RAM
ROBOTICS
AND
MECHATRONICS

Design of a Wall Latching Device

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BSc Assignment

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Chapter 1

Introduction

1.1 Background

The ship building business is a competitive one. It is vital to have an advantage over the competition to prevent the business from going broke. Standardization and automation are key to this strategy. On the other hand is manual labor still present in abundance. One of the human tasks is the inspection of ballast water tanks. These tanks keep the ship balanced while at sea. It is difficult and dangerous for a human to maneuver through the countless manholes as can be seen in figure 1.1. These manholes are also a difficulty for automatic

Figure 1.1: Interior of a typical ballast water tank.

inspection and up to now, automation of the maintenance of ballast water tanks has been unsuccessful. Currently, inspection of ballast tanks is done while the ship is in dry dock. This is an expensive operation. One of the requirements of RoboShip is therefore inspection at open sea. The RoboShip project, which is a collaboration of multiple research groups and companies, aims at the automation of the inspection and maintenance of ballast water tanks using robotics [1]. The proposed solution is a monorail through the ballast water tanks on which a multi sensor robotics system drives.

1.2 The RoboShip project

One of the main components of RoboShip is a robotics arm which is used for handling sensors and maintenance tools. The handling of tools is complicated by the movements of a ship at sea. Waves cause the ship to pitch and roll as well as moving up and down. These motions are amplified due to the length of the robotics arm and compliance in the monorail. This makes it hard to keep tools at specific locations on the ballast water tank wall. The RaM research group at the University of Twente solves the handling problem by making use of a dual staged manipulator in combination with a device which locks on the ships steel walls. The first stage of the manipulator will be used to place the stable base. This base is locked on the steel wall and a smaller secondary stage is used for the precise handling of tools. An impression of the idea can be seen in figure 1.2

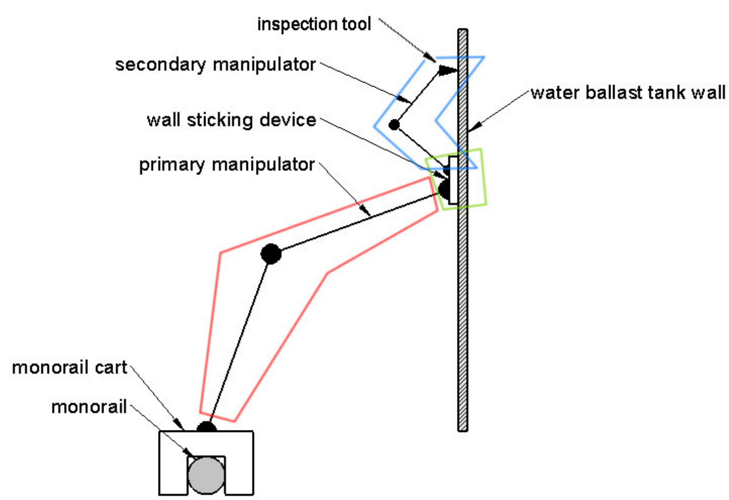

Figure 1.2: impression of dual stage manipulator which locks onto a ballast water tank wall

At the moment, an off-the-shelf electromagnet is used for locking onto the ballast tank. However, due to a thick paint coating and the design of the electromagnet, this is not a proper solution.

1.3 Research goal

The aim of this research project is to "design, construct and test devices capable of locking onto a ballast water tank's surface". The devices must provide a stable base for the secondary manipulator and balance out the forces that occur due to movement of the ship.

1.4 Report outline

The outline of the report is as follow. In chapter 2, requirements are established to provide less abstract goals. Then, functions which have to be performed are stated and literature research is used to find promising methods for adhering to the surface of ballast water tanks. A comparison table is made and the two most promising methods are investigated further. Chapter 3 focuses on the two methods based on permanent magnets and vacuum. These are designed, constructed and tested. A third device, also based on vacuum, is redesigned after the testing of the first vacuum device. Chapter 4 presents the results of the experiments and discusses the meaning of these results. Chapter 5 states the conclusions which can be drawn from this research and ends with a recommendation on the designed devices.

Chapter 2

System design of the wall anchor

In this chapter, the overall design of the wall anchor will be investigated. The requirements and functions of the system are determined and physical principles for adhesion will be investigated. The most promising methods are selected for further research using table 2.2. At the end of this chapter, initial designs are presented.

2.1 Requirements

After analyzing the problem, the following requirements are established. The base for the secondary manipulator should be locked stably to the ballast tank's wall. Preventing movement to occur in all of the 6 degrees of freedom. Furthermore, the way of "sticking" should not damage the ballast tank while it is in proper condition. So forcing a pin in the wall for support is not permissible. At last, the "anchor" has to be placed by the primary manipulator in tight spots and small openings causing limitations on the size and weight of the system. The primary manipulator must be able to lift and maneuver the equipment in place. Furthermore, the newly designed part has to be tested by the manipulator in the lab, which does have limited lifting power. Quantitative requirements are listed in table 2.1 on page 8. They are obtained from the technical documentation of RoboShip project and calculations based on the data [2]. The holding weight is the sum of device weight and the additional weight of the robotic system. The maximum acceleration is the sum of gravitational acceleration and maximum acceleration of the ship. This maximum could physically not occur. However, it could come close and some margin is therefore in place.

Table 2.1: Requirements for wall anchor

Parameter	**Value**	**Unit**
width and length of system	< 0.1	m
height of system	< 0.1	m
weight of device	< 0.3	Kg
additional weight (manipulator, tools)	< 1.0	Kg
holding weight	> 1.3	Kg
acceleration of ship in any direction	< 3.4	m/s^2
acceleration to resist	$< 13,2$	m/s^2

2.2 Functional architecture

In this section, the functional layout for proper working of the wall anchor will be established. These functions are obvious, but critical.

First, the part must fit to the primary arm. This means an interface between part and primary manipulator. Second, the part must provide an attachment point for the second manipulator. At last, the anchor must resist the exerted forces and moments due to acceleration of the wall and manipulators. The last function is split further in two separate functions. Namely, balancing forces in the directions parallel and perpendicular to the tank's wall. To show the relevant forces more clearly, illustration 2.1 is made. Inhere F_f is the frictional force, F_n the normal force F_h the holding force and F_g the gravitational force.

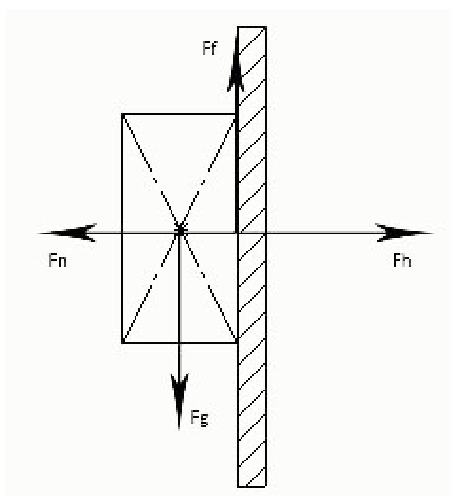

Figure 2.1: illustration of relevant forces for wall anchor

2.3 Methods of adhesion

The last two functions of the functional layout are expected to give the most difficulties. The forces parallel to the ballast water tank's wall will be constrained using simple static friction. A rubber pad ensures that the part does not slip against the wall. For now, a conservative estimate of 0.2 is used for the coefficient of friction. Inside ballast water tanks, the walls are slippery due to the water and algae. In the lab we only use a dry steel plate which is much less slippery. Measurement of friction pad and dry plate give a μ of 0.8. A normal force is needed for the friction to occur. This normal force is obtained through adhesion with the wall. A small selection of adhesion methods is made, based on physical principles and results of other research projects.

(Electro)magnets Are used frequently in wall climbing robots [3]. Magnets have the highest force to weight ratio compared to other sticking methods. Once it sticks, it will not come lose easily which makes it a highly reliable method of adhesion. The problem is that electromagnets need a bulky power supply and that permanent magnets cannot be shut off by them self. But, there are systems which make use of clever leverage to overcome the first millimeters which cause the most trouble in releasing magnets from a surface.

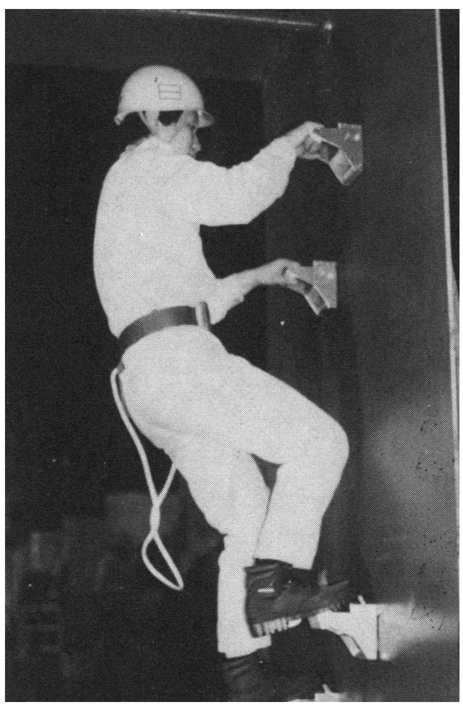

Figure 2.2: A person climbing a wall, using permanent magnets in combination with a magnet release system.[3]

Vacuum can be used to create a differential pressure [4]. This pressure difference causes a normal force, which presses a vacuum cup to a ship's wall. Vacuum also has a large force to weight ratio. It is also reliable once an airtight seal can be made. However this is also the problem with vacuum. It is hard to make a proper seal when the surface is not perfectly flat. Vacuum also needs a heavy pump. This add weight to the system. However, it is possible to place the pump on the main carriage of the robot.

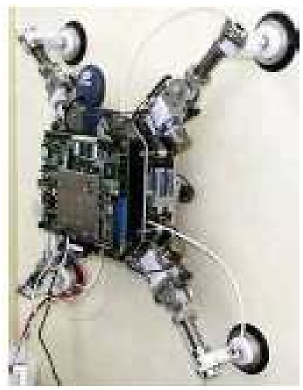

Figure 2.3: Picture of a wall walking robot using suction cups as feet [4].

Dry adhesion is a method based on animals like geckos. It works on the basis of van-der-waals forces. Huge amounts of micrometer sized hair like structures stick to all types of material due to van-der-waal bonding [6]. This method is not nearly as strong compared to vacuum and magnets. Larger surface areas are needed to achieve the same forces. The gecko feet devices are useful for instance in space, where ferromagnetic metal structures are to heavy to send to space and a negative pressure difference cannot be created due to the vacuum which is already present.

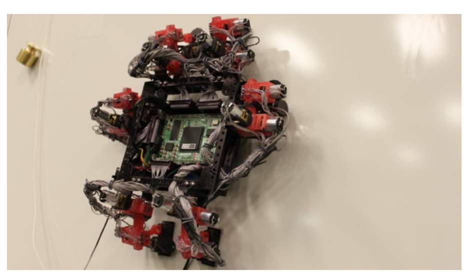

Figure 2.4: Picture of wall climbing robot using gecko like feet [6].

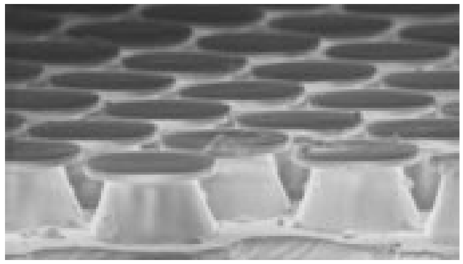

Figure 2.5: Closeup of dry adhesion pads (electron microscope)[6].

Electrostatic adhesion is based on the principle that oppositely charged particles attract each other [5]. Conductive material is charged with high voltage. The charge on the material, causes the wall to act like a dielectric. Opposite charges in the wall drift a little more to the charged plate than equally charged particles,which drift away from the charged conductor plate. The distance in between the oppositely charged particles in the wall and conductive plate, causes a net force. This net force attracts the conductive plate to the wall. Electrostatic adhesion is weak. large surface areas are the result for the forces needed in this project. This makes electrostatic plates difficult to maneuver through the ballast water tank. But electrostatic adhesion does have many benefits. It sticks to a wide variety of surfaces. It is lightweight and does not use allot of power.

Figure 2.6: Picture of electrostatic sticking device, adhering to a wall with weights attached to it [**?**]

2.4 Selecting the best method of adhesion

Table 2.2, stating positive and negative points, is made and the decision for the best methods of adhesion for our application is based on this table.

Table 2.2: Pros and cons of adhesion methods

	electro magnet	permanent magnet	vacuum	dry adhesion	electrostatic
attractive force vs weight	+	+	++	0	0
size	+	+	+	0	-
additional equipment	0	+	-	+	+
power consumption	-	++	-	++	+
ease of design	0	-	++	-	0
total plusses	1	4	3	2	1

The table is made by investigating the literature used in section 2.3. The method of dry adhesion seems not to be a practical solution. Specially designed μm size structures are needed. Moreover, dry adhesion is not as strong as compared to magnetism or vacuum. Although the benefits, the use of electrostatic adhesion is not suitable due to large surface area needed for loads of this size. However, the two remaining options of magnetism and vacuum are promising. Both of them are used often in wall climbing robots. To choose the best option, simple calculations based on the RoboShip's requirements are done. It turns out a force of 86 N [1] perpendicular to the tank's wall is needed, when a low estimated of the coefficient of friction is used. For a dry wall, a normal force of 22 N is sufficient. It turns out there are no significant performance differences in both methods at first sight. Both electro magnet and vacuum need power for them to work. This is not the case with permanent magnets. But the problem with permanent magnets is their inability to "turn off". However, there is a solution.

2.4.1 Internally balanced permanent magnet

It is possible to balance out the attractive force of a magnet by the use of springs fixed on a mechanical base structure as proposed by Shigeo Hirose et al. [3] The idea is illustrated in figure 2.7. The springs cancel the attractive force of the magnet internally, which causes the support structure to be pushed against the wall. The magnet is so called internally balanced. In theory no force is needed to control the distance from magnet to wall. This system allows for a small lightweight and in theory easy to control adhesion device, which does not consume a lot of power. This makes the IBM a potential solution. However, the balancing of the magnet and spring can give difficulties.

[1] force is mass times acceleration. Acceleration is the sum of the movement of the ship and the gravitational acceleration. Mass is the total mass of device and load. This force is divided by the frictional coefficient, to obtain the total needed adhesive force.

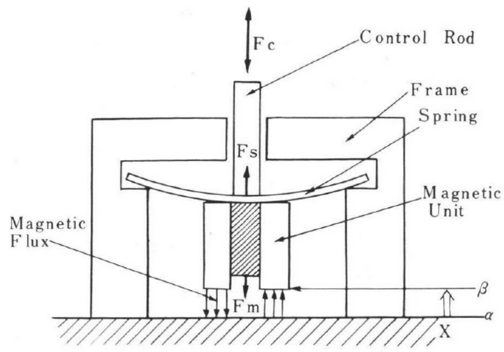

Figure 2.7: schematic illustration of internally balanced magnet.[3]

2.4.2 Vacuum

Another solution which is widely used is the vacuum cup [4]. A negative pressure difference is created inside the vacuum cup. This will cause a force on the outside pushing the cup to the wall. Unlike the magnet, a vacuum cup is only dependent on pressure and not on the wall's material. So this solution will also work on non ferromagnetic materials and is independent of the wall's paint coating. The pressure difference can be established by a vacuum pump. The pump can be placed on the main body of RoboShip, lowering the total weight of the robotic arm.

Chapter 3

Realization of the wall anchor

In this chapter, the two promising methods found in the last chapter, will be realized. Experiments are done to obtain data about the relation between magnetic force versus distance and the friction between rubber pad and ballast water tank wall. This data is used to design two prototypes. One is an internally balanced magnet. The other one is a vacuum cup with a stiff seal. A second vacuum cup is designed at the end. The new vacuum cup design tries to solve the leaking of the sealing in the first vacuum cup prototype.

3.1 Static friction pad experiment

The coefficient of friction between rubber pad and ship wall is not known. Therefore, a simple experiment is performed to get an estimate of this friction which is needed to determine the required holding force for the sticking device. The friction coefficient is used for calculating the adhesion force needed for the system to stay in place. A coefficient of about 0.8 is found for a dry coated steel plate, which acts as a stand in for a ballast water tank wall. This is simply done using some weights and a spring scale. For a moist wall, a low coefficient of 0.2 is estimated. This is a conservative estimate to account for algae and water which are present in ballast water tanks.

3.2 Experimental force versus distance curve

The idea is to balance out the force exerted by a permanent magnet with springs. Therefore, the relations of force versus distance of both springs and magnets have to be known. For leaf springs a linear model depending on the spring material and dimensions is used [8]. The calculation of the spring constants can be found in appendix B (page 29). For magnets, the relation of force versus distance is more complicated due to non-linearity. The force drops off rapidly over distance from the wall. Normally, a mathematical model should be made to get an idea of the magnet's force versus displacement curve and obtain insight in the required magnet dimensions. However, there are arguments that approve skipping this step. At first, the permeability of the paint, covering the steel plate is unknown. This means that a mathematical model must still be validated by an experiment. Secondly, A magnet which is stronger than needed, does not influence performance in a negative way. At last, the magnet retailer supplies a force versus displacement curve on their page for most of their magnet products. This is not the most reliable source of information, but it will probably give a good enough estimate of the magnet's strength. In this way we know which magnets to buy, based on the calculated normal force we need for the adhesion device. This calculation is based on the experimental result of static friction and the weight requirements established in chapter 2.

3.3 Pressure and effective area

The main parameter in the design of a suction cup is the holding force. The holding force is the product of differential pressure and effective vacuum area. Effective area is the area inside the suction cup directly in contact with the wall. Another aspect to take in consideration is sealing off the inside pressure from the outside pressure. Small leaks in the vacuum cup can cause a huge drop of vacuum pressure due to the limitations of the pump.

3.4 Internally Balanced Magnet (IBM) design

In this section, the design of the IBM will be elaborated. The choice is made to design for the smallest magnet. This magnet should still fulfill the force requirements for a dry steel wall while it should save in the amount of material needed for building the device. Stronger magnets require stronger springs, which are larger and heavier. The decision is made to only test the devices on dry steel walls, because this will be the only test environment for RoboShip the coming period. The magnet data is gathered and therefore the material and dimensions of the springs can be determined. Spring steel is chooses as spring material due to its high yield strength. Allowing the material to highly deform without plastically deforming. The desired spring constants are determined with the use of the experimental magnet result and the data supplied by the magnet retailer. The non-linear behavior of the magnet is mimicked by a stack of linear springs. This is achieved by using different spring constants and varying the point at which each spring is engaged. The constants are determined by drawing tangent lines in the graph of the magnet's force versus distance as shown in figure 3.1.

Spring constants are determined from the tangent lines and spring-steel is dimensioned accordingly (see B on page 29). A base structure is designed to hold the springs and magnet in place. This is done using CAD program Solid-

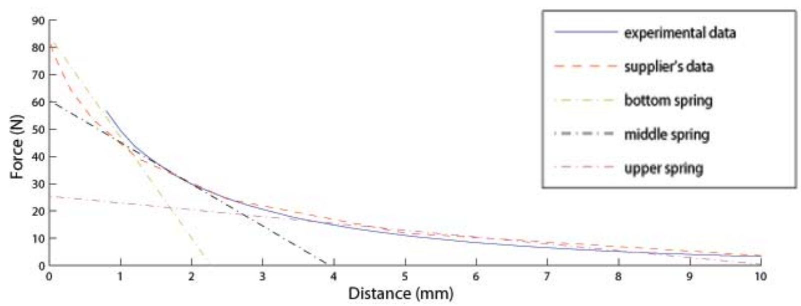

Figure 3.1: Force versus distance relation of 25 mm diameter by 5 mm hight neodymium magnet. Tangent lines represent the force versus distance relation of leaf springs. (magnet from: supermagnete.nl artikel-ID: S-25-05-N)

Works. A picture of the design is shown in figure 3.2 Two main parts can be distinguished. One is the main body colored in green. The other is the assembly (cyan rods with magenta bars), which presses on the springs (gray) and holds the magnet (blue). There are also two adjustment mechanisms installed. One changes the effective lengths of the springs by adjusting the positions of the little red blocks. By turning screws on the side, the little rim on the red block is moved. Due to the change in effective length, the spring constant is altered (appendix B on page 29). The other mechanism changes the point of engagement of the springs by moving the magenta pressure plates up and down with the nuts.

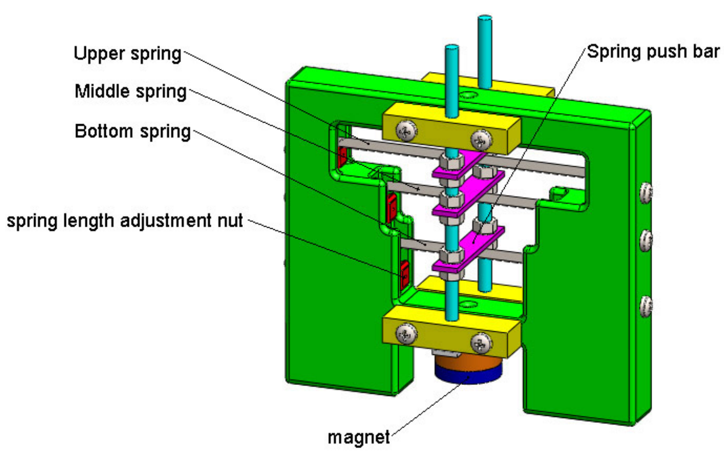

Figure 3.2: CAD model of IBM magnet drawn in SolidWorks

3.5 Vacuum cup design

The suction force of the vacuum cup is determined by multiplying pressure and area. The needed force is known from the requirements and the pressure is set by the limitations of the vacuum pump. This leaves effective area as the only free parameter. A circular cup with a hyperbolic cosine [7] dome is used due to it's strength. On top of this dome a block of material is printed to mount manipulators and make place for a hose adapter, which can be used to connect the vacuum pump. The part is drawn in CAD and 3D printed. The little holes in the picture do not go through. These dots are pilot holes which can be printed at the exact spot and make drilling easy. In this way hose adapters and manipulators are mounted with little effort.

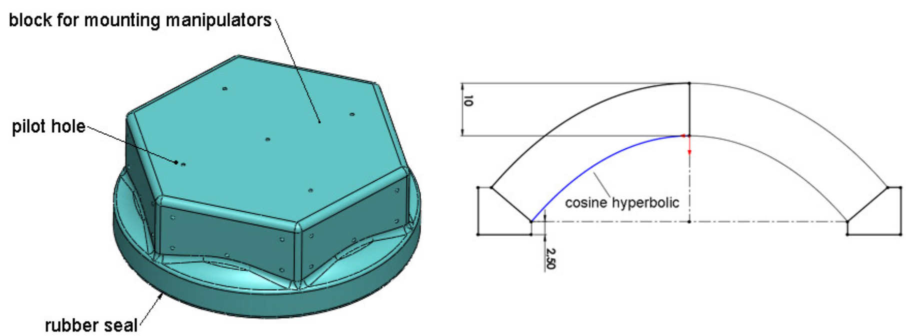

Figure 3.3: Model of vacuum cup. On the left: The complete vacuum device. On the right: cross section of the internal hyperbolic shape.
Function: $y(x) = 15e^{x/30} + 15e^{-x/30}$ with x from 0 to 30

3.6 Second vacuum cup prototype

While testing both IBM and vacuum cup, it turned out that both devices where functioning. However, there were problems. The IBM had tuning problems and the vacuum cup had a huge drop in pressure when the seal was not airtight enough. The idea arose to combine both the positive sides of both devices. The vacuum cup is reliable and strong as long as the seal is airtight. A solution would be to use a flexible seal. But, this would violate our main requirement of a stable and stiff base. The IBM solves this problem with springs. Its holding force is directed by springs through the main body. Pushing the complete structure to the wall. In the new design a standard suction cup is bought. The flexibility of the cup gives a proper seal, while the base around the suction cup gives the vacuum device the stiffness needed for a stable base. The compliance in the rubber of the suction cup which used to push the base on the ballast water tanks wall. A picture of the new design can be seen in figure 3.4.

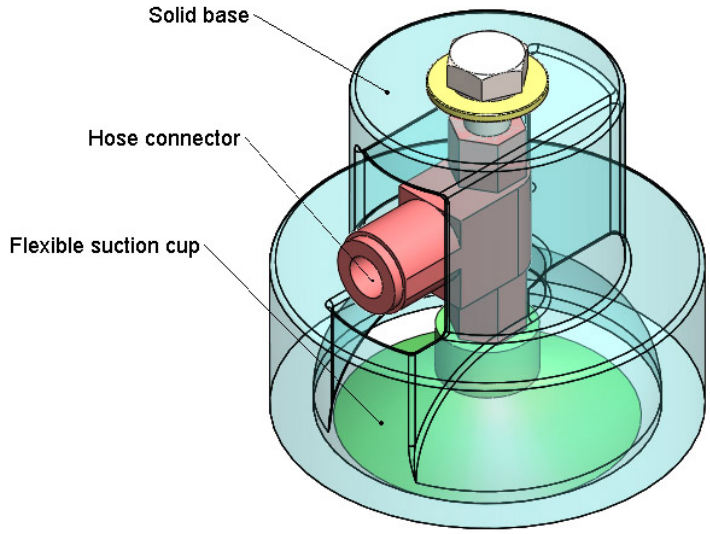

Figure 3.4: design of new vacuum cup. Suction cup is of type: ZPR50CN-08-B8. manufacturer: SMC

3.7 Testing of the adhesion devices for holding force

Experiments will be done, to see if the designs worked as expected. Tests will be done both to determine the maximum forces or weights both the IBM and vacuum cups can handle in parallel and perpendicular directions with respect to the ship's hull. Because of the fact that having a large ship in the lab is unpractical, a small 50x50 cm metal plate with coating will be used as a stand-in ballast water tank surface for the devices. The IBM or vacuum cup will be attached to the plate and a counterforce is exerted by hand. For the IBM, the counterforce will be measured by means of a spring scale. Holding forces, perpendicular to the wall, for the vacuum cups are going to be a bit more difficult to measure. The largest spring scale found, can only handle up to ten kilograms, so another measuring method will be used. The plate itself weights about 23.5 kg. The vacuum devices will be placed one at a time on the plate. The distance from the edge of the plate to the middle of the device is measured. Then the pump is turned on. A distance from the edge will be found, where the vacuum cup can barely lift up the edge of the steel plate. This distance will be recorded. Because only the edge is lifted up slightly, the holding force can be found using a leverage ratio. The holding force in the parallel direction is measured with the ten newton spring scale. However, it was not possible to get an accurate reading of the point where the vacuum devices came lose.

Chapter 4

Experiments and results

Experiments are performed to see if the prototypes fulfill the requirements established in chapter 2. Results of the tests can be found in this chapter. At the end of this chapter, the results will be discussed.

4.1 Results of the IBM device

The results of the tests on the internally balanced magnet are shown in table 4.1.

Table 4.1: results IBM measurements

Measurement	**Value**	**Unit**
Holding force + force due to weight IBM (perpendicular)	28	N
Holding force + force due to weight IBM (parallel)	26	N
force due to weight IBM	4	N
Control force (magnet down)	5.5	N
Control force (magnet up)	3.5	N

Subtracting the IBM's own weight from the holding force measurements, gives a absolute holding force of 24 N. The absolute control force could be calculated by solving a system of two equations.

$$\begin{aligned} 5.5 &= F_c + F_g \\ 3.5 &= F_c - F_g \end{aligned}$$

Adding up both equations gave the absolute control force (F_c): 4.5 N. Subtracting the bottom equation from the top one gave the magnitude of the gravitational force (F_g) acting on the magnet and spring assembly which is about 1 N. These results were obtained when the IBM was tuned for a specific location on the metal plate. Deviation could be observed when the IBM was placed at another location.

4.2 Discussion on IBM results

The results are obtained and some observations are worth noting. It was already expected for the IBM that the magnet force would drop tremendously over distance from the coated steel. This introduces more problems with the device than expected. Tuning the springs to balance out the magnet force is proven to be difficult. Proper tuning can only be done for a specific spot on the wall. This is due to the inevitable deviations in paint thickness and little dents in the steel. These deviations cause imbalance in the IBM, which has a large effect on the control force of the magnet assembly.

4.3 Results of the vacuum cups

The result of the vacuum cups are shown below. Vacuum cup V2 is the device with the commercial suction cup. The manometer on the vacuum pump stated a pressure of 11 kPa. The weight of the coated plate is 23.5 kg. This corresponds to a weight force of 235 N at 250 mm from the edge of the plate.

Table 4.2: Distance from edge of 500 mm plate at which vacuum devices could just lift the plate

Device	Distance from edge	Unit
Vacuum cup V1	100	mm
Vacuum cup V2	50	mm

The actual holding force F_h could be calculated from this measurement using leverage ratios.

$$V1 : F_h = \tfrac{250}{500-100} \times 235 = 147N$$

$$V2 : F_h = \tfrac{250}{500-50} \times 235 = 131N$$

The calculated holding force is not exact. It depends on the placement of the vacuum devices on the steel plate. However, the vacuum devices are tested in a way in which they will operate and so the measurements are accurate enough to determine if the vacuum devices fulfill the holding force requirement.

Table 4.3: holding force in parallel direction of suctions cup

Device	Holding force	Unit
Vacuum cup V1	>60	N
Vacuum cup V2	>60	N

When the pump was shut off, a quick drop in holding force was observed at the first vacuum prototype. The second vacuum cup version did not have this sudden drop. However, the second version vacuum cup was not stable when loaded in the perpendicular direction with respect to the plate surface.

4.4 Discussion on the vacuum devices

The first vacuum cup works fine only when the seal is airtight. A small leak caused by a piece of paper gives an extreme drop in pressure difference in the cup to almost zero, resulting in a negligible holding force. The second suction cup solves the leaking problem. However, the device gives stability problems when loaded in perpendicular direction with respect to the wall due to a stiffness by the rubber seal which is too low. Also the holding force is lower than expected with the areas and pressures used. A five centimeter diameter suction cup should give a holding force of about 17 kg with the pressure used during the experiments. The difference in theoretical and real holding forces can happen due to a lower effective surface area in the suction cups. Another reason could be a small leak in the system causing an airflow, which in combination with a long and small diameter tube, is giving a pressure difference between pump and suction cup. The precise reading of the holding force in parallel direction could not be obtained due to limitations of the spring scales. It is certain that the devices fulfill the requirement of holding more than 60 Newton.

Chapter 5

Conclusion and recommendation

Several interesting findings were done during testing and the results are discussed. This chapter answers the questions raised in the introduction. Furthermore, recommendations will be given on the prototypes.

5.1 Conclusion

All of the devices are light weight and have a small enough footprint to stick in the smallest spots of a ballast water tank's inner surface in short time. However, there are differences in the performances of the devices. The IBM has reliability issues. The device can only be tuned properly for one spot. When the device is moved over to a different spot with thicker or thinner paint and steel thicknesses, it is not ensured that the device will stick and release properly. Based on the requirements and literature study, permanent magnets are still the best theoretical solution. Problems are caused by the release mechanism.

The first vacuum device, the one with the stiff seal, has problems with sealing. A leak, for instance caused by a piece of paper stuck underneath, and the device will not hold on to the wall anymore. The vacuum cup does meet specification when properly sealed. Proper sealing is ensued when the vacuum device with commercial suction cup is used. However, stability is only ensured when the device is loaded parallel to the wall. Due to compliance in the rubber cup the stable base of the device can be pulled off the wall, failing the stability requirement established in chapter 2. The requirements of proper sealing and stable base for manipulator are contradicting. Compliance in the sealing is needed to properly block airflow. However, this compliance allows movement in the device with respect to the wall, failing the requirements of a stiff base.

5.2 Recommendation

The best solution for the ballast water tank would be the suction cup with stiff seal. This device does meet all the requirements established in chapter 2. When the device is loaded only in directions parallel to the wall's surface, the commercial suction device is recommended due to better sealing.

Further research could be done to find new ways of creating an airtight seal, without compromising stiffness in the attachment to an object. Is this a fundamental problem with vacuum? More research could also be performed on the release mechanisms of magnets. The research in this report focused on internally balanced magnet device. However, there are other mechanisms which could work. For instance a scissoring car jack layout which has a huge reduction ratio when almost fully extended.

Appendix A

Magnet force versus distance measurement

In this experiment, the relation between the pulling force of a magnet and the distance to a steel plate is measured, where the steel plate is coated and acts as a stand in for a water ballast tank surface. The measurement will be used, to dimension the springs for the internally balanced magnet system.

The magnet is attached to a spindle, which in turn is screwed into an aluminum square 20x20x2 mm tube profile at a distance of 1/3 of the length. The placement of the spindle, is needed due to the weight limitation of the weight scale used in the experiment. One end of the profile is rested on a fixed platform. The other end is rested on a piezo scale. This scale has a minimal indentation. Small rubber pads are placed at the resting points to allow for proper pressure points and to prevent the aluminum profile from moving. The setup can be seen in figure A.1.

At the beginning of the measurement, the spindle with magnet will be brought up to a distance of 20 mm from the steel plate. The scale will be set to zero. The M5 spindle is then turn by one quarter. This causes the magnet to be lowered by 0.2 mm due to the pitch of the spindle. The aluminum profile should be strong enough, so sagging of the beam is insignificant. The scale is read for weight measurement. This measurement is three times lower than the actual pulling weight at the magnet. Due to the constant gravitational acceleration, the weight can be converted to Newtons. After reading of the weight of the scale, the spindle is lowered again by a quarter turn until the magnet hits the plate. The distance between spindle and plate is known, because the starting height and pitch of the spindle are known.

The result of the measurement can be seen in figure A.2. There are two details in the measurement which need some attention. First the measuring distance does not go up to zero. The magnet hits the plate at the end of the measurement, so we could not go up to 0 mm. This is probably due to indentation of the piezo scale. Another detail is the much lower force of the experimental data. This is expected due to the relatively thick coating covering the steel plate. Other errors must also be taken into account. Like the accuracy of te scale and the exact placement of the spindle.

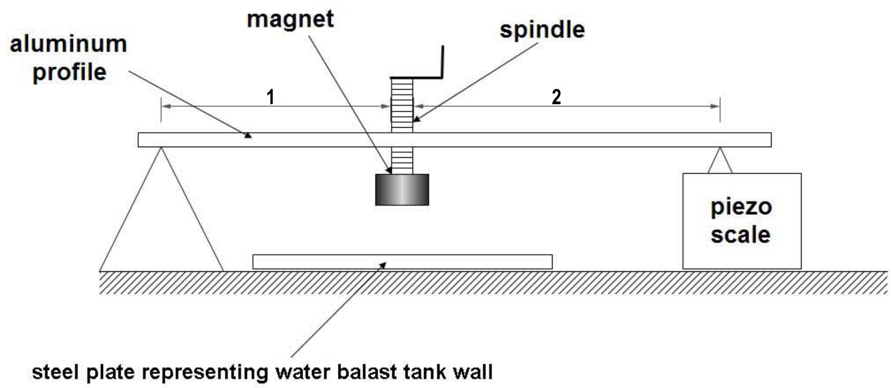

Figure A.1: Setup for measuring the relation of force versus distance to steel plate

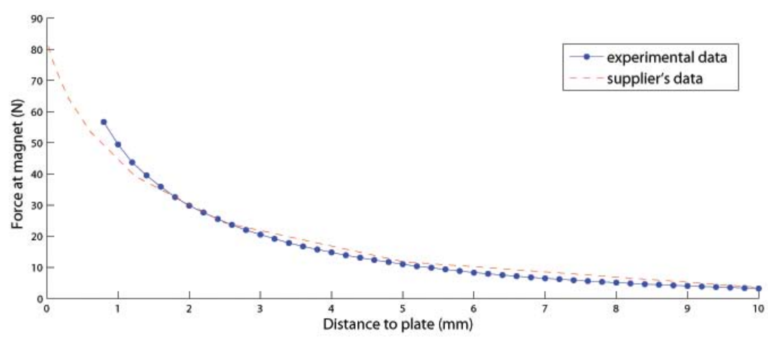

Figure A.2: Result of experiment. With 25 mm diameter and 5 mm height Neodymium magnet. Supplier is supermagnete.nl part-ID: S-25-05-N

Appendix B

Leaf spring dimensioning

The Euler-Bernoulli beam theory is used to determine the dimensions of the leaf springs needed for the internally balanced magnet. The springs in the design can be modeled by a "simply supported beam with central load". The equation for this type of beam is well known and can be found in most material mechanics books.[8] The equation is shown below.

$$F = k * y \tag{B.1}$$

$$F = \frac{48EI}{L^3} * y \tag{B.2}$$

$$where : I = \frac{1}{12} bh^3 \tag{B.3}$$

Where k is the spring constant needed in the design of the IBM. Force is represented by F and the beam deflection by y. Furthermore we have Young's modulus E and the area moment of inertia given by I, which consists of width of the beam b and thickness h. From the equations above, the dimensions of the leaf springs can be determined by:

$$k = \frac{4Ebh^3}{L^3} \tag{B.4}$$

In the IBM design, the width and thickness of the leaf springs are fixed. The length of the springs can vary, which as a consequence varies the spring constant. A length difference of $\pm 1mm$ can be achieved by turning screws on the side of the IBM, as can be seen in figure 3.2. on page 17.

Two tables can be found on the next page. Table B.1 gives dimensions of the springs and its theoretical spring constant. Table B.2 states the theoretical spring constants which can be achieved by turning screws on the sides of the IBM assembly.

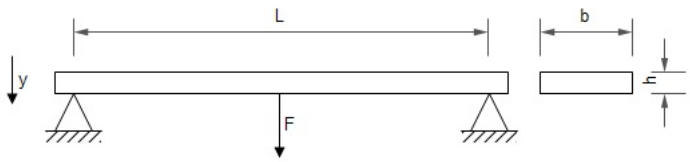

Figure B.1: Bending beam and its parameters

Table B.1: spring constants with their nominal length

spring width b = 10 mm	spring thickness h = 0.7 mm	
Spring	**Nominal spring constant**	**Nominal length L**
upper	2,8 N/mm	96 mm
middle	13,2 N/mm	57 mm
bottom	22,8 N/mm	48 mm

Table B.2: theoretical minimal and maximal spring constants due to tuning of the IBM device. Tuning is done by turning screws on the side

Spring	**Minimal spring constant**	**Maximum spring constant**
upper	2,6 N/mm	3,0 Nmm
middle	12,0 N/mm	14,8 Nmm
bottom	19,8 N/mm	27,1 Nmm

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