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Preface

It is my pleasure to present this bachelor's thesis, which delves into the potential of surface preparation using a magnetic robot compared to traditional methods in industry tanks. I would like to express my gratitude to Remotion for providing their workshop for testing and for their contribution to the project. Their engineering team provided support and guidance throughout the study, enabling a deeper understanding of the subject. I would also like to extend my thanks to Beerenberg, Equinor, and Aker BP for their assistance in this research. Their expertise in traditional grit blasting methods was critical in understanding the challenges and limitations of current practices. Overall, this study would not have been possible without the collaboration and support of these companies. It is my hope that the findings of this research will contribute to the ongoing efforts in improving grit blasting processes and lead to more efficient, effective, and safer surface preparation techniques in the future.

Summary

This bachelor's thesis examines the potential of magnetic robots in surface preparation for tank maintenance, addressing the historical challenges associated with the task such as safety risks, noise exposure, and labor requirements. The importance of complying with legal and regulatory requirements is emphasized, and an analysis of relevant laws, standards, regulations, and options is presented. The essay proposes a design for grit blasting equipment for a Magnetic Robot that meets the necessary requirements. To validate the feasibility of the proposed design, two tests were carried out. The first test involved a magnet pull test to ensure that the robot could adapt additional weight and fit for its purpose. The second test was a speed test of the grit blast nozzle to provide a rough approximation for further development. The objective of this essay is to offer valuable insights into the potential benefits of using magnetic robots for surface preparation, present an alternative and provide a foundation for further research and development in the industry.

Sammendrag

Denne bacheloroppgaven undersøker potensialet til magnetiske roboter for overflatebehandling for tankvedlikehold, og tar opp historiske utfordringer knyttet til oppgaven, som sikkerhetsrisikoer, støyeksponering og arbeidskrav. Viktigheten av å overholde juridiske og regulatoriske krav blir understreket, og en analyse av relevante lover, standarder, forskrifter og alternativer blir presentert. Oppgaven foreslår et design for sandblåse-utstyr for en magnetisk robot, og sikrer at den oppfyller nødvendige krav. For å validere det foreslåtte designet, ble to tester utført. Den første testen involverte en magnetisk trekktest for å sikre at den magnetiske roboten kunne tilpasse seg ekstra vekt og være egnet til formålet. Den andre testen var en hastighetstest av sandblåsedysen for å gi en tilnærming for videre valg og utvikling av blåse-utstyret. Målet med denne oppgaven er å vise til potensielle fordeler ved bruk av magnetiske roboter for overflatebehandling, presentere et alternativ og legge et grunnlag for videre forskning og utvikling i bransjen.

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Abbreviations and Definitions

ATEX	Atmosphere Explosible
CAD	Computer Aided Design
FM Workers	Fabric Maintenance Workers
HSE	Health, Safety and Environment
ISO	International Organization for Standardization
LED	Light Emitting Diode
M'ROV	Magnetic Remote Operated Vehicle
NDT	Non-Destructive Testing
NORSOK	The Competitive Position of the Norwegian Continental Shelf
PLC	Programmable Logic Controller
Robot	Machine with Autonomous Movement
ROV	Remotely Operated Vehicle
UHP	Ultra High Pressure

Units

cm^3	Cubic centimeter
Db	Decibel
g	Gram
kg	Kilogram
m	Meter
mm	millimetre
N	Newton
Nm	Newton-metre
RPM	Revolutions Per Minute
s	Seconds
μm	Micrometre
$^\circ$	Degrees

1 Introduction

Surface treatment is a crucial process for tanks used in various industries, including refineries, shipping, and offshore. However, it is subject to strict Health, Safety, and Environmental (HSE) regulations and is susceptible to wear and tear due to usage and time. Historically, tank maintenance has been a challenging task due to noise exposure for personnel, the danger of tank work, and the requirement for a larger labor team. To better understand the traditional methods of surface treatment in tanks, service providers and operators were consulted for their input.

Recorded noise levels from the operators revealed that workers can be exposed to noise levels exceeding 130 dB during grit blasting inside tanks. [1] Risk assessments conducted by both operators and providers indicate that these noise levels significantly reduce work hours per shift, even with the usage of double ear protection. [2] [3]The greatest risk when working in confined spaces is the recurring lethal danger of an incorrect atmosphere. Therefore, traditional tank maintenance is dangerous, challenging, and costly. This thesis aims to evaluate innovative and better solutions to reduce the risk for personnel by proposing a magnetic robot to perform the dangerous job of surface preparation task during tank maintenance.

This thesis was conducted in collaboration with Remotion, a leading technology supplier in the Magnetic Remote Operated Veihcle(M'ROV) and Magnetic Robot field. Although Remotion had previously developed their compact M'ROV "Pluto" as part of their offerings, the objective of this thesis was to adapt Pluto for grit blasting operations in industrial tanks. By using Pluto, the operator can remain safe on deck while the magnetic robot takes all the risks inside the tank. It was crucial that the robot was tailored to meet the requirements of the offshore oil and gas industry and Remotion's aspirations.

1.1 Remotion

Remotion is a company based in Sandnes, Norway, that specializes in innovative surface treatment technology. Their surface treatment technology includes two primary categories of robots. The first category is designed for pipelines, while the second category is the use of programmed autonomous M'ROVs(Magnetic Robot). Since its establishment in 2013, Remotion has primarily focused on the development of M'ROV technology, which can perform various other tasks such as visual inspections, habitat installations, friction welding, non-destructive testing (NDT), and lighter construction work in the refineries, shipping and offshore industries.

As part of their continuous improvement efforts, Remotion aims to expand their services by developing a smaller robot that can provide a solution for the challenging task of surface preparation inside tanks. The objective is to create a smaller robot that will allow Remotion to offer accurate and efficient surface preparation services for tanks of various sizes and expand their services within the industry.

1.2 Objectives

The main objective is:

- Investigation and evaluation of the usability of Pluto with integrated grit blasting equipment for surface preparation during tank maintenance.

This is divided in to the following sub-objectives:

- Identification of constraints through literature study and an investigation of regulations that are relevant to the industry and the intended purpose.
- Ensure that Pluto satisfies the constraints discussed in the study.
- Pull test of magnet fitted on Pluto, to ensure that the additional weight of equipment and purpose was adequately supported.
- Design of grit blast equipment, based on the literature study and constraints.
- Conducting a speed test on the nozzle during grit blasting, to determine the appropriate equipment based on the test results.
- Ensure robot and grit blast equipment satisfies the constraints.
- Investigate the coherence of magnetic robot for surface preparation inside tanks.

2 Constraints

For the magnetic robot designed for surface preparation in tanks used in the refinery, shipping, and offshore industry to comply with legal and regulatory requirements, it is essential to conduct a thorough analysis of the relevant laws, standards, regulations, and options. This analysis should cover all aspects, from obtaining approvals and demonstrating compliance with safety and environmental standards to securing necessary permits and licenses for operation. By evaluating the legal and regulatory landscape, the development of the robot is not only compliant but also fit for purpose. Ultimately, this will lead to safe and efficient operations, minimized risks and liabilities, and compliance with regulatory requirements.

2.1 Regulations for Tank Entry

To ensure safety during tank entry and work, relevant laws and regulations assign responsibilities to the employer, certified issuer, and the owner of the installation or tank. The employer must notify the Norwegian Labour Inspection Authority of the appointed certificate issuer, who is responsible for ensuring safe work practices and necessary safety measures.[4] Workers are responsible for following safety measures and using personal protective equipment, while reporting any safety hazards or concerns. Ultimately, workers are responsible for their safety and that of their colleagues by adhering to laws and regulations for hazardous environments.[5]

Ensuring the safety of personnel during tank entry requires a shared responsibility among all parties involved, including the robot operator. Although not responsible for securing the tank, the operator plays a crucial role in adhering to proper procedures and cooperating with others to ensure a safe environment. Furthermore, the robot design must allow for remote shut down from the deck, as tank entry may not always be feasible due to safety concerns. By prioritizing safety during the robot design process, it can contribute significantly to the overall safety of tank entry and work operations.

2.2 ATEX-Regulations

ATEX refers to a set of European Union directives that outline regulations and procedures to protect workers, other individuals, and property against the hazards associated with explosive atmospheres.[6] To ensure safe usage of equipment in the offshore oil and gas industry, it is necessary to comply with ATEX regulations to mitigate the risk of explosions. Building ATEX mobile robot solutions is a challenging task due to the limited variety of electric ATEX components, which are often physically larger as well. However, temporary non-ATEX approved equipment can be utilized in compliance with the NORSOK Z-015 standard.[7] The NORSOK Z-015 standard, developed by the Norwegian petroleum industry, includes Chapter U98 which outlines specific requirements for non-ATEX-approved equipment that the robot must adhere to in order to ensure safe operation in this industry.[7] The U98 chapter mandates that equipment with possible ignition sources must be powered from sockets connected to the lowest level of the ignition source control system, shut down all potential ignition sources in case of power loss, and obtain approval from the responsible person for equipment placement and use.[7] Accurate documentation is crucial, including a conformity declaration marked to indicate that thorough assessment is required. The supplier of the equipment must provide documentation of potential ignition sources, deviations, and other information that could cause ignition, particularly electrical.[7] Categorizing the robot according to a standard would simplify the assessment process, increase the approval rate among responsible parties, and make it more suitable for a wider range of jobs.

2.3 Surface Treatment

Surface treatment involves a sequence of tasks that are crucial in ensuring the reliable performance of equipment, structures, and installations. It consists of four individual steps; cleaning, surface preparations, coating and inspection.[8] Each step important for the success and longevity of the treated infrastructure.

This thesis specifically focuses on the second step, surface preparation, which is critical for ensuring proper adhesion of the new coating. Coating and adhesion are determined by surface profile. Inadequate surface profile can lead to premature failure and the need for costly repairs.[8]

According to the industry standards it is necessary to ensure that the magnetic robot can create the appropriate surface profile. NORSOK M-501 mandates using grit as the blast medium and grading the surface profile in accordance with ISO 8501 and ISO 8503. The ISO 8501 specifies that the blast cleaned surface must meet the cleanliness requirements of Sa2$\frac{1}{2}$ surface profile and 30-75 microns (1.2-3.0 mils).[9] Grit blasting is the most commonly used surface preparation technique in the industry, as it is recommended by NORSOK, ISO, and paint manufacturers.[10] [11] Remotion indicated that grit blasting will be the surface preparation method of choice for this robot, as it has to meet the standards mentioned.

2.3.1 Grit Blasting

Grit blasting is a surface preparation technique that uses high-pressure compressed air to propel abrasive particles. When designing a grit blasting robot, it's important to consider several critical parameters to ensure optimal performance. One of these parameters is grit size, as larger grit particles create larger craters on the surface and increase roughness.[12] Blasting pressure should also be optimized to achieve the desired surface roughness and increase efficiency. The distance between the nozzle and the surface is another important consideration for optimal performance.[12]

In addition to the above parameters, the blasting angle is a crucial factor that can impact the efficiency and desired surface roughness. Studies have shown that an angle between 60 and 80 ° is optimal for increasing surface roughness efficiently. However, increasing the angle beyond this range can result in a decrease in roughness.[12] Therefore, it's essential to carefully choose the blasting angle to achieve the desired surface roughness while maintaining efficiency.

Blasting time is another critical parameter that needs to be optimized to achieve the desired surface roughness.[12] However, the blasting time needs to be considered in the context of nozzle speed. Increasing the nozzle speed can decrease the surface roughness of the blasted surface, allowing for a shorter blasting time. Conversely, decreasing the nozzle speed can increase the surface roughness. To achieve the desired surface roughness in a more efficient manner, it is crucial to optimize the nozzle speed. This requires the integration of autonomous movement in Pluto's grit blasting equipment, as manual handling can result in inconsistent speed. Hence, Pluto becomes a magnetic robot with autonomous movement to maintain a constant nozzle speed.

2.4 Remotion's Attributes

Remotion proposed the development of a robot that would meet the specific requirements of the project, including a weight under 25 kg to comply with the Working Environment Act and enable a single worker to handle it.[13] The magnetic robots primary objective was to partially replace some of the labor-intensive tasks typically done by Fabric Maintenance (FM) workers. Although the robot was not intended to complete all surface treatment work, it was expected to undertake a significant amount of surface preparation work in accordance with relevant standards. To achieve this, Remotion suggested that the robot should have a compact and lightweight design, enabling it to access tight areas and smaller tanks. Additionally, the robot was intended to have a considerable range of motion, allowing it to perform tasks in various orientations, such as on the floor, wall, or even upside down on the ceiling of a tank. Remotion also proposed that operators have an unobstructed and clear field of view from outside the tank to ensure efficient operation of magnetic robots inside the tanks.

2.4.1 Pluto

Figure 1 illustrates Pluto, which was originally designed to be a small M'ROV capable of performing surface preparation using an Ultra High Pressure (UHP) washer. In order to adapt Pluto for grit blasting operations it is essential to ensure that the grit blasting equipment is integrated into the robot without changing the core functionality of Pluto. The design of Pluto is optimized for compact size and operation, which is crucial for its suitability in this context.

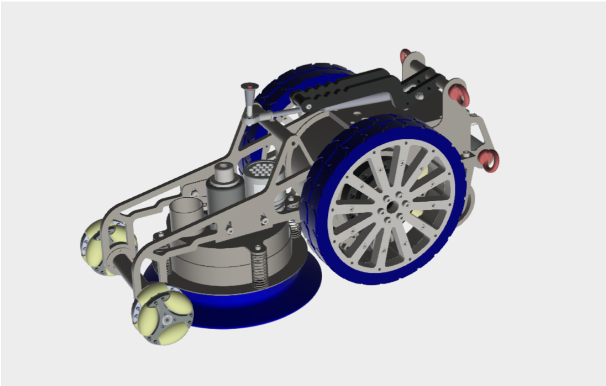

Figure 1: Pluto with UHP-Washer *(Remotion)*

2.4.2 Remotions Surface Treatment Experience

Remotion has previous experience in the surface treatment industry, particularly with the use of magnetic robots. Another surface treatment project their undertaking includes grit blasting of ships' hull. In such projects, it is known that the harsh grit environment can cause wear and tear on the surrounding equipment. Based on this experience, Remotion suggests that the robot should be well-protected from grit, dust, and debris during grit blasting operations.

3 Magnetic Remote Operated Vehicle Pluto

The previous chapter of the thesis highlighted various constraints that must be take into consideration when designing a magnetic robot, such as regulations, technical requirements, environmental coherence, and attributes of Remotion. These constraints are crucial in determining the feasibility and success of the robots design, and it is necessary to thoroughly evaluate and account for them during the design process.

It is worth noting that prior to this thesis, Remotion had already developed an M'ROV called Pluto illustrated in Figure 2, which was designed to be a compact and versatile device for surface preparation tasks. Although it is not specifically intended for tank entry and grit blasting, the design of Pluto is well-suited for the purpose of creating a grit blasting robot for tanks. Its low weight and compact design make it suitable for potential grit blasting equipment, allowing for easy maneuverability and access to confined spaces within the tank.

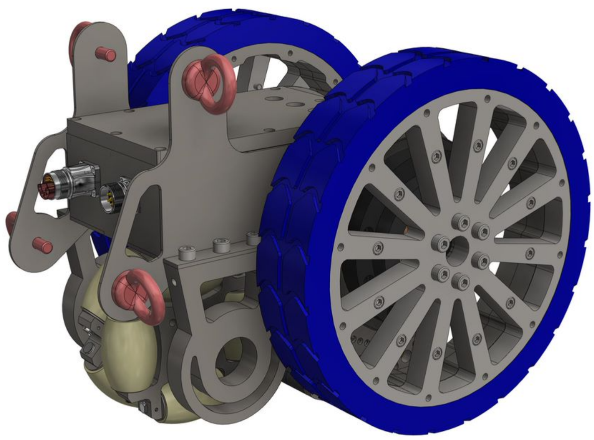

Figure 2: Magnetic Remote Operated Vehicle Pluto *(Remotion)*

The M'ROV's consists of two wheels, each propelled by a separate electrical engine. A permanent magnet is mounted to the frame, which generates a force that is transferred to the wheels when the magnet is near a metal surface. To maintain balance, an omni wheel has been mounted at the back of the robot, which distributes the magnet's force at three points, ensuring that the robot remains stable while in motion.

The design of the grit blasting equipment needs to be compatible with the existing structure and functions of Pluto. In other words, the design should take into account the dimensions, weight, and balance of the M'ROV, as well as its power and control systems, so that the attachment can be easily integrated with the robot without compromising its performance or safety. Therefore, the initial design of Pluto serves as a reference point for the development of the grit blasting equipment.

3.1 Magnetism

To ensure that the robot maintains optimal magnetic attachment power, it is crucial to maintain an appropriate distance between the magnets and the metal surface. Figures 3 and 4 display the maximum and minimum distances at which the magnet can be placed. The design also includes three intermediate distances, namely 5.5 mm, 7 mm, and 8.5 mm. The maximum value of 10 mm enables the magnet to move over more uneven surfaces, while the minimum value of 4 mm provides a higher attachment force.

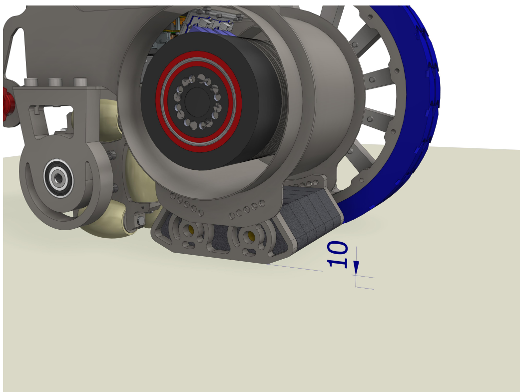

Figure 3: Magnets Maximum Distance *(Remotion)*

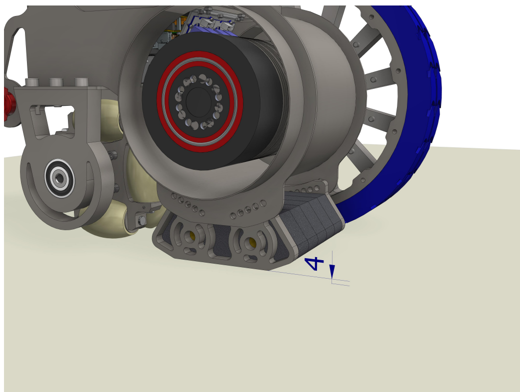

Figure 4: Magnets Minimum Distance *(Remotion)*

Additionally, in robotics technology, the magnetic field in the surroundings is a crucial consideration, and this can be manipulated using Halbach arrays. These arrays are constructed by arranging magnets in specific patterns with opposite polarizations, resulting in a strong magnetic field on one side and a weaker field on the other. This design makes Halbach arrays ideal for robotic technology, as the weaker side does not interfere with electronic components, while the strong side provides a high-force attachment to surfaces. While the complex calculations necessary to determine attachment force using Halbach arrays fall outside the scope of this thesis, physical tests conducted provide a foundation for ensuring that the robot's attachment force is sufficient to support necessary attachments and equipment, especially considering its ability to operate in all orientations.[14]

3.2 Magnetic Pull Test

As previously mentioned, it is important to make sure that the magnet has enough attachment force for the robot to perform its task. Magnet pull tests, are a method of measuring the strength of a magnet's magnetic field and its ability to attract or repel other objects. However, several factors can affect the accuracy of the results, making it necessary to consider these factors carefully during the testing process.

The tests were conducted at Remotions workshop, which is located in Forus, Norway. This workshop is equipped with all the necessary equipment and facilities to carry out extensive testing on robots. The workshop holds unique features which includes a large metal wall purposely constructed for testing, along with a steel plate bolted to the floor to facilitate this process.

The test was performed on a 20 mm steel plate in a workshop, using a 2 metric ton gantry crane to move the magnet. To avoid overloading the scale used, a pulley system was implemented, making the scale 2:1. This means that the readings on the digital scale are only half the actual weight. The scale used in the test was a Brecome digital scale, accurate to 100 grams and capable of measuring up to 400 kg.[15]

Before each pull, the scale was zeroed, and the magnet's weight was measured, which was found to be 7,6 kg, including shackles and lifting gear. It is important to consider the weight of the magnet as it is a part of the pull weight, and not factoring it in can lead to inaccurate results.

During the pull test of the magnet, maintaining the perpendicular position of the magnet to the metal surface is important to obtain accurate results. Tilting the

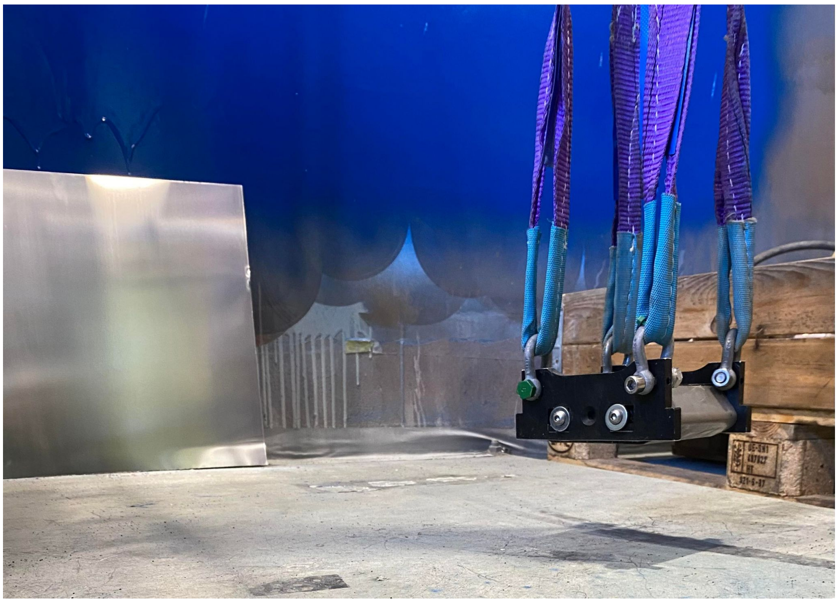

Figure 5: Setup for the Pull Test

magnet during the test can cause inconsistencies in the measurement as the magnetic force is strongest when the magnet is parallel to the surface. Any tilt in the magnet will distribute the magnetic force unevenly, resulting in an inaccurate measurement of the magnet's strength. To prevent this, four evenly distributed points were used to pull the magnet during the test.

The tested Neodymium magnet show in Figure 6 belongs to the N52 grade and comprises five individual magnets, each with a volume of 152 cm^3 and a weight of 1070 g. This suggests that the entire Halbach array magnet, including the two Ø12 mounting holes, has a total volume of 250 cm^3 and weighs 5350 g.

To create different distances between the magnet and the steel plate, Aluminum plates of different thicknesses (1.5 mm, 6 mm, and 10 mm) were stacked on top of each other. The choice of using Aluminum plates was made because Aluminum has a relative permeability of around 1, which means it does not easily allow magnetic fields to pass through it. Therefore, the Aluminum plates were used to create the desired distance between the magnet and the steel plate without affecting the strength or quality of the magnetic field. By stacking the plates in different combinations, the

Figure 6: Pluto's Magnet that was Subjected to Testing *(Remotion)*

distance between the magnet and the steel plate could be adjusted.

The test was conducted three times for each distance, with the aluminum plate being located differently each time based on the magnet's placement. Additionally, the magnet and aluminum plate were placed on different spots of the steel plate during each test. This was done to reduce inaccuracies in distance between plate and magnet. It was also noted that the connection between the magnet, aluminum plate, and steel plate was properly secured.

3.2.1 Test Results

The test results are presented in Tables 1 and 2: one for the north side and one for the south side of the Halbach array. Each table has six columns, with the first column displaying the distance between the magnet and plate surface created by the aluminum plates. The following three columns display the first, second, and third attempts for the pull test, and the fifth columns shows the maximum value among these three attempts. The sixth column displays the difference between the highest and lowest values in the three attempts.

Table 1: Test Results: North Pole of Halbach Array Magnet

Distance [mm]	Primary trial [N]	Secondary trial [N]	Third trial [N]	Max Load [N]	Differential [N]
1	7285	7422	7226	7422	196
2,5	5832	5793	5851	5851	58
4	4850	4752	4791	4850	98
5,5	3849	3829	3908	3908	79
7	3220	3240	3181	3240	59
8,5	2455	2553	2513	2553	98
11	1850	1869	1850	1869	19
12,5	1575	1555	1565	1575	20
17	897	907	897	907	10
21	534	534	544	544	10
27	249	249	249	249	0

Table 2: Test Results: South Pole of Halbach Array Magnet

Distance [mm]	Primary trial [N]	Secondary trial [N]	Third trial [N]	Max Load [N]	Differential [N]
0	2262	2223	2183	2262	79
1,5	1271	1278	1261	1278	17
3	744	746	740	746	6
4,5	469	475	475	475	6
6	322	328	322	328	6
10	141	138	149	149	8
20	39	41	41	41	2
26	18	19	19	19	0

Figure 7 displays the maximum values for north and south side of the magnets, for the distances conducted in the tests.

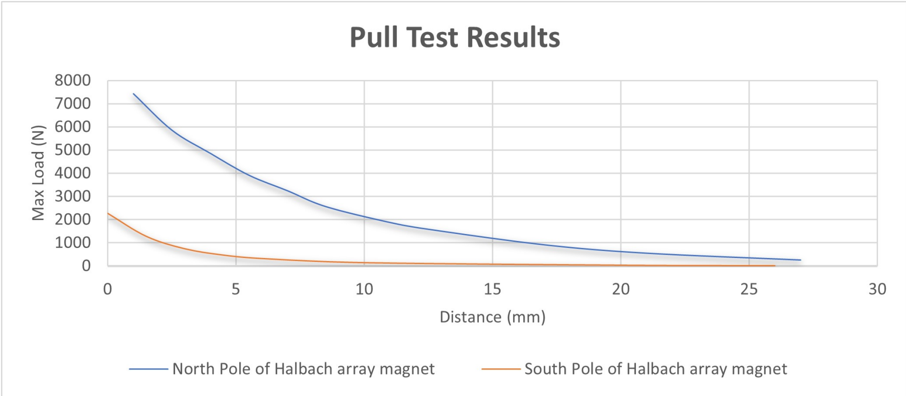

Figure 7: Test Results of Magnetic Pull Test

3.2.2 Discussion

When conducting a magnet pull test, various factors can affect the accuracy of the results, and it is crucial to account for them. One such challenge is maintaining a clean testing environment due to the presence of dust and debris. Using plates to create a distance between the magnet and the test object may also be imperfect due to the possible presence of debris or dust between the plates, even after cleaning.

Another factor that could have affected the magnet pull test is the observation that some of the plates had dents, particularly during the 2.5 mm distance test. The pressure from the magnet as it was placed on top of the plates could have caused these dents. Using harder metal plates such as low carbon steel could have minimized this issue, but potentially affected the permeability. The dents could have resulted in a smaller gap between the magnet and the steel surface, leading to a higher pull value. Additionally, the magnet had a 1 mm protective plate mounted to the north pole, which could have affected the measurements' accuracy. This plate could have introduced uncertainty about the actual distance between the magnet and the test object, as the magnet and protective plate was glued together, thus potentially resulting in a lower measurement of the magnet's strength.

The 20 mm steel plate used in the test had an uneven surface, which may have resulted in the magnet not creating the highest possible load. However, this could have led to a more realistic load as it more accurately reflected the real-world conditions of metal surfaces.

Additionally, the steel plate was partially covered in a thin layer of paint, which could have contributed to imprecise measurements. The paint layer could have prevented the magnet and aluminum plates from making full contact with the surface, leading to lower pull values. The presence of a paint layer on the metal surface could lead to similar issues when the robot tires come into contact with it.

The use of a gantry crane for the magnet pull test can lead to imprecise results. Gantry cranes are known to have some level of inaccuracy, which can affect the results of the test. Additionally, during the test, a pulley system was employed due to the scale's maximum weight capacity of 400 kg, while the pulls being tested were around 750 kg. It is worth noting that the friction and other mechanical factors involved in the pulley system may have contributed to the overall inaccuracy of the results. Although the tension in the system remained relatively static throughout the test, any variation in the friction or other mechanical factors could have affected the results of the test. Furthermore, the magnet being pulled was connected to the pulley system through 4 individual connection points. This may not have been the most practical setup, as the magnet may have been able to tilt slightly, even if it was not noticeable to the human eye. Any slight tilt in the magnet pull can cause the measurement to be inaccurate. This inaccuracy may also be present due to the robot's distribution being supported at three points. But a more stable and reliable connection method may have been preferred to ensure the magnet remained stable during the tests.

Finally, human error may occur, which is why it is crucial to ensure that the equipment used is accurate and reliable, noting that the highest rating was not receivable or saved on the scale, which could affect the actual readings of the results. To minimize any potential errors, the test was conducted three times, the scale was zeroed before each pull and change of location and position on plates. The importance of accurate measurements taken in the tests, will be considered in chapter 3.4

3.3 Electronics

To expand upon the foundation of Pluto, an examination of the electronics that the robot relies on is necessary. Pluto is equipped with two electrical motors that play an important role in the robot's movement. These motors are specifically designed to power the robot's main two wheels, which in turn allow the robot's movement. The motors are capable of generating a continuous torque of 1.76 Nm, and are capable of achieving this up till a maximum speed of 3230 RPM. Overall, the motors are an essential component of Pluto's design, providing the necessary power and control required to move the robot and carry out its tasks.

The emergency brake or fail-safe is a crucial safety mechanism that plays a vital role in preventing accidents or damage in the event of a power failure in the robot. Located within the robot's electrical box, it consists of a relay that is responsible for cutting off power to the electrical motors, which drive the vehicle's movement. The relay works by continuously demanding power to keep the motors operational. In the event of a power failure or an emergency shut-down command, the power supply to the relay will be cut off, immediately triggering the relay to cut off power to the motors and causing them to stop

3.4 Mechanical

The gearbox utilized in the robot is not a standard off-the-shelf component, but rather specially designed and manufactured for this particular application. Although its efficiency is unknown, the gearbox has a confirmed gear ratio of 160:1, meaning that the output shaft rotates 160 times slower than the input shaft. As previously mentioned, the maximum speed of the electric motor is 3230 RPM, resulting in the wheels turning at 20 RPM. Therefore, the maximum speed of the robot is limited to 0.323 m/s or 1.16 km/h.

By utilizing information about the continuous torque of the electric motors and the planetary gear ratio, it is possible to calculate the pull force of the robot. However, this calculation does not take into account several factors such as the weight of Pluto, umbilical, grit blast hose, loss of moment through planetary gear and bearings, and the friction between the metal surface and rubber tires.

Figure 8 provides an overview of the working height of the robot in different scenarios. The blue line in the figure indicates the robot's working height when climbing a wall, which is calculated by subtracting the downward force of the robot's weight from the moment generated by the electric motors through the planetary gear onto the surface. This estimate also takes into account the weight of the umbilical and grit blast hose, which is approximately 20 N/m.

The working height of the robot in a tank ceiling is also illustrated in Figure 8, along with the percentage of deviation in the actual attachment force during operation from the magnet pull test conducted in the workshop. To determine this height, the maximum load from the pull test was subtracted from the force of the robot's weight. The efficiency of the attachment force is also indicated in the figure, highlighting the potential reduction in attachment force caused by the umbilical and grit blast hose, at an offset distance of 4 mm (orange) and 10 mm (grey) that the robot may experience. This provides an understanding of the potential loss of efficiency in magnet attachment force under real-life conditions compared to the magnet pull test. It also helps in determining the appropriate safety factor required to calculate the robot's maximum working height.

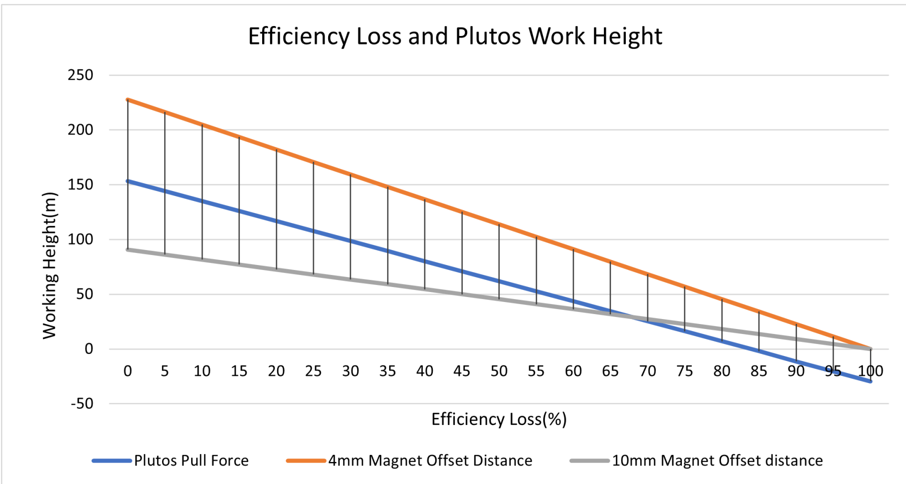

Figure 8: Correlation Between Efficiency Loss and Pluto's Work Height

4 Grit Blast Equipment

The swing arm is responsible for holding the grit nozzle and moving it back and forth to blast the surface. This design was developed after carefully considering Remotion's known factors and constraints discussed in earlier chapters. The guiding principle behind it is simplicity, which is achieved by minimizing the number of moving parts and incorporating a single moving component. An illustration of the grit blasting Equipment is shown in Figure 9.

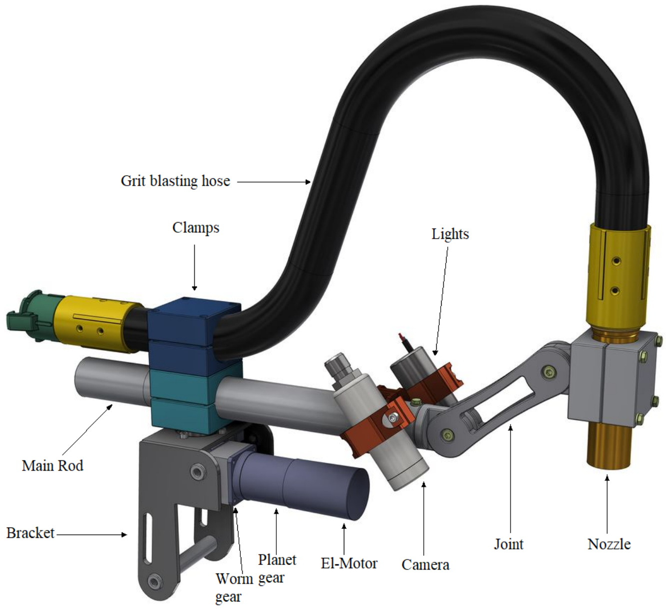

Figure 9: Grit Blasting Equipment *(Remotion)*

A bracket is used to connect the M'ROV frame and the grit blasting equipment, which is secured by four eye-bolts. The bracket also holds the worm gear that links the electrical motor to the main rod. To further reduce the ratio in the transaction, a planet-gear is placed between the electrical motor and the worm gear. Mounted over the worm gear is a clamp that stabilizes the sandblasting hose and main rod during movement. At the far end of the aluminum tube, there is a joint that enables adjustment of the nozzle's distance and angle. Notably, a camera and lights are mounted before the joint and attached to the main rod.

4.1 Grit Blast Speed Test

The tests were conducted at Remotions workshop. This workshop is equipped with all the necessary equipment and facilities to carry out extensive testing on robots. The workshop holds unique features for M'ROV and magnetic robot testing which includes a large metal wall purposely constructed for testing. The test was conducted to gain a better understanding of the parameter of blasting time, this required a speed test of the grit blasting nozzle. This test was carried out to measure the maximum speed at which the nozzle could move while creating the proper surface profile.

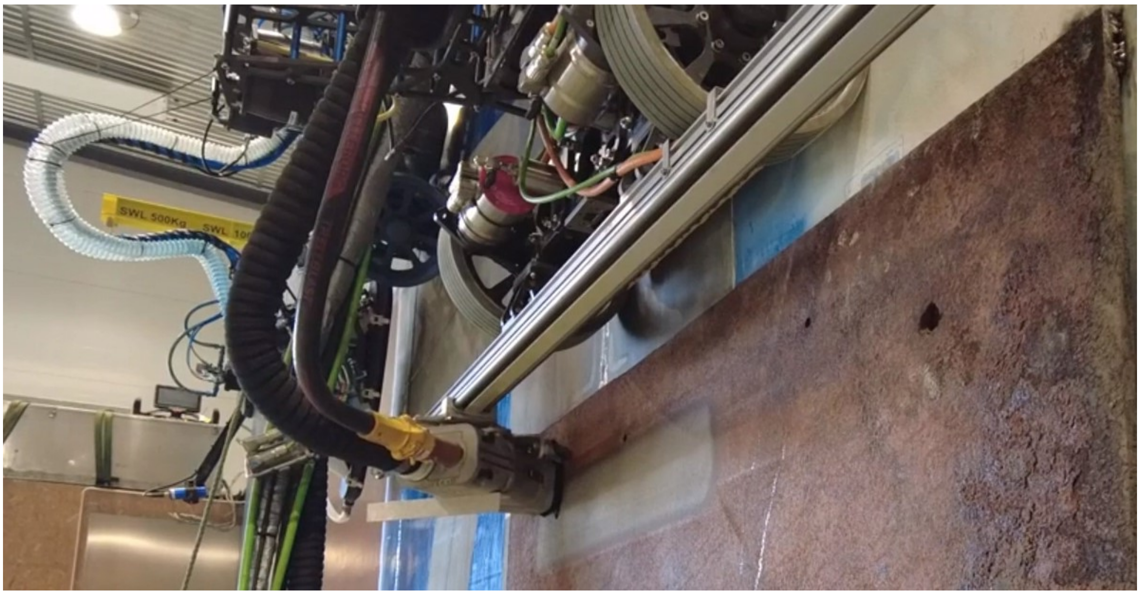

Figure 10: Nozzle Speed test on Flake Rusted Surface

As previously mentioned, blasting time is one of the parameters involved in grit blasting. To ensure the optimal blasting results, it is essential to adjust the nozzle speed accordingly. Therefore, a speed test was conducted on different surfaces, such as painted, plain metal, and flake-rusted surfaces, utilizing one of Remotion's other robots, shown in Figure 10. The purpose of the test was to determine the range of nozzle speed required for each surface, to achieve an acceptable surface profile while having the highest possible speed.

The grit blasting speed test was performed using Remotion's magnetic robot, Helios, equipped with a linear tool connected to a Pinovo grit blasting nozzle. The pilot has precise control over the blasting process, as they can adjust the speed and length of the nozzle's movement. While grit blasting manufacturers express their efficiency in terms of square meters per hour, to evaluate the angular speed of the swing arm and corresponding RPM through the gears into the electrical motor, these calculations must be converted to meters per second.

The test was conducted multiple times until the optimal surface profile was achieved, while maintaining the highest possible nozzle speed. To evaluate the surface profile of the blasting process it was measured and evaluated using a combination of measuring equipment, namely the Elcometer 124 measuring device, the Elcometer 122 Testex replica tape, and the Elcometer comparator type G. Figure 11 shows Elcometer 122 Testex replica tape that was used to transfer the surface profile to the replica tape, which was then measured using the Elcometer 124 to provide surface roughness results. Figure 12 shows the comparator type G , that was used in accordance with ISO 8503-2, a standard for steel substrate preparation for painting, to further ensured an accurate and reliable result.

Figure 11: Surface Profile: Rust Flaked Surface

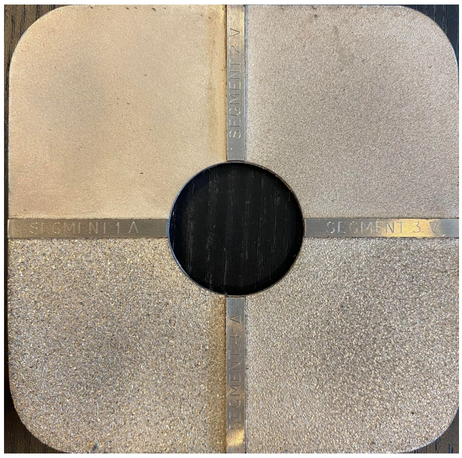

Figure 12: Comparator Type G

4.1.1 Test Results

Equation 1 shows the time and length required to create the appropriate surface profile for plain metal, equation 2 for rust flakes, and equation 3 for painted metal. Table 3 displays the corresponding speed and surface profile.

$$\text{Plain metal surface} = \frac{1}{24}\frac{\text{m}}{\text{s}} = 42\frac{\text{mm}}{\text{s}} \tag{1}$$

$$\text{Rust- flaked surface} = \frac{1,1}{34}\frac{\text{m}}{\text{s}} = 32\frac{\text{mm}}{\text{s}} \tag{2}$$

$$\text{Painted surface} = \frac{1}{54}\frac{\text{m}}{\text{s}} = 19\frac{\text{mm}}{\text{s}} \tag{3}$$

Table 3: Test Results: Grit Blast Speed Test

Surface	Speed [mm/s]	Elcometer 124	Comparator G
Plain	42	60 μm	medium
Rusted	32	56 μm	fine
Painted	19	60 μm	medium

4.1.2 Discussion

In grit blasting, the speed of the nozzle is an important parameter that can affect the surface preparation process. In this case, it was found that the speed over the rusted surface was not measured to be medium with the comparator G. This indicates that the speed was too high and may have resulted in an under-prepared surface. It is also important to note that comparing uneven surfaces using a comparator may not be the most accurate method, and there may have been some human error involved in the measurement process.

However, it is important to note that the surface roughness was measured with tape and within the range, indicating that the speed was still within acceptable limits for the surface being blasted. Additionally, the speed for rust flaked surface fell between the slowest and fastest speed, this implies that if the nozzle speed is adjustable, it may be possible to slow it down a bit to create a rougher surface profile. This would ensure that the desired surface roughness is achieved according to ISO-standards.

This is an important consideration, as different surfaces may have varying degrees of rust and corrosion, which can affect the blasting process's efficiency and the resulting surface roughness. Therefore, it's essential to consider the specific surface's condition and optimize the blasting parameters accordingly to achieve the desired surface roughness.

Pinovo is a different grit blasting system than what is planned for the robot. Different blasting equipment may have varying specifications and parameters, such as the blasting angle, grit size, and blasting pressure, which can affect the blasting efficiency and the resulting surface roughness. Therefore, it's essential to look at the results as an approximation and not a factual speed, and use the appropriate equipment for the specific application and optimize the parameters accordingly.

4.2 Electrical Specification

Figure 13 illustrates a block diagram used to explain the basics of the robot.

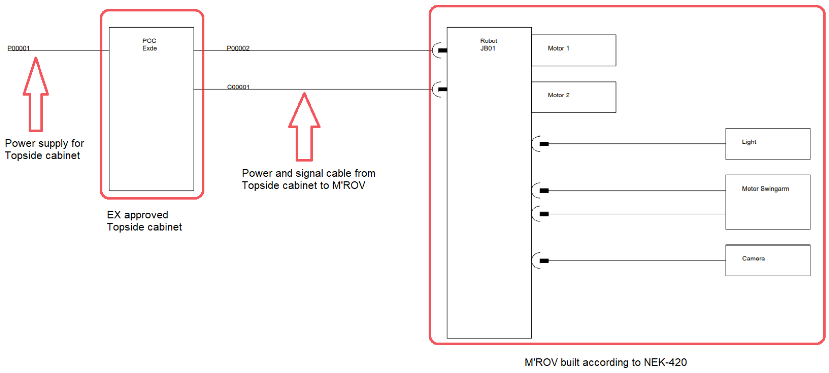

Figure 13: Magnetic Robot's Intended Block Diagram *(Remotion)*

The topside control cabinet contains the power supplies and Programmable Logic Controller (PLC), as well as an antenna that connects to the handheld controller. The cabinet is designed to comply with ATEX-standards, making it safe for use in hazardous environments that require specific safety standards. The electronics of the robot are built in accordance with NEK 420, electrical installations in hazardous areas.

Three electrical accessories have been added to the grit blast equipment, namely the electrical motor, light, and camera. The electrical motor has a power output of 134 Watts and is capable of operating at a speed range of 0-4000 RPM with a continuous torque of 0.32 Nm. The LED light is specifically made for grit blasting purposes and is well-suited for the task. The camera is specially ordered to match the grit-resistant glass of the light and is designed to be compact, making it easy to mount and suitable for its intended purpose.

4.2.1 Electronic Control System

The handheld controller serves as a component that ensures efficient and effective operation of the robot. By providing easy control of the robot, the operator can adjust its autonomous movement, as well as manually control its features. The controller is designed to be user-friendly and intuitive, allowing the operator to quickly and easily switch between autonomous and manual control modes. This helps to minimize errors and increase precision in the robot's movements, ultimately leading to more accurate and efficient surface preparation in tank maintenance. Figure 14 illustrates the controller and the position of its various functions, while Table 4 outlines the controls and their respective functions in a more detailed manner.

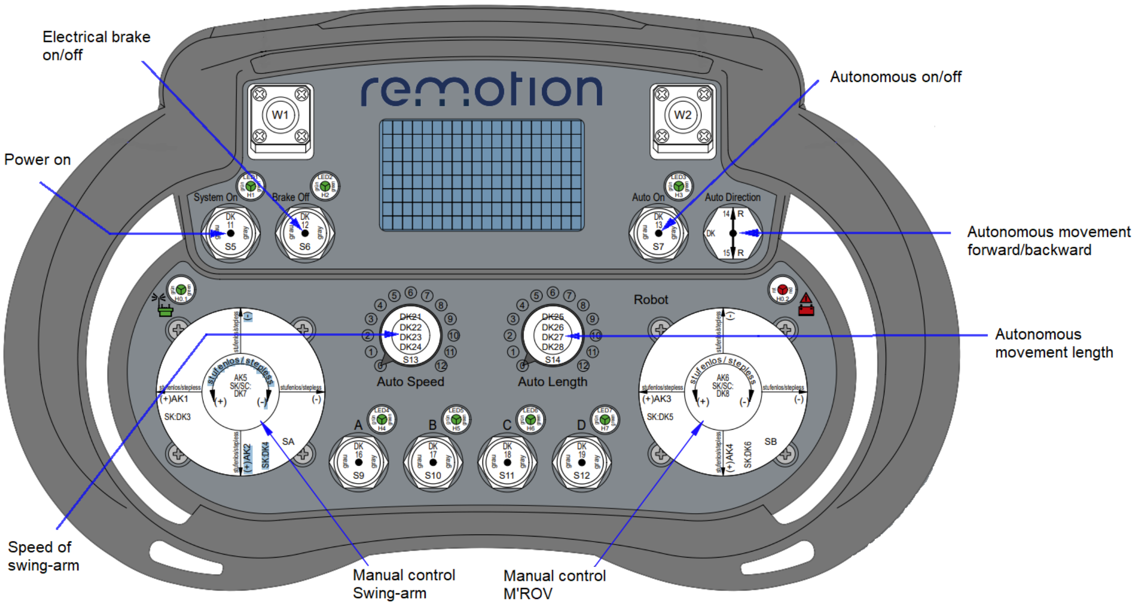

Figure 14: Handheld Controller for Operation *(Remotion)*

Table 4: List of Controller Functions

Controls	Function
On/off Button	Controls power On or Off
Toggle switch	Forward or Backward of autonomous movement function
Autonomous on/off switch	Activate or Deactivate the Magnetic Robots Autonomous Movement Function
Electrical brake Button on/off	Stops the Magnetic Robots Ability to Move
Right Joystick	Manual Control of Magnetic Robot Movement
Left Joystick	Manual Control of Swing Arm Movement
Left Knob	Adjusts the Speed of the Swing Arms Movement
Right Knob	Length Movement Adjustment per Swipe

4.2.2 Magnetic Robot Autonomous Movement

To optimize the surface preparation during grit blasting, it is crucial to optimize the autonomous movement of the robot. Figures 15 and 16 illustrates the robot's swing arm that moves back and forth between the right and left, covering a maximum angle of 120°. As it reaches one end, the robot moves forward or backward at a maximum speed of 323 mm/s while blasting, indicating that the maximum speed is adequate to move the required nozzle speed of 42 mm/s before changing the swing arm's direction. The handheld controller can adjust the swing arm's angle and the robot's step length during autonomous movement through the PLC.

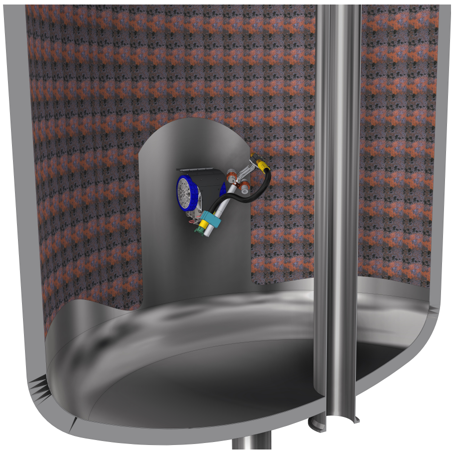

Figure 15: Swingarm in Right Position *(Remotion)*

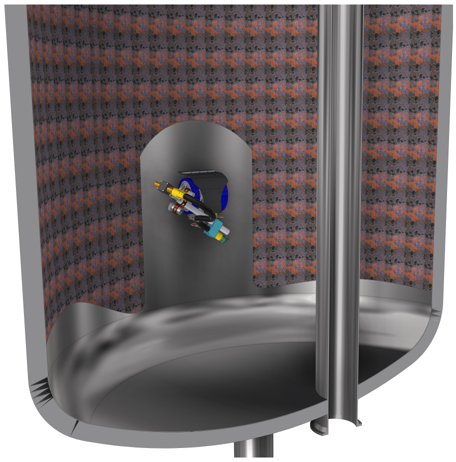

Figure 16: Swingarm in Left Position *(Remotion)*

4.3 Mechanical Specification

A planetary gear with a 10:1 ratio is mounted between the electrical motor and the worm gear, resulting in the output shaft rotating ten times slower than the electrical motor. The planetary gear has a 94 % efficiency, meaning 6 % of energy is lost due to friction. Worm gear, the last gear between the electrical motor and swing arm, has a 30:1 ratio and a 62 % efficiency, causing a loss of 38 % of submitted energy due to friction.

According to the grit blast speed test, the highest recorded speed was 42 mm/s, resulting in a swing arm rotational speed of 0.62 RPM. The gears allow the swing arm to rotate 300 times slower than the electrical motor, requiring the motor to operate at a speed of 186 RPM, and the torque distributed at the swing arm being 56 Nm. At such low speeds, the moment and potential changes in rotational direction appear to be negligible for further calculations on yield strength on the main rod's combined parts illustrated in Figure 17. The single-stage planetary gear with a 10:1 ratio was used due to weight and space limitations, despite the availability of two-stage gears with higher ratios.

Figure 17: Main Rod *(Remotion)*

The two accessories mounted on the main rod are a camera and a light. Both of these electrical parts come with a compact aluminum housing and a durable cover that keeps the glass dust proof and securely in place. This feature also allows for easy replacement of the borosilicate glass, which ensures transparency even in harsh grit blasting environments. The camera and light are mounted to the main rod using specially made aluminum clamps.

The rubber shield is a component of the robot's design, mounted on the frame illustrated in Figure 18. Its purpose is to reduce the wear and tear caused by grit during blasting. This feature helps to reduce the impact of ricochets that may be propelled at the robot during the process. Additionally, the rubber shield helps to keep some of the grit that accumulates on the surface away from the robot, reducing friction between the rubber tires and the surface.

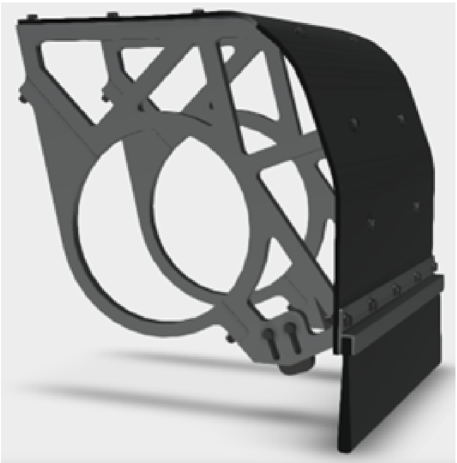

Figure 18: Frame with Rubber Shield and Adjustable Stoppers *(Remotion)*

The frame shown in Figure 18 also includes adjustable stoppers that prevent the robot from tilting forwards. This feature ensures the robot can maintain its position and orientation during usage, reducing the risk of damage or injury to personnel or equipment. Overall, the the frame is a crucial element of the robot's design, providing essential protection and stability during grit blasting operations.

Figure 19 and 20 illustrates the role of the joint in the robot's swing arm. This joint serves a function in allowing for adjustments to be made to one of the grit blasting parameters, which is the distance between the nozzle and the surface. Moreover, the illustration in Figure 19 and 20 provides an overall picture of the robot's design and functionality. It gives a clear understanding of how the different components of the robot work together to achieve the desired task of surface preparation in tank maintenance.

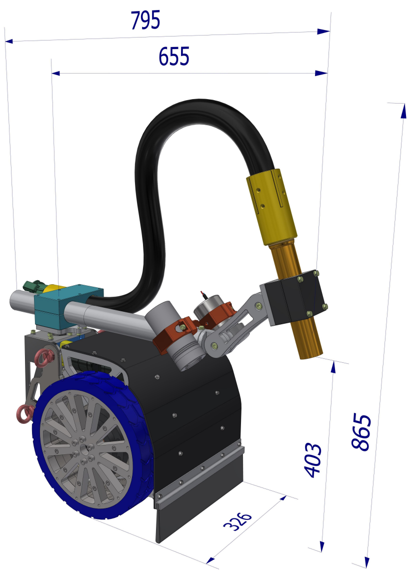

Figure 19: Grit Blast Nozzle at Maximum Distance(mm) *(Remotion)*

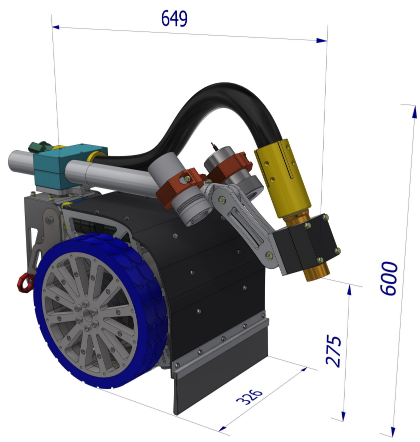

Figure 20: Grit Blast Nozzle at Minimum Distance(mm) *(Remotion)*

5 Discussion

The thesis covers the identification of constraints through literature study and investigation of regulations, but it does not investigate customer-specific criteria for requiring the robot. However, it considers the existing design of Pluto and ensures that it satisfies the constraints and added equipment.

A pull test was conducted on an existing N52 grade Neodymium magnet, but it did not include the specific array for the Halbach array or the possibility of demagnetizing through time. The design of the grit blast equipment was created to fit Pluto, but its functionality has not yet been tested, and the compilation was done with Inventor, which may not necessarily indicate good functionality. The testing of grit blast nozzle speed was done to get a better understanding of nozzle speed, but it did not feature the exact grit blasting system. The development of the robot was based on ensuring that the robot with grit blast equipment satisfies constraints discussed in the earlier chapter, but some relevant information fell out of the scope of the thesis, such as Halbach array calculations, dust and debris protection of bearing and moving parts, calculations of bearing, calculations of the frame, and yield strength of force-carrying structures. Therefore, it may not be feasible to investigate the coherence of the magnetic robot for surface preparation inside tanks, but the robot is built for it and needs operation time to verify its effectiveness.

5.1 Implication for Design

The safety feature of the Magnetic robot to shut down if tank entry is not available due to safety reasons is a critical aspect to consider when operating in potentially hazardous environments. The fail-safe relay's ability to stop the robot's movement ensures that any risk of danger or injury to personnel and equipment is minimized. This safety measure is particularly important when the robot is used for surface preparation, as it can perform tasks that are difficult and dangerous for humans to do.

The use of the NEK420 standard for building the robot and designing the topside control cabinet in an ATEX-safe manner is a crucial aspect of ensuring the safety of the robot's operation. The NEK420 standard is specifically designed for electrical installations in potentially explosive gas atmospheres, and meeting these requirements is essential for safe operation in such environments. In addition, designing the topside control cabinet in an ATEX-safe manner ensures that it is safe to use in conjunction with the robot, as it is responsible for controlling and communicating with it. Categorizing the robot according to these standards may simplify the assessment process and increase the approval rate among responsible parties. This, in turn, could make the robot more suitable for a wider range of jobs, including those in potentially hazardous environments.

The Working Environment Act sets a limit of 25 kg for what a single worker can lift and carry. The robot weighing 30 kg does not meet this requirement, but the detachable swing arm weighing 9.7 kg makes it possible to comply with the regulation by carrying them separately at 9.7 kg and 20.3 kg. This not only ensures compliance with the Act but also makes the robot more user-friendly and easier to transport for a single worker. By making the swing arm detachable, the robot can be easily disassembled and moved around, which is particularly useful when the robot needs to be transported to a different location or orientation. It also reduces the risk of injury to the worker as they are not required to lift and carry the entire weight of the robot, making it safer to handle.

The test results indicate that the robot can provide a strong attachment force of 4850 N when placed at a minimum distance of 4 mm from the metal surface. This high attachment force indicates that the robot is capable of performing tasks that require a strong grip, such as holding onto surfaces during surface preparation. However, when the magnet is placed at a maximum distance of 10 mm, it can provide a lower attachment force of 2110 N. While this may be suitable for tasks that require the robot to move over uneven surfaces, it may not be enough for tasks that require a stronger attachment force, such as when working on high tanks where there will be additional weight due to grit blast hoses and umbilicals hanging from the robot.

The design of the grit blast equipment and frame was aimed at seamlessly integrating with Pluto's core functionality. While relying solely on the visual representation of the Computer Aided Design(CAD) software, such as Inventor, can pose a challenge in assessing its effectiveness. The design process took several steps to ensure that the design meets the requirements. An additional frame was created to accommodate Pluto, which includes a rubber shield built to protect the system from grit, dust, and debris during the blasting process. Furthermore, the swing arm involves a simple design consisting of a single moving component that reduces the possibilities of wear and tear due to grit, dust, and debris. The rubber shield and swing arm design are integral to ensuring the longevity and reliability of the system during the grit blasting process.

The swing arm of the grit blasting equipment features an adjustable joint that allows for customization of the nozzle angle and offset distance between the nozzle and the surface being blasted. The offset distance can be set anywhere between 275 mm to 403 mm, providing a range of options for optimizing the blasting process for this specific equipment. Additionally, there is the option to mount the nozzle in different ways on the clamp or use a different nozzle altogether, further increasing the range of adjustments for the offset distance.

Conducting a test to determine the nozzle speed is a critical aspect of optimizing the efficiency of the grit blasting process. This helps in establishing a baseline for the required speed and calculating the necessary ratio, allowing for the selection of an electric motor capable of providing a consistent torque through RPM changes. This ensures that the robot maintains a steady speed and achieves the desired surface profile, leading to an efficient operation with reduced time requirements. In essence, optimizing the grit blasting process offers the potential for increased operational efficiency and shorter completion times.

5.2 Limitations for Design and Further Improvements

Regarding ATEX certification, it may be possible to make the robot ATEX certified even though grit blasting is associated with the possibility of static electricity and sparks. Ensuring the robot's safety in potentially explosive environments is important, and ATEX certification would help achieve this.

In addition, retrofitting a camera to the robot would be beneficial, as it would provide a stable image to the pilot, improving the precision and accuracy of the grit blasting process. Overall, implementing these suggestions would enhance the robot's performance and safety and should be considered in future development.

During grit blasting, grit may accumulate on the surface being blasted. This can result in an increased distance between the rubber tires and the surface, which weakens the magnetic attachment force. Therefore, further improvements in dust, debris, and grit protection may be necessary, not only for the magnetic system but also for the bearings, structure, and other components of the robot.

Assuming that the magnet's efficiency is compromised in real-life conditions due to various factors, such as the weight of the hose and umbilical, which can prevent the magnet from being pulled perpendicular to the robot, and the robot's three-point balance, it becomes challenging to determine a safe factor for the robot's work height. To ensure the robot's safe operation, it is essential to test the correct working height and calculate a safe factor for further development. This will ensure that the robot can function efficiently and safely in real-world conditions.

Replacing the magnet can be a useful step in improving the attachment force of the robot during surface preparation. With a stronger magnet, the robot can better adhere to metal surfaces, preventing accidental detachment and ensuring greater safety for the operator and equipment. This also enables the robot to work on a wider range of tanks with varying thickness and surface conditions, as a stronger magnet can maintain a secure attachment force even on rough and uneven surfaces.

6 Conclusion

The implementation of robots for surface preparation offers several notable advantages, such as the ability to perform tasks in hazardous environments without risking human safety. Moreover, the use of robots reduces the need for labor teams, thereby reducing labor costs and increasing efficiency. The robot design complies with relevant laws and regulations, ensuring that the robot can safely operate in various industries, including refineries, shipping, and offshore. Additionally, the robot is adjustable to suit specific parameters for grit blasting, such as nozzle distance, angle, and blasting time. The results of this thesis provide a valuable understanding of the benefits of using robots in surface preparation, and serve as a foundation for further research and development in the industry. In conclusion, the implementation of robots for surface preparation has a potential to transform the industry by improve workplace safety and efficiency.

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