. Use of the library is straightforward, it allows you to create multiple threads (command sequence to be executable), starting them, and lastly joining them back into the stream of sequential code execution. An example of this is demonstrated by Figure 7.

Figure M.7: Parallel execution of moving all four legs's servo angles to 90 degrees for the bottom servo, and 0 degrees for the top servo.

```
def first(): # (90, 0), (90, 0), (90, 0), (90, 0)
    # 1
    t1 = multiprocessing.Process(target=north.leg_to_angles, args=(90, 0))
    t2 = multiprocessing.Process(target=east.leg_to_angles, args=(90, 0))
    t3 = multiprocessing.Process(target=west.leg_to_angles, args=(90, 0))
    t4 = multiprocessing.Process(target=south.leg_to_angles, args=(90, 0))


    t1.start()
    t2.start()
    t3.start()
    t4.start()

    t1.join()
    t2.join()
    t3.join()
    t4.join()
```

Conclusion to the manual:

This manual covers most capabilities of the script and the hardware, however some are left out. These reasons include the sheer verbosity of the elaboration it would require to go into detail about the encapsulated functions of the pca6985 for example. Those curious among the readers may look at the documentation of this library at the webpage;

https://learn.adafruit.com/16-channel-pwm-servo-driver/python-circuitpython

Many planned functionalities are unfinished, this means that in the files you may find disabled (commented) functions. Please review them and if you deem them useful develop them further and use them to make the Hull Cleaner great.

We wish everyone who takes up the challenge of improving the prototype in any way good luck and a fun developing experience.

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