RAM ROBOTICS AND MECHATRONICS

Establishing Stable Wall-contact with Multirotor Platforms

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BSc Report

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Abstract

In this report the design, construction and testing of a mechanism for establishing stable wall contact with UAV's is described. First a overview of the applications and existing solutions is given. From the applications a set of specifications is derived which is used in the design of the prototype. The prototype consists of a carbon fiber tube with two lower supports and a suction cup. This prototype is tested and the results lead to a second design iteration. The final design uses a spring mechanism to absorb the impacts, a servo paired with a wire to detach the suction cup and a special approach controller to ensure a stable impact from a distance. The system is again tested and results of this show that it is capable of impacting, attaching and detaching from a surface multiple times with a success rate of 55%.

Contents

Chapter 1

Introduction

This chapter gives a short introduction to the assignment. First some context of the assignment is discussed followed by the project description. Next the background research and literature are given and finally an outline of the report is stated.

1.1 Context

AEROWORKS

AEROWORKS is an European research project performed at multiple Universities and companies. It aims at creating a new generation of ARW's capable of autonomously performing maintenance and inspection tasks. The main focus for these tasks will be related to infrastructure and industrial structures (including windturbines). In order to achieve this new technologies are being developed under AEROWORKS. This includes the research into cooperation between multiple ARW's, user friendliness and easy implementation into the existing infrastructure maintenance are also important aspects of the project. [1]

Aerial Robotic Workers

An Aerial Robotic worker (ARW) is a robot capable of two things: it is capable of performing a task using a manipulator (such as a robotic arm), and it is also capable of flight. In short an ARW is a flying robot with a mechanism to physically interact with the outside world. The variety of tasks an ARW could perform is nearly limitless due to the versatility of manipulators and the capability to reach locations which humans cannot easily access. Currently aerial robots (such as quadrotors) are already being used to perform limited tasks such as inspection and surveillance of structures and other objects. However, with regard to actually performing tasks which include physical contact and manipulation limited practical progress has been made. [1] [2]

Applications

The commercial availability of drones has generated more interest in ARW's then ever before. A reason for this is the fact that there are many applications for ARW's [1]. One of these applications is inspection and repair tasks. Currently many types of installations are difficult to access and expensive to inspect and repair. A good example of one of these installations is a windturbine. Drones are already being used for inspecting windturbines for damages and indications of failure. However, sometimes more action is required. This leads to the desire for ARW's to physically interact with their environment. The problem with interaction is that currently ARW's are not stable enough to perform these tasks. This problem of stability is addressed later in the report.

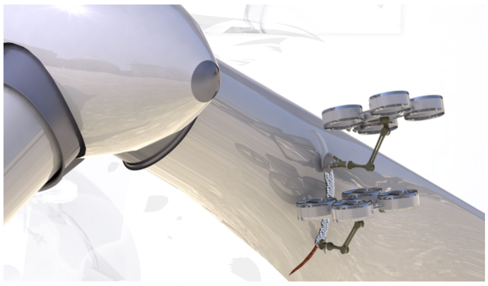

Figure 1.1: **An example of a task performed by an ARW [1]**

1.2 Scope of the assignment

Exact definition

The exact definition for this bachelor assignment as given by H. W. Wopereis, MSc is as follows:

"The goal of this project is to design a mechanism to establish stable wall-contact with an ARW to enable more precise manipulation tasks with the ARW's manipulator. To achieve this, first different approaches have to be explored. Based on the results of this study, a mechanism has to be designed and integrated with an available ARW. The mechanism has to be experimentally evaluated to demonstrate it's effectiveness. One of the main challenges in this assignment is the limited payload of the multirotor, which restricts the weight of the mechanism. The mechanism should restrict the manipulator's freedom of movement as least as possible."

1.3 Literature research

This chapter depicts some of the research done at the start of the assignment. It features a small description about the current problems with stable wall contact and a wide range of robots already capable of connecting with a surface in some way. A short overview is given here. Some examples given here are for perching or non UAV applications but were added due to their novel approach or special relevance to the assignment.

Stable wall contact

Perching is a viable option for getting ARW's in stable positions. However perching usually enables the ARW to simply attach itself to a surface in order to save energy. For the interest of ARW's this is not always the only quality desired. Currently one of the main problems for ARW's is instability during manipulation.

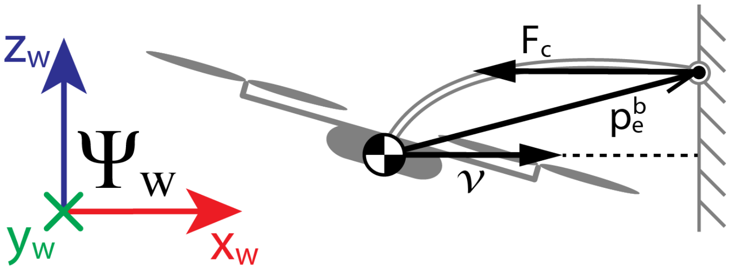

Figure 1.2: **A Schematic overview of the forces acting on a drone with a manipulator while touching a wall. F_c being the reaction force of the wall on the end-effector and P_e^b being the position of the end-effector [3]**

This instability is due to numerous factors including the fact that usually the end-effector is not aligned with the center of gravity. This will result in a moment on the ARW which can cause stability problems. Furthermore when performing tasks that require a certain amount of pressure on the end-effector of the manipulator, a certain reaction force is generated. This leads to the drone drifting away from the wall. These problems limit the effectiveness of ARW's with manipulators greatly. In order to solve this problem a way of making stable wall contact is needed. This approach is somewhat different from perching since the ARW would only use this stable wall contact to compensate for instability generated by use of the manipulator. [3]

Vertigo

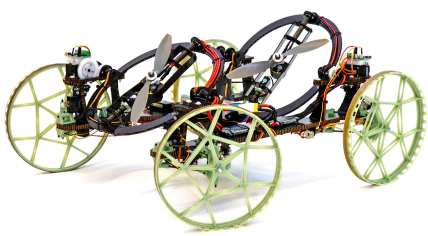

Figure 1.3: **vertigo [4]**

Vertigo is a wall climbing robot using two tiltable propellers enabling it to climb walls and transition from ground to wall with ease. It uses four wheels to generate a stable wall contact in conjunction with the two rotors. The robot was a joint project by Disney research and ETH (Eidgenössische Technische Hochschule). It aims to extend the ability of robots to travel in outdoor and urban environments. Vertigo has an interesting approach as to attaching to a wall. The connection is made stable simply by applying a pressure to the wheels. This generates enough drag to counter the downward force, although the force is also partly countered by the propellers. The Vertigo shows that simply pushing the wall could be a viable way of establishing stable-wall contact for a ARW. [4]

Waalbot

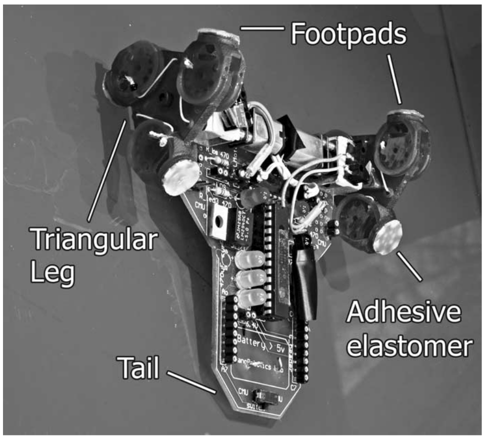

Figure 1.4: **Waalbot** [5]

Another method of establishing contact is demonstrated by Waalbot. This small robot uses two attachers with dry elastomer adhesive pads on them. These pads are able to stick to the wall after a preload pressure is applied to them (around 30 kPa). After applying this pressure the pads can generate an adhesion pressure of around 45 kPa. When walking it uses a moment about the wheel to detach the previous pad. The main scientific principle for this adhesion is the van der Waals force generated by the large surface of the elastomer. Originally Waalbot was intended to use gecko-like synthetic fibrillar adhesives, but since these are not yet commercially available the polymer adhesive Vytaflex 10 was used.[5]

Magnetic attaching

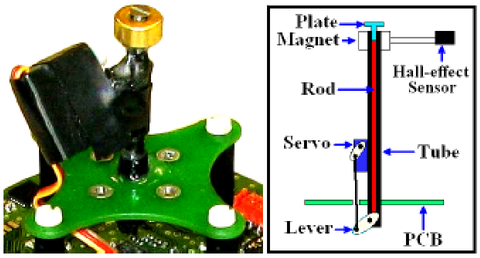

Figure 1.5: **Attacher/Detacher mechanism using a magnet** [6]

Another way of making a connection with a surface is demonstrated by the Swarmanoid project. This project aims to dock UAV's for use in larger groups of robots. One of their attacher mechanisms uses a permanent magnet in order to provide the normal force required to keep the drone attached to the roof. To make sure that a good connection is made, a Hall-effect sensor is placed next to the magnet. This sensor can be used in conjunction with the magnet to search for suitable attachment positions when they are spread over the surface. When a connection is made the mechanism uses a rod connected to a servo to detach. The thin layer of air between the metal of the surface and the magnet will be enough to reduce the force in order for the UAV to fly away. [6]

Pin connector

Another interesting development of the Swarmanoid project mentioned before is using a pair of pins to attach. Instead of relying on adhesion or attraction this prototype simply penetrates the surface it wants to attach to. This is done by pushing a set of sharp steel needles into the surface upon contact. Although this attacher was implemented on a fixed wing drone instead of a quadcopter its attacher and arm are fixed in a horizontal fashion making this design of interest. [7]

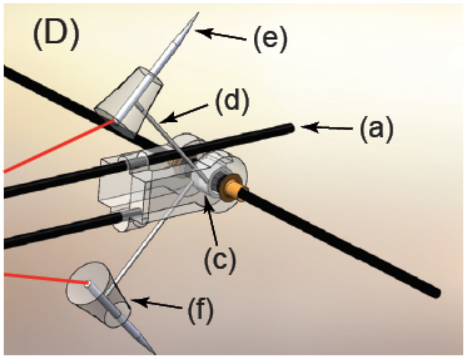

Figure 1.6: **the pin connector in it's retracted position** [7]

SURFY

SURFY is a robot which is designed to climb walls and perform cleaning and inspection tasks. It does this by walking up the surface via two arrays of suction cups. These suction provide attachment to the surface and are powered by a

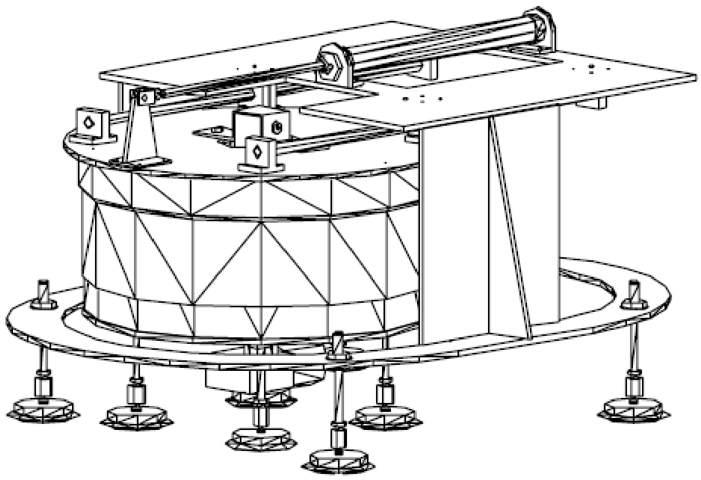

Figure 1.7: **A drawing of the SURFY robot [8]**

small vacuum pump within SURFY itself. The rings alternate in state and thus allow SURFY to make steps by moving the unattached part each time and then switching between rings. SURFY shows that suction cups are a viable option for creating wall contact, although its use for ARWs is questionable due to weight. [8]

Small legged wall climbing robot

Finally, there is also an interesting development from the Chiba institute of technology in Japan. This small legged wall climbing robot has a very simple design with the exception of its attachment method. It uses passive suction cups in order to provide the adhesive force needed to cling to the wall. However the issue with passive suction cups is detaching. In order to solve this an elegant solution has been found. As can been seen in Figure 1.8 a piece of nylon string is attached to the edge of the cup. When detaching this string is pulled causing the edge of the cup to rise and break the vacuum. The advantages of this system is that it is very lightweight and easy to construct.[9]

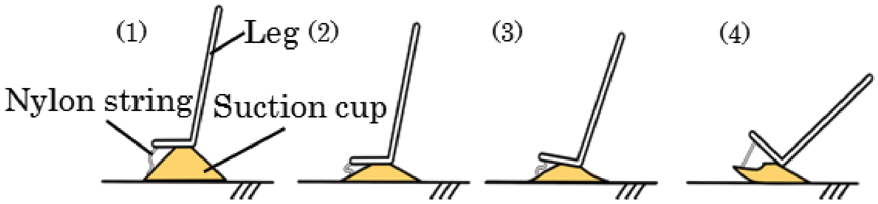

Figure 1.8: **The detaching of the passive suction cup [9]**

Overview

A short overview is given of the prototypes

Prototype	Attachment method	Advantages	Disadvantages	Source
Vertigo	Pushing with fans	Easy transition	High power requirement	[4]
Waalbot	Dry elastomer	lightweight	Only works on flat surfaces	[5]
Magnetic attaching	Permanent magnet	Strong attachment	Power consumption and only on metallic	[6]
Pin connector	Penetration	Strong adhesion	Damages the surface	[7]
SURFY	Active suction cups	Easy attaching/detaching	High power consumption and only on flat surfaces	[8]
Small legged wall climbing robot	Passive suction cups	low power consumption, easy to produce	Only on flat surfaces	[9]

Table 1.1: A short overview of different prototypes and projects

1.4 Outline

This report details the design of a mechanism in three stages: Introduction, prototype and final design. The introduction details all the preparation and context needed for the design. The rest of the report details two design iterations. These consist of setting of specifications, designing and experiments. The result of the first design iteration is the prototype and its performance. This is used as input for the second design iteration. This process could be repeated but after two iterations the design was deemed satisfactory enough to not warrant the time for further work within this assignment. At the end of the report a conclusion and suggestions for further work are given.

Chapter 2

Specifications

The specifications can be split into two categories: Requirements and objectives. The requirements specify what should be met by the design and objectives specify what should be as good as possible. Many requirements are driven by the existing hardware at RAM. Therefore a small summary about the existing hardware is given here.

2.1 Hardware

Please note that some of the hardware is still under development and thus is subject to constant change. The quadcopter currently in use by RAM is a in-house design. It features a pretty standard layout with four rotors (7.0 N of thrust each) , pixhawk controller and IMU. It has the option to be controlled by either remote control or by control software on an external computer. It also features reflective markers for use with optical tracking systems (optitrack), which enables it to be positioned by simply setting a setpoint or a height. Although it is possible to be deployed outside it is usually employed indoors. It has the option to fly with either a battery or use a cable for power (which extends the flight time). The mass is 1.45 kg and the payload limit is around 0.6 kg and it has no propeller guards at the moment. For mounting various mechanisms and sensors a mount can be fixed on top of the quadcopter. This mount is made of ABS and is 3d printed at RAM.

2.2 Requirements

1. **The mechanism has to be fitted on the existing quadcopter of RAM.** This comes from the fact that the quadcopter is readily available and has proven to be a good experimental platform. And thus has to be used

2. **The mechanism may not weigh more then 500 g** The weight should be limited by the payload limit of the existing quadcopter. However some extra margin is take for safety

3. **The mechanism has to be able to carry 30 N of weight at a distance of 0.40m between the center of gravity and the surface.** The distance to the edge of the propellers is slightly below 0.40 m. Thus the mechanism has to attach at least 0.40m from the surface. The weight is overestimated to ensure a safety margin and allow for some flexibility in choosing parts.

4. **The mechanism may not hinder the manipulator arm mounted under the ARW.** In order to have use the mechanism should not be to big or cumbersome in conjunction with any manipulator.

5. **The mechanism may not produce a deflection at the center of gravity greater than 0.10 m when attached to the wall.** If manipulation is desired the ARW should not deflect to much when attached. At more than 10 centimeters this would probably start to be problematic.

6. **The mechanism may not cause a moment greater than 1.0 N m on the center of gravity of the ARW** When accounting for the weight of the ARW and its mechanism the force left is around 8 N. This means that in one direction exactly between the rotors (which is the direction most likely to feature the mechanism) 4 N at a distance of 0.28M is available. This would be able to counter a moment of 1.12N m, however some has to be left for maneuvering.

2.3 Objectives

1. **The costs of the mechanism should be as low as possible.** Saving money leads to more funds available for further research and thus should be a goal.

2. **The general example application for the mechanism should be the case of windturbine maintenance (although this is not always binding).** The windturbine represents a foreseeable use of the mechanism and provides some ideas for how to evaluate the design.

3. **Energy consumption of the mechanism may not hinder the ARW in it's tasks and thus should be as low as possible.** Having a energy hungry system is undesirable so it is best to avoid this in the early stages.

Chapter 3

Design of the prototype

In order to better motivate and document the design choices which were made the mechanism is split into three parts: attacher, boom and connector. The attacher represents the part of the mechanism which attaches to the wall. The boom is the material connecting the attacher to the connector. And the connector fixes the boom to the frame of the ARW. This division is made based on the fact that these three parts fulfill different functions and are also physically separate. The requirements and objectives are linked fairly naturally to the separate parts.

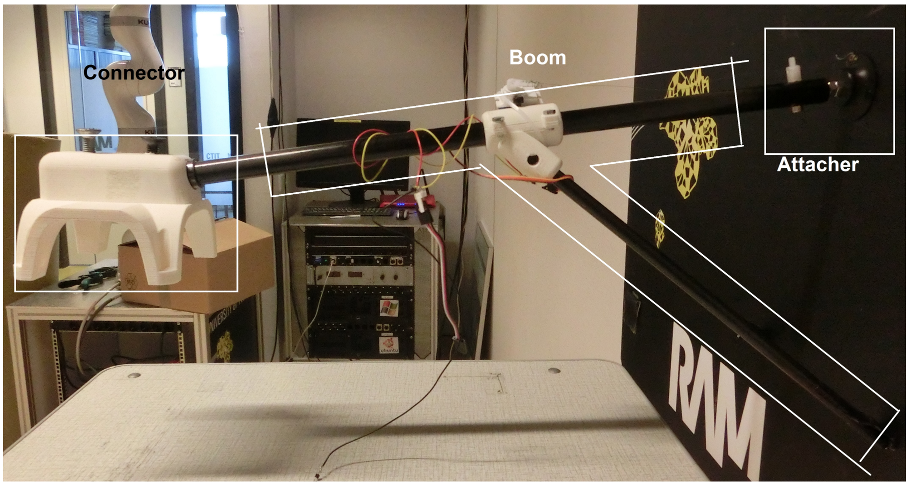

Figure 3.1: **An overview of the different parts of the prototype**

3.1 Attacher

The attacher has to provide the connection to the wall. The main function of the attacher is to generate the forces and moments needed to fix the ARW. First the method of attaching has to be considered. In order to give an overview of this ,a short table with possible options gathered from various sources is given in Table 3.1. From this table a selection is made based on the following reason. Firstly the magnetic options are discarded because they do not comply with the objective of using the windturbine as an example. Using magnets would simply limit the mechanism to much with regard to places it could attach (since large parts of windturbines are not made of metal). Secondly

Attachment method	**Possible surfaces**	**Advantages**	**Disadvantages**
Permanent Magnet	Ferromagnetic materials only	Lightweight, small, large force	Hard to detach
Electromagnet	Ferromagnetic materials only	Easy to detach	Heavy, high power consumption
Passive suction cups	Flat surfaces	Easy construction, lightweight, somewhat compliant	Hard to detach
Active suction cup	Flat surfaces	Easy to detach, variable force	Heavy, high power consumption
Adhesion (glue)	Depends on glue	Easy construction, cheap, lightweight	hard to detach, needs to set
Adhesion (dry polymer)	flat, smooth surfaces	lightweight, easy construction	Still experimental, needs substantial pre-load pressure
Penetration	Soft surfaces	Very sturdy connection	Complicated mechanism, damages surface

Table 3.1: An overview of different attachment methods

due to practical reasons adhesion due to glue and penetration are discarded. Penetrating the surface is deemed too damaging and waiting for glue to set would take too long. Finally, active suction cups require to much weight and extra additions, and is thus also discarded. This means that only two options are seen as viable attachment methods: passive suction cups and adhesion using dry polymers. The difference between the two options makes for an interesting comparison while they are similar enough to keep the rest of the system constant.

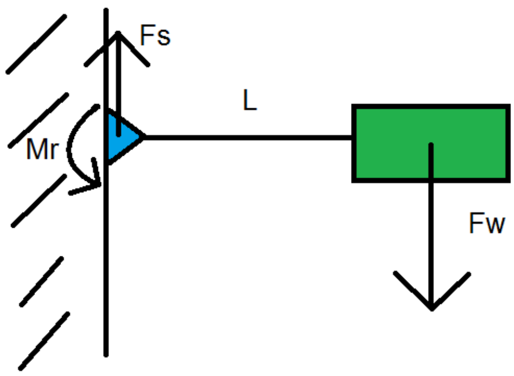

Figure 3.2: **Initial force and moment calculations**

In order to make a choice of what suction cup/dry polymer to use, some calculations are needed. The purpose of the attacher is to counter all forces and moments caused by the weight of the ARW and some external influences such as wind. As a safety factor 30 N is assumed to be the weight of the ARW. Figure 3.2 shows a simple overview of the forces and moments in the system. Assuming the system to be at rest and using Newton's first law the force balance can easily be made. Fw is the force due to the weight of the ARW and Fs is the shear force by the attacher to counter this force, so:

$$F_w = F_s = 30N$$

In the requirements it says that the mechanism should support the ARW of 30 N at 0.40 m from the wall. Thus with L being 0.4, Mr being the reaction moment we get:

$$M_r = 0.4 * 30 = 12Nm$$

This leads to the conclusion that in order to satisfy the requirements the attacher should provide a shear force of 30 N and a moment of 12 Nm. While the shear force seems to be within the specifications of some options found the moment causes a bigger problem. Especially for the suction cup it would be hard to resist such a moment. In order to solve this a new approach is needed. Some thinking led to the setup as seen in Figure 3.3.

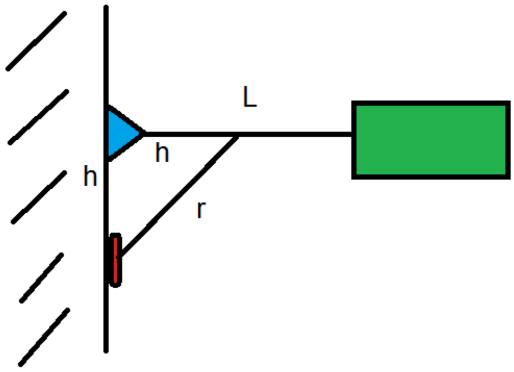

Figure 3.3: **Setup with lower supports**

The addition of the passive supports removes the need for the attacher itself to counter the moment. Instead the moment is countered by a normal force from the attacher in combination with the arm due to the support (length h). This leads to the following relation for the normal force Fn and length of the arm h.

$$M_r = F_n * h = 12Nm$$

Taking h to be 0.20 m seems realistic as the mechanism should not hinder the manipulator under the ARW to much. This leads to a required normal force of 60 N. Using the Pythagoras theorem r can be easily calculated to be 0.28m

According to the specifications given by the company convum at 60% vacuum their suction cups have a adhesion pressure of about 61 kPa. This leads to the required diameter for the suction cup to be about 0.0354 m. However since they are only supplied in certain sizes the choice was made for a suction cup with a diameter of 0.040 m which provides 76.9 N of normal force.

Figure 3.4: **The suction cup used.**

According to the findings of the team working on Waalbot [5], there is a dry polymer called vytaflex suitable for functions like this. Vytaflex supposedly has a adhesion pressure of around 45 kPa. Thus when used a pad of 0.0013 m^2 would be required Finaly some though is also given to prevent rotating in the horizontal plane when attached to the wall. In order to prevent this movement the choice was made to go with two supports instead of one. When these are placed at an angle so that the distance between them is 0.10m they could provide a reaction moment of about $0.10 * (76.9 - 60) = 1.69 Nm$. in the horizontal direction. This can all be seen in Figure 3.1 and Figure 4.2.

3.2 Boom

The boom has to connect the other parts of the mechanism and provide the sturdiness to keep the whole intact. The first decision is about the material for the boom. This material choice is mainly based on specific modulus as well as availability and price. The specific modulus is relevant since both the weight and stiffness of the boom are very important properties (which are represented by the specific modulus). Comparing easy to obtain and workable cheap materials three options were considered: Aluminum, carbon fiber and PVC. Please note that data for carbon fiber varies greatly due to differences in production processes. In Table 3.2 it can be seen that carbon fiber is the best choice out of the three materials.

Material	**Specific modulus** ($*10^6 m^2 s^{-2}$)
Aluminum	26
Carbon fiber	31.3
PVC	2.35

Table 3.2: Comparison of specific modulus (young's modulus over density)

A tube has been chosen as the shape for the boom since it provides a good distribution of stress and is easy to connect to other parts. With the shape and material known, some calculations can be done in order to find the right dimensions of the tube. For this, the Euler-Bernoulli beam equations for cantilevers are used.
For the case of a distributed load and a point load the deflection of a beam comes down to:

$$w(x) = \frac{qx^2(6L^2 - 4Lx + x^2)}{24EI} + \frac{Px^2(3L - x)}{6EI}$$

With w being the deflection at x, L being the length of the cantilever q being the distributed load, E being the young's modulus, I being the second moment of inertia and P being the point load. All these equations are put into a MATLAB script which can be found in appendix A. After putting in the data for carbon fiber it was found that an outer diameter of 16 mm and an inner diameter of 14 mm would produce a bending of around 22 mm at the tip.

This is well within the requirements. For the connectors on the attacher smaller carbon tubes were chosen since they only have to deal with the compression. A short explanation about the design of the support connector (the part which makes sure the supports are linked to the main boom) is given, the result can be seen in Figure 3.5. The decision was made to use 3d printing technology in order to quickly design and produce this connector. In essence it consists of three cylinders which some connecting material in between. The main cylinder is for the boom and the two smaller ones facilitate the supports. Some holes are added so the top can come off and the tubes can be secured by small screws.

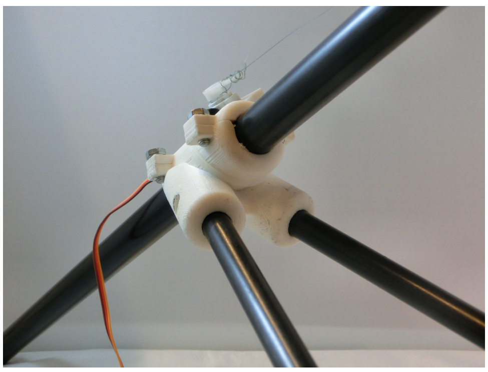

Figure 3.5: **The support connector**

3.3 Connector

In order to secure the boom and the attacher to the ARW, a connector is needed. However, it was advised to not put much effort in making an elaborate design for the connector. This is because the connector used in the BsC assignment of Teun Bartelds [3] could be used after some small modifications. One of these modifications is placing the boom at an 10 degree angle. At this angle the ARW can approach the surface with good speeds. Also it enables to provide a force of 3.5 N when the rotors are at about 75 % of their max power. The calculations can be found in the appendix (under calculations for pushing force). A force of 3.5 N is good enough to ensure a connection for the suction cup.

Chapter 4

Evaluation

In order to test the design, the actual performance has to be compared to the specifications. For the requirements this is quite straightforward. However, the objectives are somewhat more difficult and evaluating them failed to add meaningful information to the report. Therefore the objectives are omitted here. But performing some more realistic tests however, does help the design of the system. From the specifications and field tests new specifications are derived for the second design iteration.

4.1 Evaluation of Requirements

1. **The mechanism has to be fitted on the existing quadcopter of RAM.**
   Has been met by designing and 3D printing a new base for the Mechanism.

2. **The mechanism may not weigh more then 500g** The mass of the mechanism including base was 315 g.

3. **The mechanism has to be able to carry 30 N of weight at a distance of 0.40m from the wall.**
   First the suction cup was tested by applying a normal force to it. A force was applied while using a force gauge. The maximum normal force that could be measured was 75 N. After applying more force it was difficult to asses at what point the suction cup let go. Since the required force for the cup is set at 60 N it was deemed sufficient to construct the mechanism. After construction, the mechanism with the lower supports was again tested using the force gauge. In this instance it was stuck to a wall and the force was applied to the end of the boom. Again the maximum force was hard to estimate, however the system was stable at 32.1 N at the end of the 0.40 m boom. Finally, the mechanism was tested by attaching the ARW on the wall and letting it hang for 5 minutes. The weight of the drone was 14.5 N and was fully suspended by the mechanism.

4. **The mechanism may not hinder the manipulator arm mounted under the ARW.**
   The mechanism is mounted on the top of the ARW and thus does not hinder the manipulator.

5. The mechanism may not produce a deflection greater than 0.10 m when attached to the wall.
   The mechanism was attached to the wall and a force of 30 N was applied to the end of the boom. The deflection was measured compared to the unloaded state. Please note that this approach neglected the weight of the boom itself. The deflection measured was around 0.025 m. As can be seen in Figure 4.1. This is somewhat higher than anticipated from the calculations. It is suspected that this has to do with the following: bending in the lower supports, the suction cup bending and the errors in the youngs modulus of the material.

6. **The mechanism may not cause a moment greater than 0.8 N m on the center of gravity of the ARW.**
   The mass of the mechanism including base was 315 g. The center of gravity of the UAV is located in the middle of the quadcopter. However since the base has its center of gravity close to being directly above the center of gravity of ARW, it is assumed that for small angles it does not contribute to the moment significantly. The distance between the attacher and the center of gravity of the ARW is 47 cm. This was measured by using the marks left from the fixing bolts. However a small correction is needed. Since the boom is attached 0.11 m above the center of mass. This leads to an extra 0.019 m of arm. The mechanism without base has a mass of 154 g and has a weight of around 1.50 N. Thus the moment the mechanism causes at the center of gravity is 0.489*1.50 = 0.733 Nm.

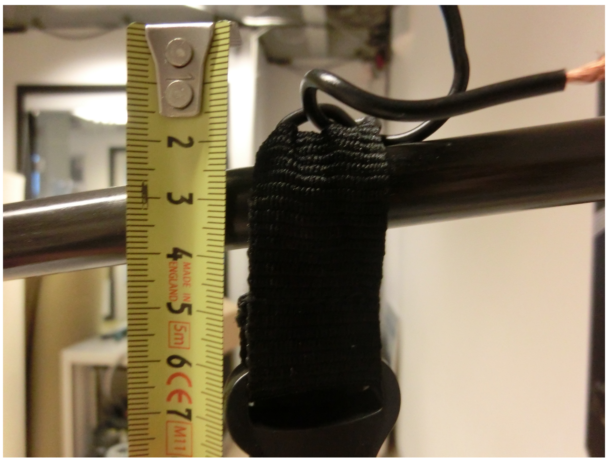

Figure 4.1: Measuring the bending of the mechanism when applying a force of 30 N at 0.40 m from the wall

4.2 Experiments

In order to ensure the prototype mechanism is actually practical in more realistic environments a few experiments were performed. These were performed at the flight lab of RAM or in the smartXP lab. Both locations featured a nearly identical OptiTrack visual tracking set-up. The OptiTrack data is combined with IMU data from the ARW itself. The ARW used is a home build quadcopter from RAM. The docking tests were performed on a smooth table surface.

The docking test were performed as shown in Figure 4.2 and explained here. First the ARW takes of and hovers at a height of around 0.80m. At this height effects from the ground are less severe and there is still enough space left at the top of the table. Next the ARW moves slowly towards the table. It is positioned between 10 and 15 cm from the table. At this position the last checks are done to assure the angle between the boom and the wall is as close to 90 degrees as possible.

When everything is in order the control of the ARW is switched to contact mode. Contact mode is a different controller developed at RAM and is designed to apply a constant force to a surface using an ARW [10]. The force to be applied is set at 2N, next the controller translates this into a pitch. When not connected to a surface this pitch causes the ARW to accelerate in forward direction.

Once the ARW hits the surface, a force is applied to the suction cup enabling the creation of the lower pressure inside the cup. Since the boom is not in line with the center of gravity of the ARW, a moment is also generated by the impact. There are two reasons why this does not cause the drone to be unstable. Firstly the stability in the direction of the boom (at an angle of 90 degrees with the surface) is provided by the fact that the system is fixed. The suction cup provides a normal force when it is pulled, so when the ARW would tend to drift away from the wall it is kept in place. Secondly the stability is upheld by the contact controller which continues to attempt to provide a force against the surface.

After impact, the ARW is lowered by changing the height setpoint. This is done until the lower supports make contact with the surface of the table. At this point the motors are turned off using the manual arming switch. Finally the drone is at rest and stays in position on the surface.

Figure 4.2: **Docking with the prototype mechanism.**
1. The ARW is positioned in front of the wall.
2. Contact mode is engaged and the ARW accelerates towards the surface.
3. Contact is made while the controller keeps the system stable.
4. The ARW is lowered and the motors are turned off

4.3 Initial results

After performing the experiments, some valuable lessons were learned. The mechanism appeared to perform very well within its specifications (and sometimes even beyond). However, in the more real world applications some problems were encountered. First it was noticed that the system would be able to fix the ARW to the wall, however detaching it was not possible. Attempts were made by trying to pull the ARW from the wall using its own motors. These were unsuccessful since the ARW failed to provide enough force, and became unstable when switching to the regular controller (so going out of contact mode).
Secondly the distance at which the ARW could be switched into contact mode was very limited. When switching at a distance larger than 20 cm the ARW would have a error in the yaw. This was not properly compensated for and caused the ARW to drift away from the perpendicular axis with the surface. Sometimes this drift was so extreme that the ARW completely missed the table causing it to crash (since it would either hit the table with rotors or only a single lower support).
Finally on the rare occasion that the ARW managed to have a successful impact the suction cup would not stick to the surface. It could be observed that the ARW bounced of the wall or would slip, both causing crashes.

This led to three conclusions: Some sorts of detaching mechanism has to be added to make the mechanism more practical, a stable approach has to be guaranteed in which the yaw drift problem is solved and a mechanism to cope with the impact has to be added so that an impact will reliably result in a connection. In order to make some more defined specifications a few conditions are set. After a quick analysis using video footage from the experiments and kinematic analysis software it was determined that the approach speed just before docking was around 2 m/s. Therefore the situation for which the specifications are set is an approach from 1.5 m at 2 m/s. The 1.5 meter is to ensure the distance is significantly larger than when using the contact controller (also this means the experiments can still be done at the RAM flight lab which is convenient). The other specifications are still in effect but are omitted here for readability.

Requirements

1. **The mechanism has to be able to detach from the surface when instructed to do so remotely.**
2. **The ARW has to be able to successfully impact with the surface from a distance of 1.5 m at a speed of 2 m/s.**
3. **The mechanism has to be able to reliably connect to the surface upon impacting under the conditions of requirement 2.**

Objectives

1. **The mechanism should be able to attach and detach as many times as possible without landing.**

Chapter 5

Final design

In order to satisfy the new specifications, multiple additions had to be made to the system as a whole. In order to facilitate the detaching a detacher has to be added. For the impacting the problem is a little more complicated. After deliberation it was decided that two steps had to be taken. First compliance has to be added to the mechanism. This should ensure that the energy of the impact is absorbed instead of directly put into the ARW. However this still will not fully solve the problems. Since the combination of the regular and contact controller cannot handle the approach a new controller has to be devised. The combination of controller and compliance should lead to reliable and stable connections after an approach. For convenience the design here will be split into three parts: Detacher, Approach controller and Compliance.

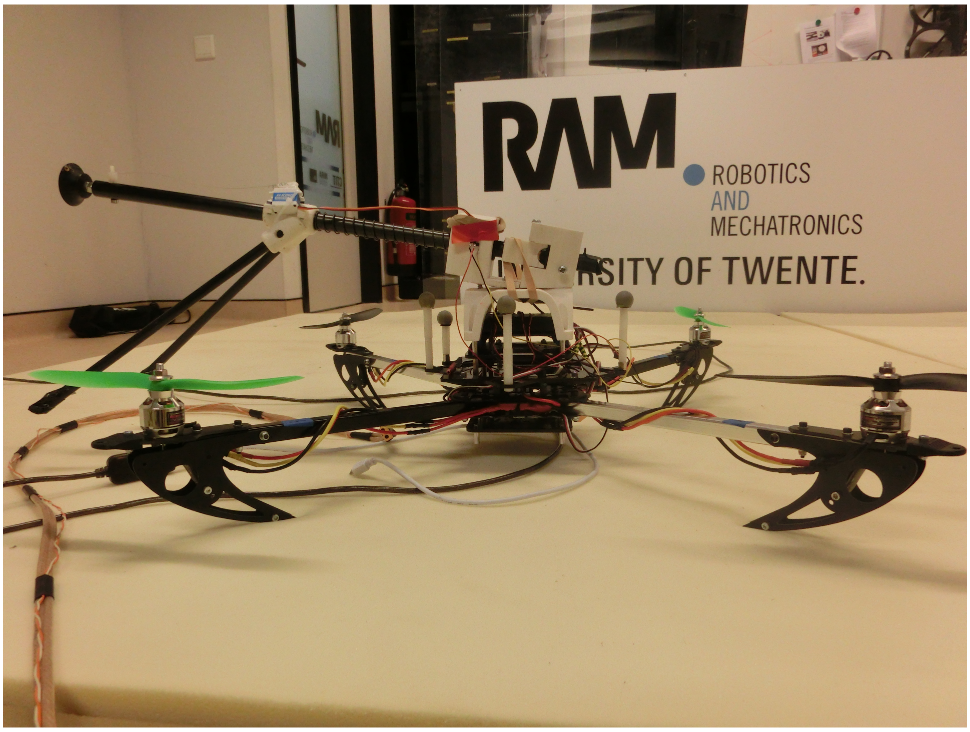

Figure 5.1: An overview of the entire system mounted on the ARW

5.1 Detacher

The mechanism is attached to the surface using a passive suction cup. The advantage of this system is that it does not require energy to stay attached after the initialization. This is also a disadvantage since detaching cannot be done by simply cutting the power. However,once the vacuum is broken, the cup is released. The challenge is to break the vacuum in such a way that the cup can be reused. Inspiration on how to achieve this was found in the research done by the Chiba Institute of Technology in Japan [9]. In their design a piece of nylon string lifts up the edge of the suction cup. When the edge is lifted the pressure is equalized and the cup releases. However, attaching a leg on the boom was deemed impractical for the mechanism.

Thus a piece of string was tied to a small ring. This ring was superglued to the edge of the cup cup and guided towards the connector. Here a small servo is used to pull the wire on command. Since the cup is flexible it returns to its natural state once the force on the string is removed. The servo is linked to the remote control for the ARW and thus can be activated remotely.

Figure 5.2: **The detacher mechanism**

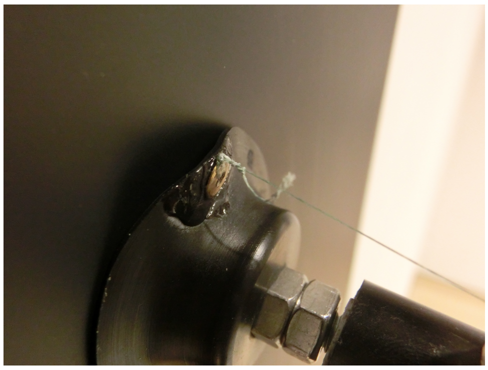

Figure 5.3: **The suction cup in deflected state**

5.2 Approach controller

The approach controller has to ensure the ARW can reliably impact with the wall from 1.5m away and at a speed of 2.5 m/s. It was attempted to do this with the contact controller. However after some failed attempts, a close look was taken at the contact controller code. As also described in [10] the problem lies in the yaw control. In the freeflight controller the yaw control is done by controlling the momentum of the rotors, but in the contact controller the yaw has to be controlled by both the momentum and a roll action. This is due to the fact that the contact controller is designed for pushing against a surface and thus assumes it has a contact point. In order to compensate for yaw errors the roll action is used (in combination with the momentum of the rotors) to compensate. This is effective when pushing against a surface, but when the contact controller is activated while not connected this has unwanted effects. Any small error in the yaw would cause the ARW to change its roll resulting in a large translation and thus missing the surface or crashing upon impact.
Thus the approach controller had to be designed. First the user can define the approach speed and the approach yaw. These are then fed into the freeflight controller as setpoints by the following code. These pieces of code are all in a loop and executed in sequence. They also work in a larger framework of code and thus send and receive data from for instance the free flight controller.

```
if(flightmode == APPROACHMODE)
```

```
    {
      vRefX = setpointApproachSpeed*cos(setpointAlpha);
      vRefY = setpointApproachSpeed*sin(setpointAlpha);

      errorYaw = setpointAlpha - tf::getYaw(msg->pose.pose.
         orientation);
      omegaRefYaw = Kp_yaw*errorYaw;

      approachPitchLimit = 10.0;
    }
```

This causes the ARW to fly in the direction of the yaw at the approach speed. A limit for the pitch also has to be set, the reason for this is that if the ARW would attempt to accelerate too much it could have a pitch bigger than 10 degrees. Since the boom is at a 10 degree angle it might fail to connect if the pitch angle is much higher than 10 degrees. Thus the approach pitch limit is set at 10 degrees since this is not done in regular flight.

After flying for a certain amount of time (the controller theoretically works for any practical distance from the surface) an impact is made. Since the approach controller simply provides imputs and limits for the regular freeflight controller it is not really stable when attached to a surface. Thus the control has to be switched to the contactmode. In order to make sure this doesn't happen while still on approach a check is made.

```
if ((flightMode == APPROACHMODE) && (abs(msg->twist.twist.linear
   .x) > 0.5))
     {
       flightCheck = true; }
```

Thus if the forward velocity of the ARW is larger than 0.5 m/s the controller recognizes that it is in approach mode. Please note that x is body fixed and thus is always in the forward direction of the ARW (the direction at which the mechanism is fitted). At the moment of impact the system experiences a relatively large deceleration (or negative acceleration). Since the acceleration of the ARW is measured, it can be used to detect when to switch between control modes. The following code shows this switch:

```
if ((flightMode == APPROACHMODE) && (flightCheck == true) &&
   (ax < -2))
     {
       flightMode = CONTACTMODE;
       flightModeMsg.data = flightMode;
     }
```

The value for the deceleration is taken from other research [3] [10] and from testing in the flightlab. Please note that the code shown here has been slightly altered for readability and is part of a much larger framework of code.

5.3 Compliance


Figure 5.4: **The old mechanism [3]**

When making an impact on the surface, a lot of energy is transferred into the system. This caused problems for the prototype when attempting to connect to the surface. One of these problems was the system becoming unstable or bouncing of the wall. Thus it was decided that compliance had to be added to the mechanism. A mechanism design to absorb the impact of the ARW already exists for use in earlier research [3]. It was decided that using this design as a starting point would save time and guarantee a certain measure of reliability. Two main adaptations have to be made. Firstly the old mechanism has a rubber band functioning as its spring, so a more detailed analysis is needed for the new mechanism to determine the spring constant. Secondly the locking mechanism needs to be up scaled and fixed on the drone. The old mechanism uses a servo motor to position the boom at a certain angle. This is not designed to carry the weight of the drone and only a single angle is needed.

Spring calculations

As a start the maximum deflection of the spring is defined to be 0.15 m. This is the distance which the mechanism can be deflected without the rotors touching the surface (and some room to spare for yaw error). The approach speed is set at 2.0 m/s. The mass of the system is somewhat overestimated at 2.0 kg in order to allow for the weight of a manipulator. This leads to the kinetic energy of the system leads down to:

$$E_{kinetic} = \frac{1}{2}mv^2 = \frac{1}{2} * 2.0 * 2.0^2 = 6J \tag{5.1}$$

It is assumed that all energy of the impact will be stored in the spring. At a maximum deflection of 0.15 m Equation 5.2 shows how much energy is stored in the spring.

$$E_{spring} = \frac{1}{2}k\Delta u^2 = \frac{1}{2} * k * 0.15^2 \tag{5.2}$$

Thus using Equation 5.1 and Equation 5.2 the desired spring constant can be determined.

$$k = \frac{E_{kinetic}}{\frac{1}{2}\Delta u^2} = \frac{6}{\frac{1}{2} * 0.15^2} \approx 175N/m \tag{5.3}$$

Next a spring has to be selected based on the following requirements:

- The spring constant has to be around 175 N/m
- The inner diameter has to be larger then 16 mm
- The spring has to be able to be compressed 150 mm from the uncompressed state

After some searching a spring was selected with a spring constant of 170 N/m with an inner diameter of 17.9 mm. The uncompressed length is 208 mm and the fully compressed length is 28 mm. Since this spring was slightly longer than needed a bit more compression could be achieved and thus the slightly to low spring constant is not problematic.

Locking mechanism

A problem with a spring system is that it tends to oscillate. In order to prevent this a locking mechanism is implemented which only allows the boom to move in one direction. The mechanism was already designed for use in earlier projects [3]. However the design had to be upscaled and addapted for the new application. Also for completion sake a short overview of the functioning of the locking mechanism is given. The base of the mechanism is a hole with linear bearings for the tube to move through. As can be seen in Figure 5.5 there are two gears on the side of the tube. The gears have a spherical hole in them as can be seen in Figure 5.6. The diameter of the hole are decreasing as the gears are turned. So when moving in the allowed direction the friction between the boom and the tube keeps the hole open. When moving in the locked direction the gears will turn and the hole will close on the boom.

This will cause the friction to increase and prevent the boom from moving further. When more force is applied in the locked direction the gears will turn more resulting in a tighter grip on the boom. This mechanism should prevent the mechanism from oscillating upon impact. For the upscalling the hole had to be re-sized to fit the boom. Also some adaptations had to be made to accommodate the larger bearings. Finally the locking mechanism was again set at an 10 degree angle with the base so that it would be horizontal when impacting and still provide a force of 2N to attach the cup.

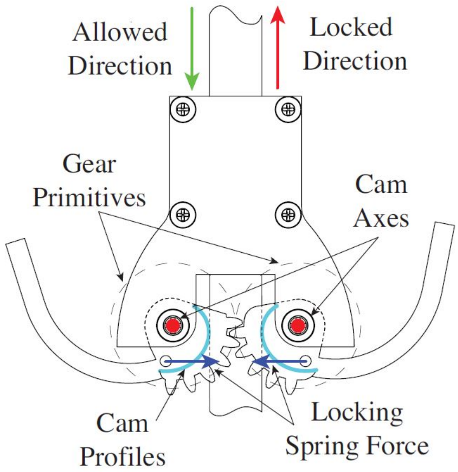

Figure 5.5: **The locking mechanism [3]**

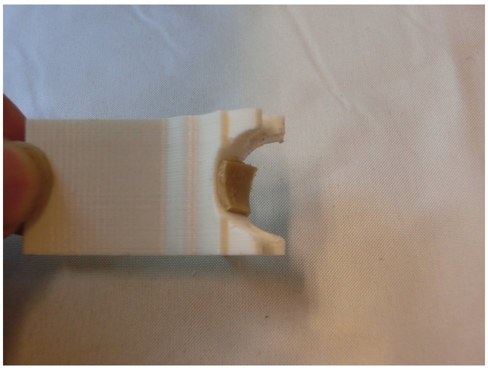

Figure 5.6: **The left locking gear**

Chapter 6

Final evaluation

After all the improvements on the final design had been implemented testing was required. Again this is done by comparing performance with the set specifications. Also some data is given on the success rate of attaching and detaching multiple times. This also addresses the objective for the final design.

6.1 Evaluation of requirements

1. **The mechanism has to be able to detach from the surface when instructed to do so remotely.**
   The servo was able to make the suction cup release very reliably and without breaking the mechanism.

2. **The ARW has to be able to successfully impact with the surface from a distance of 1.5 m at a speed of 2 m/s.**
   The approach controller in combination with the compliance leads to very stable impacts even at slightly higher speeds (2.5 m/s).

3. **The mechanism has to be able to reliably connect to the surface upon impacting under the conditions of requirement 2.**
   Impacts would not always lead to a stable connection to the surface (see the next paragraphs for more details)

4. **The mechanism may not weigh more then 500g** The new mechanism has a slightly heavier base (due to the compliance) and weighs 412 g. (The boom has not changed and thus the moment and carrying requirements are still met).

6.2 Final experiments

In order to test the requirements and the objectives, testing was again performed. Similarly to the previous experiments, the flying was done in the flight lab of RAM. For these experiments a different method was used. First the ARW takes off and hovers at a height of 0.80m. Next the approach controller is set with a forward speed and the contact controller is given the angle at which to push once active. The forward speed was set to 2.5 m/s and the angle is 10 degrees for reasons mentioned before. A visual check makes sure the ARW is somewhat in front of the table. If everything seems okay the approach controller is activated. This causes the ARW to impact with the surface. Upon impact the software should switch to the contact controller. When this leads to a stable connection the height setpoint is lowered until the lower supports makes contact with the surface. The motors are manually turned off and the drone is at rest. When this is successful the motors are activated again. Slowly the ARW is raised by setting the height setpoint to 0.80m again. When this height is reached the ARW is still using the contact controller. Using the servo the vacuum in the suction cup is broken causing the ARW to be detached. After the detaching, the ARW is still pushing against the surface. While still pushing a setpoint about 1 m behind the ARW is set for the freeflight controller. The switch to free flight controller is done manually via the control software. After the switch the ARW goes to its setpoint and is ready to repeat the approach. This is repeated multiple times or until a failure occurs.

6.3 Compliant mechanism

Some problems were encountered during construction and testing of the compliant mechanism. Since the boom is very slippery (due to grease from the bearings and it being carbon fiber) and there are some defects in the gears good friction is not always ensured. This was partially solved by using small rubbers on the inside of the gears as can be seen in Figure 5.6. Regardless of this a problem was that friction either became too large on the entire system (in both ways) or the system was not effective in locking. In the end the functioning of the system was partially sacrificed in order for the boom to still move freely. This resulted in a very overdamped system which would still not oscillate but would also not reset to an equilibrium position. Thus during repeated testing the system would be more and more compressed. Efforts to solve this could not be implemented due to time constraints but are suggested in the chapter on future work.

6.4 Experimental success rate

One of the objectives for the final design was that the system should be able to attach and detach multiple times. In order to evaluate this experiments were performed following the procedure stated above. This was done and gave interesting results. They are displayed in Table 6.1 in which "I" stands for impacting, "A" for attaching (and turning off rotors) and "D" for detaching. The numbers represent which attempt in the series it is (for example "I"-1 is the first impact and "D"-3 is the third time detaching). An x marks success which is defined as following. For impacting: hitting the surface without crashing or requiring manual interference. For attaching: attaching to the surface such that the ARW can disable its motors and hang without moving for at least 1 minute. And for detaching: detaching from the surface using only remote commands and being able to move to a set point away from the surface.

Experiment No.	**I-1**	**A-1**	**D-1**	**I-2**	**A-2**	**D-2**	**I-3**	**A-3**	**D-3**
1	X		X	X	X	X	X	X	X
2	X	X	X	X	X	X	X		
3	X								
4	X								
5	X	X	X	X	X	X	X	X	X
6	X	X	X	X					
7	X	X							
8	X	X	X	X	X	X	X		
9	X	X	X	X	X	X	X		

Table 6.1: Succes rate for docking

First some interesting results are explained here. Experiment 1 failed to attach on attempt 1 since it started to slide down. Instead of letting it fall and slide down, it was decided to test the detaching by activating the motors again before the minute had passed. Experiment 4 and 5 led to cleaning the surface which improved the chance of attaching. Finally experiment 8 was the only experiment in which the dettacher mechanism failed. After quick inspection this appeared to be due to some loose wires (which was easily fixed with some tape).

The experiments revealed some interesting things about the mechanism. Firstly it can be seen that impacts are always successful, especially when compared to the prototype (which would not produce any stable impacts under the conditions), the success rate for impacting is 100%. Secondly it can be seen that detaching is almost always successful (the exception being loose wires). Out of 14 times attaching only 1 detaching failed. The success rate for detaching is thus 93% (but should be 100% for future experiments). The problem for docking multiple times is apparently the attaching. Out of 20 impacts, 13 lead to successful giving a success rate of 65 %. Finally it can be seen that repeatability is an issue, since 6 out of 9 times the system can impact, attach and detach once. However for two times this rate drops to 5 out of 9, while for three times it is 2 out of 9. The biggest problem thus seems to lie in the suction cup releasing after attaching or sliding down during rest. The succes rate for multiple cycles of impact, attaching and detaching is 55%.

Chapter 7

Conclusion

7.1 Conclusion

In this report, the design, building and testing of a mechanism to establish stable wall contact with an ARW is described. Different types of drones and robots for comparable applications have been researched but none can perform the functions desired for the assignment. In the prototype design a carbon fiber boom is fitted with a suction cup at the end. Two carbon fiber supports are attached to the boom so that the moment on the suction cup is limited. The boom is connected to a base which is mounted on top of the ARW. Tests revealed some problems with the prototype design which were addressed in the second iteration. Firstly a spring and a one way locking mechanism are added which will absorb the impact. A servo is used to pull a spring connected to the edge of the suction cup such that it can be released upon remote command. Also a special controller is added for the approach of the ARW. This controller sets a certain speed towards the surface and switches to a different controller when impacting with the surface. Tests of the final design reveal that the ARW is able to successfully impact, connect and detach from the surface in around 55% of the attempts. An overview of the system mounted on the ARW can be seen in Figure 5.1.

7.2 Further work

In order for the entire system to be better a few things could be addressed: The problems with the locking mechanism, better approach controller and scaling.

Locking mechanism

A major problem with the compliance is that the locking mechanism is not effective. Currently there are two options: too much friction in both directions or not enough difference between the friction in both directions. One option to solve this would be to more finely 3-D print the gears so that they have a larger contact surface. Another possibility would be to have coating of a somewhat less smooth material on the boom, since it is very slippery at the moment. However, all of this does not solve the more fundamental problem with the locking mechanism. Namely that it has to be unlocked by actuating the gears with an outside force. This could be solved by installing a servo on one of the axes and having it be remote controlled which has proven to be effective. This would mean the boom could be released in flight.

Better approach controller

Currently the approach controller has some limitations in that it has certain speeds and limits on pitch angles. Although this does not really hinder the performance directly, improvements could still be made. Depending on the distance between the ARW and the surface higher speeds could be reached. An example would be to install an optical system which can measure the distance and angle of a surface. When approach mode is engaged the controller would calculate the positioning such that the same impact speed and angle are realized as in the old controller with the difference being that the speed could initially be much higher (with the ARW slowing down before impact).

Scaling

In order to make the design useful for more than just this specific case, the design parameters should be scaled. The two parameters that should be given for the system are the mass of the system and the length of the boom. The mass of the system is defined as the mass of the drone + 10% (to compensated for the weight of the system and have some safety margin). The length of the boom is to be determined by the size of the drone and should be long enough so to make sure that the rotors will not touch the surface. The mass is m (in Newtons) and boom length is L (in meters). First the moment on the wall is calculated.

$$M_w = m * L \tag{7.1}$$

Assuming that the lower supports always attach at the middle of the boom the reaction moment generated by the suction cup is.

$$M_r = \frac{1}{2} L * F_n = M_w \tag{7.2}$$

The normal force generated by the suction cup at 60% vacuum is 61 kPa. Thus the normal force is:

$$F_n = 61000 * \frac{\pi}{4} * D^2 \tag{7.3}$$

Thus simplifying makes the diameter of the suction cup as a function of m is:

$$D = \sqrt{\frac{m}{3812.5 * \pi}} \tag{7.4}$$

Furthermore the diameter of the boom has to be determined as a function of m and L. The maximum value for the deflection simplifies the equation to:

$$w_{max} = \frac{mL^3}{3EI} + \frac{qL^4}{8EI} \tag{7.5}$$

with q being the distributed load due to the weight of the boom itself and thus also dependent on the diameter via:

$$q = F_{tube}/L = (m_{tube} g)/L = \pi(r_o^2 - r_i^2)\rho g \tag{7.6}$$

With r_o being the outer radius of the tube and r_i being the inner radius of the tube. With I also being dependent on the radii.

$$I = \frac{\pi}{4}(r_o^4 - r_i^4) \tag{7.7}$$

The entire system is thus dependent on the radii of the tube (and the material choice). Finally the spring constant was already a variable of the mass (and compression length). As can be seen in Equation 5.1 Equation 5.3. With these equations the system can be scaled for different sizes of drones and even types of ARW's

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Appendix A

Matlab scripts

Calculations for the bending of the tube

```
clear all;
close all;
x = 0.4; %point at the axis (m)
xarray = [0:0.0001:x];
l = 0.5; %length of the beam (m)
p = -30 ;  %point load at the end of the beam (N)
E = 30E9; %young's modulus (N/m2) 69E9 aluminum, 30E9 carbon fiber?
ro = 0.008; %outer radius of tube (m)
ri = 0.007; %inner radius of tube (m)
I = (pi/4)*(ro^4 - ri^4); %area moment of inertia (m^4)
v = l*pi*(ro^2 - ri^2); %volume of tube (m^3)
rho = 1600; %density of tube material (kg/m^3) aluminum = 2712 carbon fiber = 1600
m = rho * v; %mass of tube (kg)
f = m*-9.81; %force of tube due to gravity (N)
q = f/l;   %distributed load (N/m)
yield = 414000000; %yield stress for aluminium  (Pa)
Z = I/ro; %section moduls of the cross section of the beam m^3
stress = -(p*l)/Z;
specific = E/rho
w1 = (p * x^2 * (3*l - x))/(6*E*I); %solution for deflection for pointload
q1 = p; %shear force for end load
m1 = p*(x-l); % moment for point load

w2 = (q * x^2 * (6*l^2 - 4*l*x + x^2))/(24*E*I); %solution for deflection for pointload
q2 = p*(l-x); %shear force for end load
m2 = -(q*(l^2 - 2*l*x + x^2))/2; % moment for point load

x = xarray;

```

```
wa1 = (p .* x.^2 .* (3.*l - x))./(6*E*I); %solution for
    deflection for pointload
qa1 = p; %shear force for end load
ma1 = p.*(x-l); % moment for point load

wa2 = (q * x.^2 .* (6.*l^2 - 4*l.*x + x.^2))./(24*E*I); %
    solution for deflection for pointload
qa2 = p.*(l-x); %shear force for end load
ma2 = -(q.*(l^2 - 2.*l.*x + x.^2))./2; % moment for point load


W = w1 + w2;
Q = q1 + q2;
M = m1 + m2;

[W Q M ]
[yield stress]
if yield<stress
    'failure'


else
    'okay :)'
end
Wa = wa1 + wa2;
Qa = qa1 + qa2;
Ma = ma1 + ma2;

figure
subplot(3,1,1)
plot(x,Wa)
subplot(3,1,2)
plot(x,Qa)
subplot(3,1,3)
plot(x,Ma)
```

Calculations for the connection forces

```
clear all;
close all;
alpha = 0;  %angle deviation from normal to the wall (degrees)
l = 0.40*cosd(alpha) ;  %length boom (m)
w = -30;      %Weight drone (N)
Fs = -w;    %Shear force by the wall
Mw = w*l;     %Moment on the wall (N m)
Mr = -Mw;     %reaction moment by the wall (N m)
p = 45000;    %pressure of suction cup (N/m^2)
Fn = 0;
```

```
r = 0;
Fa = 0;
d = 0;
a = 0;



%%%%%%%%%%%%given cup diameter%%%%%%%%%%%%%%%
%d = 0.030; %given cup diameter (m)
%a = 0.25*pi*d^2; %required area suction cup (m^2)
%Fa = a*p; %resulting normal force

%%%%%%%%%%%%given length%%%%%%%%%%%%%%%%%%%%%%%
r = 0.20;   %given length to lower support (m)

Fn = Mr/r;  %calculate normal force required at support length (
    N)

%%%%%%%%%%%%given normal force%%%%%%%%%%%%%%%%%%
%Fn = Fa;    %given normal force of suction cup (N)

%r = Mr/Fn;  %calculate support length required at normal force
    (m)


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

a = Fn/p; %required area suction cup (m^2)
d = sqrt(a/(0.25*pi)); % required diameter suction cup (m)

%Fa = available suction force, Fn = required suction force, r=
    length to
%lower support, d = required diameter suction cup
[Fa Fn r d]'
```

Calculations for spring forces

```
clear all;
close all;

%inputs
m = 2.0; %mass in Kg
%k = 3160; %spring constant in N/m
dzeta = 1; %damping factor should be 1 for critical damping
v = 2.0; % impact speed in m/s
%f = 20; %impact force
u = 0.15; %deflection in spring max

```

```
%calcs

%c = 0.35; %damping coeficient manual



ek = 0.5*m*v^2; % kinetic energy due to speed in J

ed = ek;



f = ed/u; % force used to stop the drone
a = f/m; % initial deceleration
t = 1+(v/a); %time to decelerate the dron at the acceleration
    caused by the force to stop it

k = f/u;
c = 2*sqrt(k*m); %c for critical damping
test = k*u
```

```
clear all;
close all;

w = 20; %weight in newtons
p = 20.4; %force generated by props in newton at 75%(4*7)
a = 10;  %angle of attack in degrees (down is positive)

f = sind(a)*(p) %force left for pushing against the wall in
    newton
s = sqrt(f^2+w^2);     %safety factor
if s>p
    'BOOM'

else
    'should be fine'

end
```