A UAV mechanism for autonomous landing and transportation of cargo

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"If you don't have a consensus that it's nonsense, you don't have a breakthrough."

Burt Rutan

KTH Industrial Engineering and Management

Examensarbete MMK 2014:28 MKN118

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Sammanfattning

Användningen av robotar blir allt vanligare i vardagen och robotar kan klara av allt mer komplexa jobb. Obemannade luftfartyg (UAV) är en del av denna revolution och de dominerar luftrummet i robotområdet. Framsteg inom elektronik har i hög grad bidragit till de snabba framsteg i robotar och UAV, genom att minska kostnaderna och samtidigt öka kapacitet och minska strömförbrukningen av komponenter. Gemenskapen för öppen källkod har dessutom i hög grad bidragit till utvecklingen och användningen av UAV i allmänhet. Multi-helikoptrar är ett nytt ras av UAV som har tagit fart senare tid på grund av deras mekaniska enkelhet med stöd av komplexa elektriska komponenter och algoritmer för stabilitet. I dag användas helikoptrar och andra UAV främst för flygfotografering, men deras användning inom andra områden är fortfarande mycket begränsad, bortsett från forskningsprojekter till exempel på universiteter och några andra företager. UAV har en stor potential för att användas som befordringsmedel och de kunde därmed kraftigt minska kostnaderna och leveranstider. Flera hinder måste övervinnas innan detta kan bli verklighet. För att nämna några hinder för transport av gods med UAV är deras begränsade förmåga av att uppfatta miljöer och också utmaningen med automatisk grepp av last av olika former och storlekar som ligger på marken. Målet med detta examensarbete är att hitta en ny och robust mekanisk lösning på problemet där huvudfokus kommer att ligga på att ta tag i lasten.

Nyckelord: UAV, Last, Befordringsmedel, Multi-copter, Dockning

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Abstract

The utilisation of robots is becoming more and more common in every day life and robots are capable of accomplishing assignments of increased complexity. Unmanned Aerial Vehicles (UAVs) are part of this revolution and are dominating the skies of the robotic field. Advancements in electronisc have contributed greatly to those rapid advancements of robots and UAVs, by reducing cost while increasing the capabilities and reducing power consumption of components. Open source communities have furthermore greatly contributed to the development and usage of UAVs in general. Multi-copter's are a newly introduced breed of UAVs that have been gaining momentum recently due to their mechanical simplicity supported by complex electrical components and algorithms to keep them stable. Today multi-copters and other UAVs are mostly used for aerial photography but their usage in other applications other than in research projects at universities and some other companies is still very limited. UAVs have a great potential to be used in transportation of cargo and consequently greatly reduce cost and shipping time. Multiple obstacles need to be overcome before this comes a reality. To name some obstacles facing transportation of goods with UAVs are their limited capability to sense the environment and also the challenge of automatic grabbing of cargo of various shapes and sizes located on the ground. The goal of this thesis is to find a novel and robust mechanical solution to those problems where the main focus will be on grabbing of the cargo.

Keywords: UAV, Cargo, Transportation, Multi-copter, Docking

Foreword

I would like to thank my supervisor, Ulf Sellgren for his help especially by pointing me in the right directions at times when I was confused and had missed what the important factors were in my thesis work. I also want to thank Kjell Andersson Professor at KTH and Fredrik Sjögren at MSC Software Sweden AB for their help in solving complex issues within MSC. Adams. As an aviation enthusiast I have been flying aeroplanes and building small radio controlled unmanned aircrafts throughout my life. I have been greatly inspired by those who accomplish to solve previously thought impossible problems with their innovation, engineering skills and their unstoppable mindset of doing the impossible. The work of the engineers at NASA in the Mercury, Gemini and Apollo programs as well as the work of Elbert Leander "Burt" Rutan to achieve the unthinkable have inspired me to progress aviation in the form of unmanned aircrafts. Last but not least I would like to thank my fiancée and my mother for their tremendous support throughout my thesis work.

Tryggvi Stefánsson
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Abbreviations

GPS	**G**lobal **P**ositioning **S**system
UAV	**U**nmanned **A**erial **V**ehicle
CAD	**C**omputer **A**ided **D**esign
PDS	**P**roduct **D**esign **S**pecification
DOE	**D**esign **O**f **E**xperiments

Symbols

μ_u	Coefficient of static friction	No unit
μ_d	Coefficient of dynamic friction	No unit
V_{max}	Maximum velocity at impact	m/s
H_{max}	Maximum height in free fall	m
g	Gravitational acceleration	m/s^2

Chapter 1

Introduction

As of today unmanned aerial vehicles (UAVs) have come increasingly popular, especially multi-copters, due to their mechanical simplicity and low cost. The most common application for UAVs is with out a doubt aerial photography in different fields. The potential to use them in other applications has been explored, one of them being transportation of goods. Multiple obstacles need to be overcome as well as regulation and ethical perspective need to be taken into account before transportation of goods can become reality. Technical challenges are here divided here into two categories, sensing and understanding and gripping of cargo.

The first category, sensing and understanding, allows the UAV to sense the environment and make decision based on those observations. This topic is vast in robotic research today, for example in making autonomous cars. When entering new unknown territory, the UAV needs to be able to avoid all obstacles on the ground as well as in the air.

The second category, gripping, is about using the UAV to pick up cargo autonomously and to allow the UAV to securely grab the cargo that can vary in size and shape. Today autonomous flying can be easily achieved by readily available UAVs or custom made UAVs by installing a flight controller computer. By using a special platform that can be fixed manually to the cargo by the user will greatly reduce the complexity of such equipment since the size and shape of the lower platform is known, resulting in a lower weight of the equipment attached to the multi-copter allowing the UAV to carry heavier cargo over longer distances. Using this platform, greater robustness can be more easily achieved since the platform will always have the same size and shape. Furthermore, this can also help with autonomous flight since the main constraints today are landing the multi-copter. If the UAV is able to recognise the platform located on the cargo on the ground, complex sensing can be avoided making this a feasible option today for pick up and transportation of cargo.

The main focus of designing such a platform must therefore be to increase the robustness and making it as insensitive to environmental factors like dust, water, temperature, wind and wear of the equipment that affects the coefficient of friction. This thesis work therefore aims to answer the questions of what the best way is to accommodate for the inaccuracy in landing at a predetermined location and how can the robustness of such a system be maximized.

1.1 Background

Unmanned aerial vehicle (UAV) usage has increased greatly the last couple of years both in government usage as well as company and amateur usage. This is partly because of great advances in the technological development over the last couple of years. For example batteries have undergone a huge increase in power versus weight ratio as well as price has been greatly reduced by batteries like lithium polymer and lithium iron. UAVs have also benefited from the development of smart phones and small computers but with them a great development has taken place in sensors like accelerometers, gyroscopes, compasses and GPS (Global Positioning system) sensors as well as great reduction in size with increased efficiency of processors and other electrical components. All these developments have greatly advanced the UAVs and made them capable of flying fully autonomous missions and being capable of stabilising the aircraft in flight. Especially has one type of unmanned aerial vehicles benefited from this technological development namely multi-copters.

Multi-copters are generally equipped with three to eight motors located far from the center of the vehicle. To keep the multi-copter aloft the motors turning opposite directions are required to give the same amount of upward force. This is done by a feedback circuit on-board that senses the orientation of the multi-copter and controls the rotational speed of each motor. Generally the propellers have a fixed pitch so the mechanical layout is very simple compared to the traditional helicopter that uses two propellers, one to generate the upward force and another located on the tail that counteracts the torque generated by the main propeller. The movement of the multi-copter is therefore achieved by altering each motor's angular velocity instead of using mechanical actuators that change the pitch of the helicopter blade respectively. This simpler mechanic is of great interest since it reduces maintenance, increases the robustness and lowers the operational cost. Multi-copters could also be said to be safer for people due to the fact for the equivalent weight of the helicopter, a multi-copter has a higher number of propellers, compared to traditional helicopters. In addition each propeller has lower kinetic energy

than the main propeller on the helicopter and therefore will cause less damage or injury on impact.

1.2 Purpose

Multi-copters today are much used in various kinds of aerial photography but have until now not been a feasible solution for transporting goods. Over recent years the interest in using them for transporting goods has grown[4], as well as in allowing them to operate more autonomously. Multiple challenges are facing the operation of using multi-copters to pick up and deliver packages. The main difficulties are to accomplish a fully autonomous landing due to the complexity of different environmental factors that the multi-copter needs to sense, process and avoid. Today's flight controllers or computers are very limited when it comes to sensing and understanding environmental factors. Popular flight controllers like the Pixhawk [5] designed by the open source and open hardware project PX4, supported by the Computer Vision and Geometry Group, Automatic Control Laboratory and autonomous system lab that are all part of the Swiss Federal Institute of Technology (ETH) Zurich as well as by multiple individuals and manufactured by 3D Robotics Inc. However popular, the Pixhawk controllers are very limited when it comes to sensing the environment. The Pixhawk relies on GPS, magnetometer, barometer, accelerometer and a gyroscope to be able to determine internal values of the aircraft as the position, heading, altitude and attitude of the aircraft. It can support other sensors like different distance sensors, airspeed sensor and an optical flow smart camera. All the current capabilities of current flight controllers for UAVs are therefore only or mostly capable of sensing the internal values but not the external environmental values like trees, power lines, roads, animals and other obstacles on the ground or in the air such as birds or other air crafts. Furthermore the flight controllers can not sense the conditions on the ground, like the slope, bumps, water or ice or other factors required to make an fully autonomous landing. As of today, UAVs are therefore capable of a fully autonomous flight but require that they are flown in known locations without any other air traffic or environmental obstacles. Therefore to make an autonomous landing the conditions of the landing site and other environmental factors need to be well known and a location with large view of the sky is required.

To be able to sense the environment multiple additional sensors are required but with added sensors the computational power required greatly increases. With added sensors and more powerful computers the size, weight, cost and inefficiency of this equipment make it an infeasible solution as of today. Although a lot of research is ongoing in this field making UAVs and other robotic vehicles better capable of sensing the environment,

for example in many universities as well as at auto manufacturers. The problems of autonomous landing to pick up goods are therefore finding the goods, full capability of understanding the environment, descending to the cargo to be picked up accurately and lastly locking the cargo securely to the multi-copter so the cargo can be transported to a predetermined location where it is then released. The cargo to be transported can be of variety of shapes and sizes and therefore require a universal solution capable of accommodating all the different shapes for the goods.

The purpose of this thesis is therefore to develop a solution for multi-copters that allows them to pick up cargo in a robust manner.

1.3 Problem Definition

As described previously multiple problems need to be solved to allow for a fully autonomous pick up and transport of goods by a multi-copter. Upon descending to the package to be transported a mechanical solution is required to lock the multi-copter to the package. Being able to land the multi-copter on the package with great accuracy is hard to accomplish especially under different environmental effects like strong winds. This thesis work will only focus on the mechanical aspect of a platform to mount onto the multi-copter and another platform to mount on the cargo to be transported. The main purpose is to increase the robustness of the contact and locking mechanism that also allows for little accuracy (1-4 [cm]) for the multi-copter to land. The platform needs to accommodate for different orientation of the multi-copter at the time of contact and also be insensitive to accumulation of dirt. The solution needs to consider different velocities respectively between the platforms. Multiple parameters are to be considered: the maximum velocity between the multi-copter and the ground platform at contact, the angular and horizontal misalignment, mass of the multi-copter, mass of the docking platform, dampening coefficient and stiffness between the platform and the multi-copter as well as the coefficient of friction in all contacting mechanisms.

1.3.1 Boundaries of thesis

This thesis work will only cover the mechanical aspect, the geometry and dynamic simulation of mating the two platforms together, the cost and as well the robustness. Little consideration will be given to electrical or software solution for example integration of sensors and actuators. The thesis will focus on trying to reduce the accuracy needed to align the two platforms together. No physical testing nor any physical prototypes will be constructed. The thesis work is to be done only by calculations and computer simulations.

1.3.2 Assumptions

It is assumed that the multi-copter is capable of bringing the two platforms in contact with certain amount of accuracy defined in the PDS so that a secure connection can be established. It is furthermore assumed that the size of actuators needed is sufficient to accomplish the task and no calculations or other estimations will be done regarding the power of actuators (motors, magnets, etc.).

The maximum loads are assumed to take place when the multi-copter falls freely from a height of $H_{max} = 0,02[m]$ under different angles as defined with the design cases. The maximum vertical velocity upon impact is assumed to take place after a free fall from this height H_{max} and is calculated from equation 1.1.

$$V_{max} = \sqrt{2gH_{max}} \tag{1.1}$$

Dampeners and springs used in the design are assumed to behave linearly and all other bodies to be rigid. Furthermore no plastic deformation is expected to occur.

In all simulation and calculations the input from the multi-copter flight controller are ignored. This is done to represent worst case scenarios where the multi-copter has turned off the motors and is falling onto the platform. The inputs from the multi-copter flight controller oppose motion and could both help with docking as well as oppose docking. Factors from this will kept in mind but in calculations and simulations will not be introduced, but it will be mentioned whether they have negative or positive effect on the docking between the two platforms. Furthermore, inertia due to the multi-copter will be ignored based on the assumption that the inertia of the multi-copter will in general help with docking since it opposes the motion of the multi-copter and will have negligible effect compared to the motor inputs from the flight controller.

Chapter 2

FRAME OF REFERENCE

2.1 Multi-copters

The layout or set-up of multi-copters can vary greatly but they all have in common that they utilise two or more motors with attached fixed pitch propellers. The orientation of the multi-copter is then controlled by different angular velocities on each motor that rotates, yaws, pitches or elevates the multi-copter. A very popular multi-copter is the quad-copter as on figure 2.1 that utilises four motors and propellers, hence the name.

FIGURE 2.1: A very common type of multi-copters is the quad-copter as pictured, with four motors and propellers. Design by author for Svarmi.

FIGURE 2.2: An octocopter designed by Svarmi. Motors are arranged in a coaxial configuration

Quad-copters as well as other multi-copters can vary in their shape by having uneven spacing between the motors or different set up of the frame. The frame layout is altered to suit different applications, for example to increase or decrease the mechanical stability or to accommodate for a camera with very large field of view where parts of the multi-copter could be in the view of the camera. Additional motors are usually added to increase the take-off weight or increase robustness (figure 2.2) so that if one motor or propeller fails it will not affect the flight of the multi-copter allowing the user to land it safely.

2.1.1 Control theory

The mechanism of multi-copters is fairly simple as the only moving parts are the motors. This mechanical simplicity makes them inexpensive and easy to operate. Multi-copters are inherently unstable and require an on-board computer with multiple sensor arranged in a closed feedback loop to keep the multi-copter stable in the air by giving different signals to motors to alter their angular velocity. The purpose of the on-board computer is to read the sensor values and change the orientation or position of the multi-copter according to a desired value which can either be a user input generated by the radio controller or to achieve certain position or height preprogrammed in the flight controller. Therefore all movement is effected by changing force vectors by adjusting the angular velocity of each motor and therefore increasing or decreasing lift. Yaw or rotation of the multi-copter is also done in the same way by increasing or decreasing the angular velocity of the motors spinning in counter-clockwise motion and decreasing or increasing the angular velocity of the clockwise spinning motors respectively. An example of motor spin direction can be seen on figure 2.3.

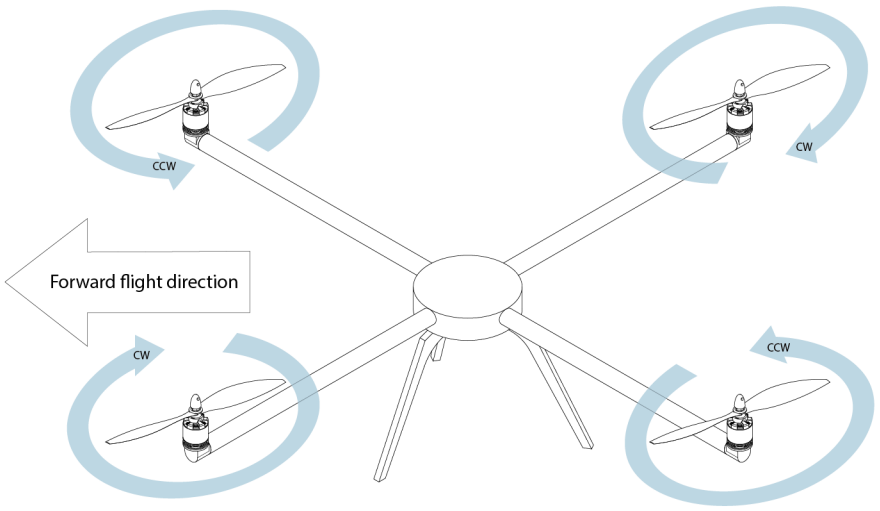

FIGURE 2.3: The spinning direction of propellers on a quad-copter in an "X" mode setup

To move forward and therefore to account for external forces caused by wind the multi-copter needs to tilt against the wind or towards the direction of flight, figure 2.4.

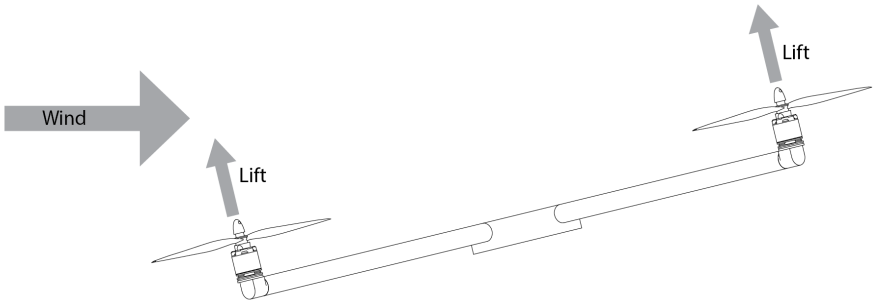

FIGURE 2.4: To counteract external forces like wind the multi-copter needs to tilt against the wind. This can be achieved autonomously by the use of a GPS on-board or other similar sensor that can detect the movement of the quad-copter with respect to the ground.

The affect of external forces like wind therefore greatly interacts with the landing of the multi-copter since the multi-copter is tilted against the wind.

2.1.2 Limitations

Multi-copters today are very capable machines and can achieve complicated autonomous flights where fully autonomous landings are a big limiting factor. The multi-copters can take off and fly trough preprogrammed trajectories fully autonomously and landing is done by lowering the multi-copter slowly to the ground with no feedback on obstacles on the ground only relaying on height measurements from barometer and an optional

distance sensor or height calculated from GPS coordinates. Therefore the landing ground needs to be known by the operator before landing takes place with no obstacles on the site. Some research has been ongoing in this field of autonomous landing [6] with added equipment, a smart phone on board the multi-copter and a computer on the ground the interacts with the multi-copter trough wireless communications and allows the multi-copter to land with greater accuracy.

2.2 Docking and berthing

In many application the need arises to connect two objects quickly and easily in three dimensional space. This can be and has been solved by a docking and berthing mechanism. Mechanisms of that sort have been involved from early days of space exploration. Where the need has often arisen to connect two space-crafts together both for crew and cargo transfer between the spacecraft or only as a connecting point to accommodate for extra thrusters or other features. Docking or berthing is therefore frequently used in space as cargo or crew transfer takes place. The transfer of crew and cargo can be done trough the docking or berthing mechanisms which is the most common case, or the transfer takes place on the outside of the two space-crafts.

Berthing mechanism in general is a simpler mechanic but the mating of two bodies is done by a mechanical crane or robotic arm that joins the two objects together. The mechanical docking is often described with two steps. The first step is often called soft docking when the two objects are first joined together. In this step a mechanical lock is actuated and then the two objects are aligned before the second step of docking, hard docking is accomplished. In hard docking the two objects are clamped together more rigidly and the purpose of this step is to make them structurally stronger and more importantly when a transfer between the two is to take place the hard locking makes a seal that can be pressurised for manned transfer between the two space-crafts.

2.2.1 A brief history of docking and berthing in space

The first docking in space was achieved by USA, with a manually operated docking between Gemini 8 and an unmanned Agena Target Vehicle on March 16, 1966, piloted by Neil Armstrong [7]. This was than followed by the first automated unmanned soft docking by the Soviet between Cosmos 186 and Cosmos 188 on October 30, 1967 [8]. Hard docking was not accomplished and soft docking was accomplished in the second attempt. Docking played a crucial part in the success of the Apollo program and the moon landing [9]. Docking was required two times over each mission when the command module first connected to the lunar module (LM) and when the LM separated in lunar orbit for landing and then docked again after landing on the lunar surface. The Gemini

project was carried out in order to, among other tasks, experiment if successful rendezvous and docking could be accomplished in space. This task was of special interest since it could greatly reduce the weight of the lunch rocket and that could have delayed the mission that USA president John F. Kennedy set out to accomplish before the end of the decade (1970) of landing a man on the moon and bring him safely back to earth.

Early docking systems were all non-androgynous [10]. In non-androgynous docking systems two different types of platforms join together. An example of that is the one of a gender like joining (male and female counterparts). Androgynous systems have the benefit over non-androgynous docking system that they are identical and can dock each other. This greatly helps in increasing redundancy and greatly reduces training required for astronauts. Androgynous system have been coming increasingly used in space and a International Docking System Standard (IDSS) and Interface Definition Document(IDD) has been published in a joint collaboration by the International Space Station membership comprised of NASA, ESA, Roscosmos, CSA and JAXA. This document was intended to increase possibilities of rescue scenarios and increase space expedition collaboration between countries and privately owned space companies [11]. Today on the international space station two different docking mechanisms are used and one type of berthing mechanism. One of the docking mechanism is androgynous while the other is non-androgynous.

2.2.2 Docking mechanism in space

The docking mechanism of the Gemini, the first mechanism to be docked in space was very simple and was merely to demonstrate that a rendezvous and docking was possible in orbit but had no other important role in the Gemini program. The Gemini spacecraft had a fairly large cone on the top of the command module and a drogue on the unmanned Agena Target Vehicle.

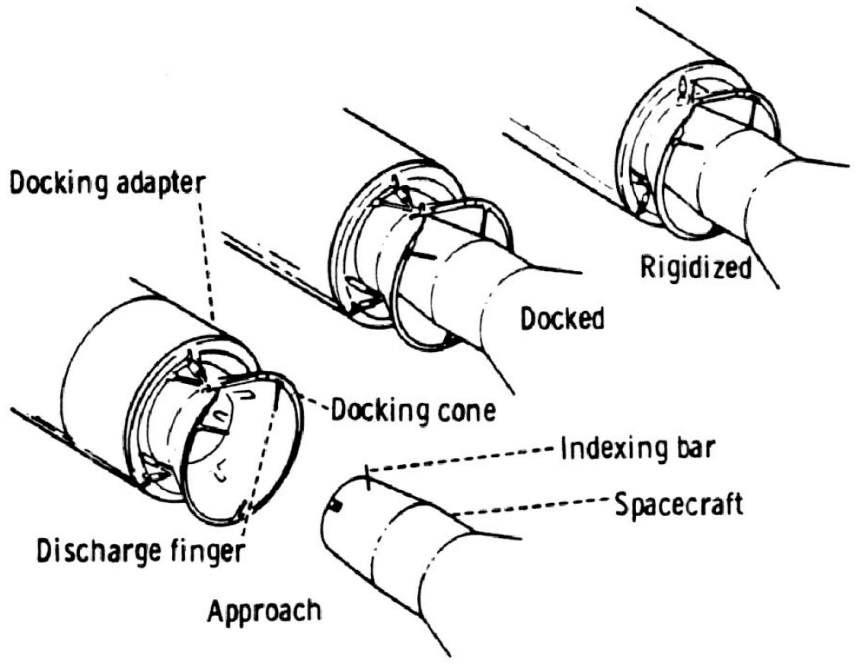

FIGURE 2.5: The Gemini docking mechanism.(Image courtesy of NASA. [1])

The first importance of a docking mechanism in space was probably demonstrated in the Apollo programme. The Apollo docking mechanism was described by Dave Scott commander of Apollo 15 and the first command module pilot to use the docking mechanism in the Apollo 9 expedition: "It is really quite important to the whole scheme of the Apollo concept - a very complex apparatus and one of the few single-point failures in the entire system. But at the end of the day, it was probably one of the more brilliant mechanical device of the programme" [9]. It can be said that this apparatus was perhaps the most underplayed of the engineering accomplishments in the Apollo programme. This docking mechanical system was in some way similar to the Gemini docking system, that is, it was non-androgynous but the main challenge it had to overcome was to allow the crew to transfer trough where the docking mechanism is located. All the active parts of the docking system were located on the command module and instead of having the dampening mechanism on the drogue it was located on the cone of the command module.

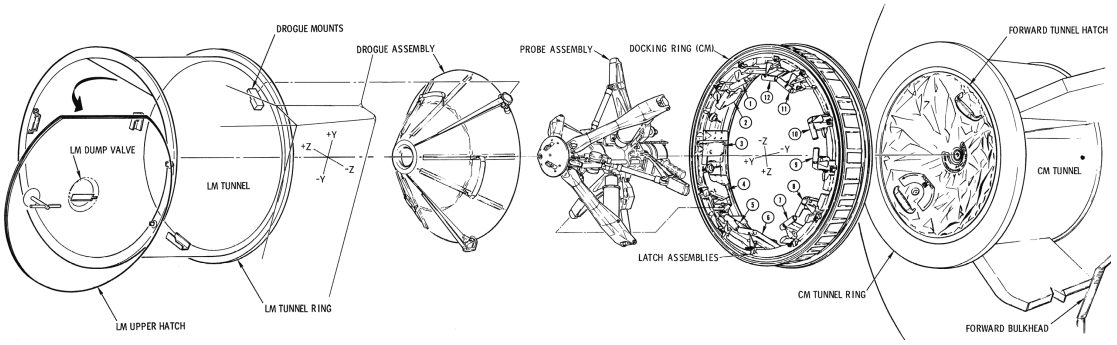

FIGURE 2.6: An exploded view of the Apollo docking mechanism.(Image courtesy of NASA. [2])

The cone of the Apollo docking mechanism could be extended before mating of the two surfaces and dampeners would than be activated with the purpose to reduce the impact force and to extend the time available to latch the two space-crafts together before they would apart again. After the latches in the front cone engaged the cone would retract and bring the two circular rings in contact, namely the LM tunnel ring and the docking ring. On the docking ring 12 latch assemblies are located but their purpose is to make a structural connection as well as a air tight seal. The air tight seal is a soft O-ring. The docking mechanism was then stowed away to allow crew transfer between the two vehicles.
The Soviets had developed similar solution to the one of the Apollo space-crafts, which also used a non-androgynous solution. Today the Russian federal space agency still uses the same docking mechanism on their Soyuz and their unmanned counterpart Progress space-crafts. This docking mechanism has gone trough extensive improvement throughout the years. Non-androgynous docking mechanisms have many advantages over androgynous mainly due to their simplicity and reduced weight. On the other hand, their main disadvantage is less redundancy, which is of great importance especially in space.

2.2.3 Other docking mechanisms

Although being a vast topic in space exploration docking system are used in many other applications. One common usage is mid air refuelling where an aircraft aligns with another aircraft, the former being the airplane carrying the fuel and the latter the one requesting fuel. After successful docking the transfer of fuel can start.

2.3 Contact theory

The contact mechanics of the two surfaces of the two platforms plays a crucial role in the performance of the product. Contact mechanics is a very complex subject and as

mentioned before, experimental data is necessary to estimate some of the parameters required for analysis. One of the biggest achievements in contact mechanics was the work of Hertz on elastic contact of semi infinite solids that was published in the year 1882. This work covers the distribution of stress in the contact zone between two bodies of a surface revolution. Although this work does not cover the impact of two spheres, further work of others like Timoshenko, Goldsmith and Johnson the work has been extended and those analysis constitutes now to what is known as the Hertz theory of impact [12]. This theory is limited in some ways and can for example not be applied for bodies having the radii of curvature at the point of contact to close to each other. The theory is therefore not applicable for example for journal bearings or plane to plane contact. To be able to apply this theory furthermore the area of contact needs to be relatively small compared to the body's radii of curvature and dimension. Also such formulas should be used with great caution on materials with large elastic strain such as rubber. To be able to apply the Hertz theory of contact one must assume that no plastic deformation occurs and therefore need to be able to come up with some kind of validation by testing or with other methods.

Chapter 3

THE DESIGN PROCESS

3.1 Design requirements

To clearly state the performance requirements for the design a product design specification (PDS) [13] was used to define the goals for the design process and can be found in Appendix C. The PDS was regularly revisited and updated as required. The need to update the PDS on regular basis was to accommodate for important factors that had not been foreseen in the beginning of the design phase and to update parameters that could be easily achieved.

3.2 Design concepts

An important inspiration for the design of the platform was sought from the design of docking system used in space when mating two objects together. Some of them are described in chapter 2. As one can assume there is quite a difference between mating that takes place in space at almost zero gravity versus mating in the atmosphere here at earth. The main difference would be the presence of gravity here on Earth as well as environmental factors, winds in particular. The forces generated by the gravitational acceleration can be a great benefit for the design of a mating system. In fact the lack of gravity in outer space causes one major difficulty in the design of a mating system. This difficulty due to lack of gravity causes the two mating platforms to bounce and separate since impacts are not perfectly inelastic and due to the kinetic energy of the objects. To accommodate for this the need for dampeners are very important to transfer some of the kinetic energy to heat or other form of energy and therefore reducing the kinetic energy of the system. The dampeners therefore increase the time that the two surfaces are in contact and hence the time frame increases for the locking mechanism to engage and lock the two objects together. For a docking system based on Earth like the one to be designed in this thesis, the gravity does help since the mating is to take place vertically and therefore parallel to the acceleration due to gravity. Even though

the gravity does help it is still very important to consider the stiffness and dampening of the system. If the stiffness is to high along with a very low dampening the two objects will bounce back depending on the relative velocity between the two objects. Therefore an under-damped system is required. With this in mind all concepts were designed to accommodate for a dampener between the upper platform and the multi-copter. Due to the weight requirements of the system it was concluded that traditional spring-gas dampeners were to heavy and rubber dampeners to be used instead. Those rubber dampeners (see figure 3.1)are commonly used in multi-copter application to isolate a camera platform from the main frame vibrations caused by the motors.

FIGURE 3.1: A typical rubber dampener designed for carrying tensional loads used on various multi-copter platforms to isolate camera system from vibrations in the main from induced from the motors

The rubber dampeners offer a great feature along with low weight that is they do provide dampening for six degrees of freedom. This benefit is graphically represented in picture 3.2.

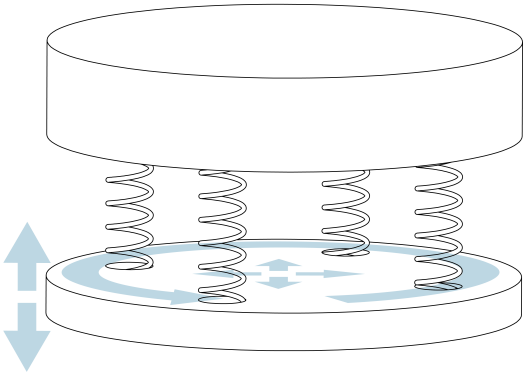

FIGURE 3.2: Having six degrees of movement for the lower platform helps to improve the docking process. Here this is represented with traditional springs but this configuration is possible with the use of rubber dampeners as seen on figure 3.1

This is a great benefit for a docking system in a way that less accuracy is needed when docking is to occur. Since the multi-copter control system strives to keep the copter level it is beneficial to have as many degrees of freedom for the lower platform so it can align to the lower platform as easily as possible. The downside of the rubber dampeners is their non-linear properties that make all simulations more complex. Therefore, for the purpose of this thesis the rubber dampener's properties are considered to be linear for reduced complexity.

3.2.1 Concept 1-A

Concept 1-A is a simple cone and drogue design inspired by early docking systems used in space exploration. The concept is assumed to have around 25 components in total. Manufacturing and assembly is fairly simple and most of the components can be manufactured with plastic injection moulding except the servo motor and the shaft holding the arms. The cam ring requires quite accurate tolerances and surface roughness and could therefore require a different manufacturing method or some further surface treatment. The contact surfaces on the arms and cam ring can greatly reduce life time of the product and are also very sensitive to environmental factors like dust that can wear the contact surfaces down and also result in an unpredictable performance. The servo motor or other similar actuators need to be placed inside the upper platform and therefore consumes a lot space that could otherwise be used for other electronic components. Due to the shape of the lower platform build up of dust or other contaminants are assumed to be minimum and that is true for all variations of Concept 1-A benefit of this system is that once the Servo motors or other actuator have locked the arms very little or no power consumption is required to keep the arms locked or open.

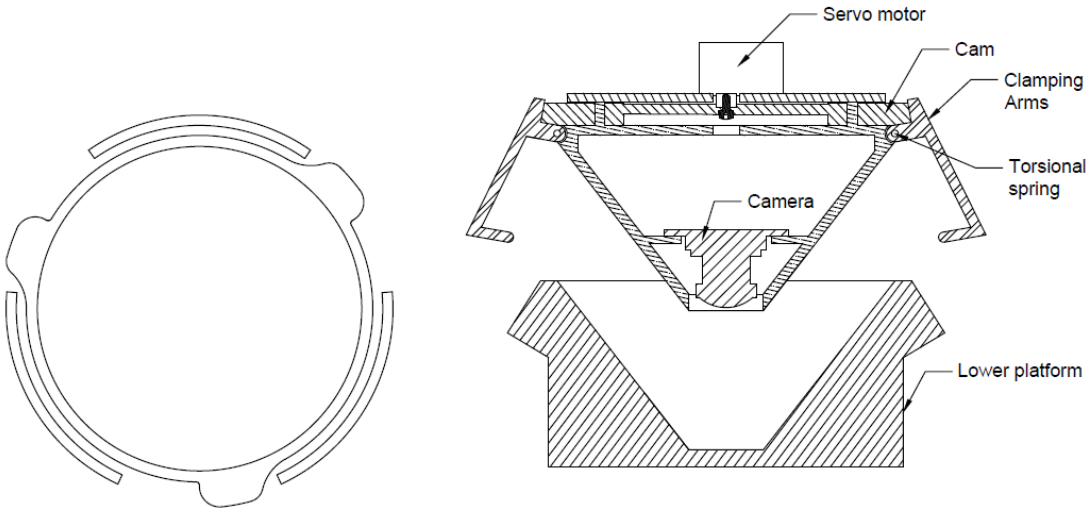

FIGURE 3.3: This concept uses arms to clamp around the lower platform. The arms are open and closed by rotating a ring that has cams attached to it. The movement is done by a single servo motor located on top fixed to the cam ring. The image on the left shows a top view of how the arms and the cam ring and how they interact

3.2.2 Concept 1-B

This concept is assumed to have approximately 25 components in total, the same as Concept 1-A since those concepts have very similar mechanism. This concept is therefore very sensitive to environmental factors and unpredictable performance due to wear of the contacting surfaces. Additionally the use of torsional springs to lock the arms in place can result in unpredictable performance under varying vertical acceleration of the multi-copter as well as varying weight of the cargo to carry. Servo motor or other actuators consume a lot of space inside the upper platform like in Concept 1-A. The manufacturing methods and problems would be very similar to Concept 1-A. The power consumption of actuators is assumed as in Concept 1-A to be very little.

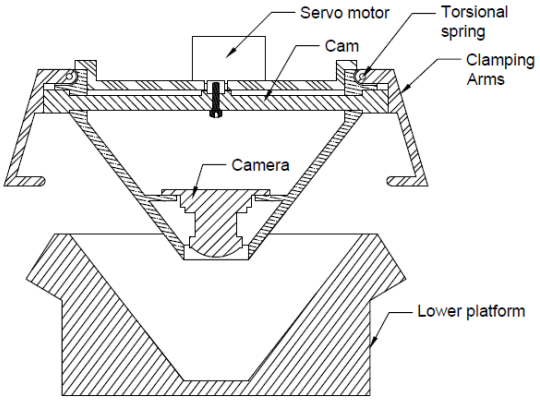

FIGURE 3.4: This concept is in almost every way the same as Concept 1-A except the cams are used to open the arms instead of closing the arms. A torsional spring is required to keep the arms locked

3.2.3 Concept 1-C

This concept is assumed to have 31 components in total. Manufacturing is assumed to be fairly simple and most of the parts could be manufactured by using plastic injection moulding except rubber bands, actuator and shafts holding the arms. Assembly time is quite high due to number of components and complex assembly. This concept is similar to Concept 1-A but instead of using cams it uses rubber band to lock the arms in place. This concept is assumed to have many of the weaknesses present in Concept 1-A except it is not as sensitive to environmental factors since there are less surfaces in contact. This concept also requires an actuator as described in previous concept that greatly reduces the space available for addition electronic components. The power consumption when arms are locked is considerable with this concept compared to Concepts 1-A and 1-B.

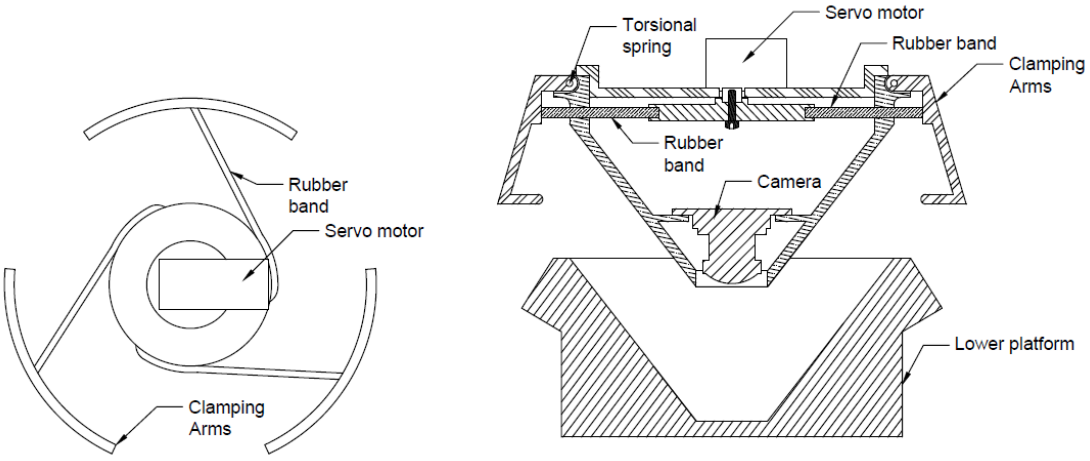

FIGURE 3.5: This concept is in some ways similar to Concept 1-A but instead of using cam ring to close the arms it uses rubber band and a pulley fixed to a servo motor. By rotating the motor and the pulley the rubber band locks the arms.

3.2.4 Concept 1-D

This concept is assumed to have 20 components in total. Due to the simplicity and low number of moving parts the manufacturing is very easy since almost all parts can be manufactured with plastic injection moulding. Assembly is also very simple and much easier than for the previous concepts. The power consumption while arms are locked or open is very little and is assumed to be under $0.025[W]$.

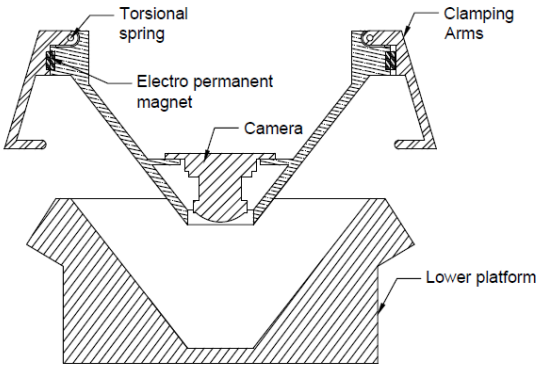

FIGURE 3.6: This concept has very few moving parts. Instead of using servo motor or other actuator as in previous concepts this one relays on another kind of locking mechanism

3.2.5 Concept 2

This concept was assumed to have about 20 components. The components are quite well suited for plastic injection molding but other complex parts are required as the servo motor, belt and the steel balls. Therefore multiple manufacturing methods are required. The concept is furthermore assumed to have little lifetime due to the moving parts, high serviceability and sensitive to environmental factors such as dust and water. The power consumption while locked or open is assumed to be very little.

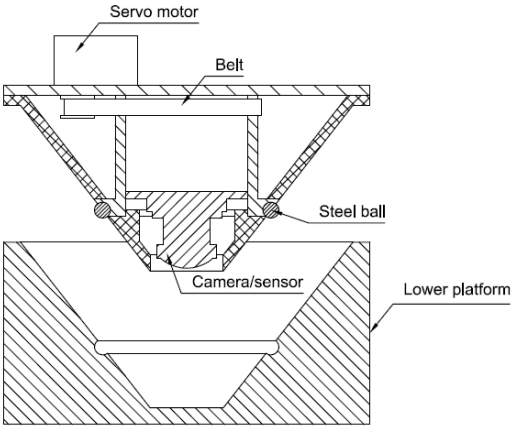

FIGURE 3.7: This concept is in many ways simple and the locking mechanism is inspired by the quick coupling used in many industries as for the air hoses and more

3.2.6 Concept 3 - Eccentric cams

This concept was assumed to have about 36 components. The components are quite well suited to for plastic injection moulding and requires very few other manufacturing methods. Assembly is quite time consuming due to number of parts. The concept is assumed to have short lifetime due to number of components and number of moving

parts. The serviceability is also very high. This concept is very sensitive to environmental factor since the clamping is provided trough friction. The power consumption when locked or open is assumed to be very little.

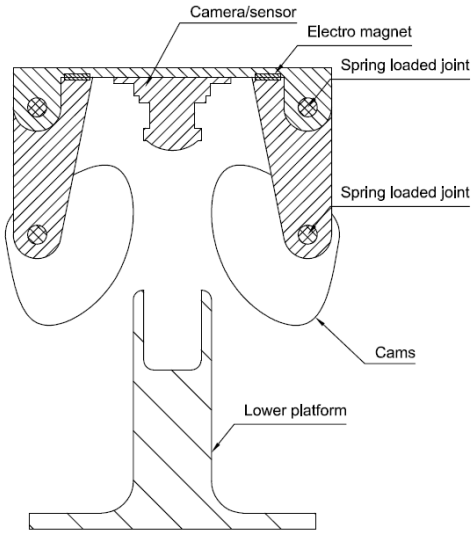

FIGURE 3.8: This concept is inspired by climbing equipment called ascender or Jumar that is specifically designed to climb up ropes. It is a one way tool meaning that to release the lower platform the electric magnets needs to be released so that the arms fold away from each other around the upper joint

3.2.7 Concept 4 - Ball end

This concept is inspired by the Russian docking system used for example on their Soyuz spacecraft. It is assumed to have 27 components in total and to be very complex to manufacture due to different manufacturing methods. Assembly is also time consuming. The lifetime is therefore very little with a high serviceability. This concept is considered to be insensitive to environmental factors. The power consumption is considerable when the platforms are locked together but very little when open.

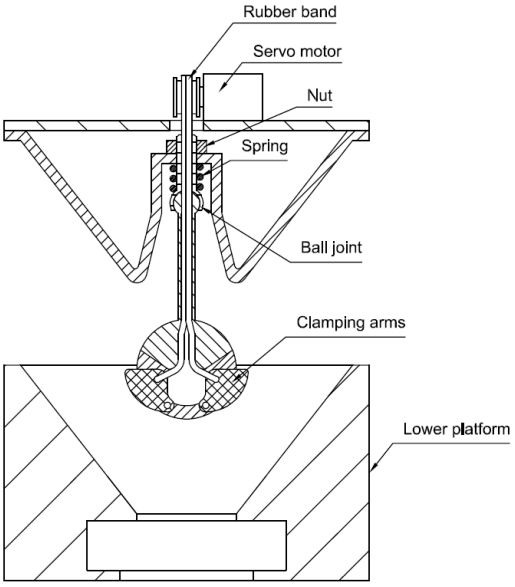

FIGURE 3.9: This concept works similarly to the one used on the Soyuz spacecraft docking system a drogue and a cone with ball end. It is very hard to implement camera or sensors in the center

3.2.8 Concept 5 - Electro magnet

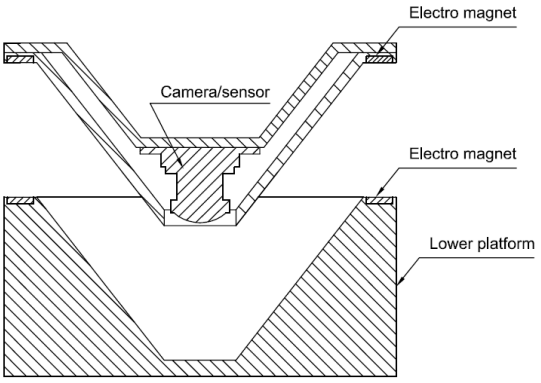

FIGURE 3.10: A very simple concept with few parts, electric magnets are used to lock and release the lower platform to the upper one. A camera or sensor can be mounted in the center

This concept was assumed to have about 12 components. The components are quite well suited for manufacturing with plastic injection moulding and assembly is very easy. Due to the simplicity and no moving parts the lifetime is assumed to be quite long as well a very low service is required. The concept is considered to be very sensitive to environmental factors such as dust that can prevent the magnets to lock safely. The power consumption is assumed to be very little when locked or open.

3.3 Adams model

To achieve a satisfying comparison of concepts and to optimize the design parameters, Adams View from MSC software was used for dynamic simulation. Due to time restrictions, no physical experiments were to be carried out within the scope of this thesis and therefore a huge consideration needs to be given to contact mechanics in Adams View. This field is very complex and subsequently hard to predict contact forces without any experimental data. This is due to the fact that the parameters set for the simulation are not solely based on material properties but also on the area of solids in contact, dampening and stiffness.

The material used for all simulation was Nylon 6/6 for both platforms and the frictional coefficients were chosen accordingly to that material. The need for exact frictional coefficient according to a manufacturer for a specific Nylon polymer were not of a great concern. This is due to the fact as mentioned before that the exact true values of normal forces could not be attained and therefore the exact true friction forces could therefore also not be determined. Furthermore the coefficient of friction is assumed to vary over the lifetime of the product and therefore a range of coefficient of friction is of more interest. The aim of the simulation within Adams was therefore finding the influences the frictional forces has on the performance of the design and making the design as insensitive to variations caused by frictional forces. Both the coefficient of kinetic friction (μ_k) and static friction (μ_{st}) were considered in the design. The values used for the coefficient of kinetic friction was 0.05 - 0.2 and for the coefficient of static friction was 0.2 - 0.35. To motive the choice to have a general value for the coefficients of frictions in stead of only one value from a specific manufacturer data sheet, was the fact that the coefficient of friction will change over the lifetime of the product. Both dust and other contaminations are likely to accumulate over time on the platforms as well as usage may scratch the contact surfaces and/or polish them. Other factors like temperature contribute to the coefficient of friction. The function used in ADAMS for estimation of frictional forces was the Coulomb friction.

The parametric model was created with design variables in ADAMS View and the same model was used for all simulations results in chapter 4. To simplify simulation a point mass was used to simulate the effect of the multi-copter. The point mass only has mass properties and no inertia properties. The reason that inertia was not included in simulations was both that no model was available of the multi-copter and therefore an estimation would be required and it was furthermore assumed that the inertia of the multi-copter would have negligible effect compared to the resistance of the multi-copter to move caused by applied forces and therefore keeping it level at all time. As mentioned

before, no simulation was done including the control mechanism of the multi-copter. The simulation set up can be seen on figure 3.11.

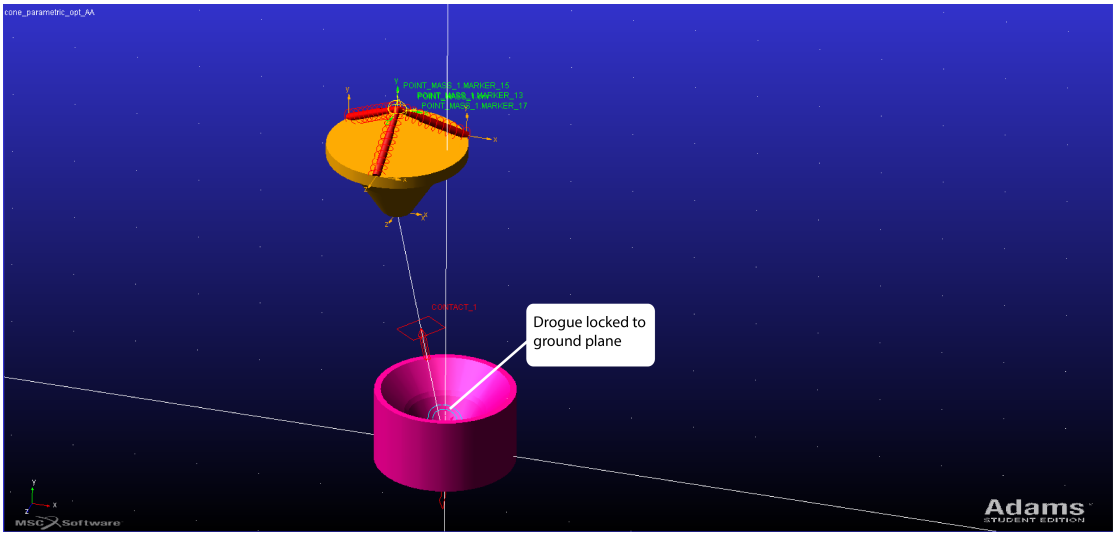

FIGURE 3.11: The setup for testing within MSC. ADAMS VIEW. Acceleration due to gravity was set in the negative direction of the y-axis

The lower platform was fixed to the ground while the upper platform was located as is described in the design cases, see figure 3.13. No constrain was therefore on the upper platforms but contact element was created between the lower platform and the upper platform as described later. To accommodate for the dampeners three spring dampeners were connected from the point mass to the top edge of the upper platform in a tripod set-up. This set-up therefore accommodated for the required movement allowing six degrees of freedom. The rubber dampeners that were determined to be used do have very little stiffness. To determine their values for the simulation multiple simulations were done for the different design cases and their values were determined as to provide under-dampened characteristics but be just stiff enough allowing the point mass to return to its original equilibrium position after impact. The values to be used for the dampeners are presented in table 3.1.

TABLE 3.1: Parameters values for spring dampeners within MSC. Adams

Stiffness [N/mm]	8
Dampening [N-sec/mm]	0.6
Preload [N]	0

It should be noted here that although these values are quite high for such a small system the spring dampeners were inclined and therefore vertical stiffness is much less than those numbers represent and can be calculated with simple trigonometry calculations at a given angle for the spring dampeners. No available data was attained on the

dampener properties and no physical tests were done for comparison. Furthermore the dampeners used in the simulation behave linearly while the rubber dampeners do behave non linearly. Simulation time of $0.5[sec]$ was used for all simulation runs with 500 steps except for where analysis for contact parameters for the impact function were analysed.

3.3.1 Normal contact forces

The true value of the normal contact forces can not be evaluated precisely without experimental data to confirm the approximation one needs to make the simulations. Therefore the goal was to find out if any pattern did arise between the geometry shape and the contact forces and to consequently minimize the contact forces. This method would therefore reduce the contact forces as possible although not predicting the exact value of the contact forces. For all cases the "Impact function model" was used in Adams that assumes a Hertzian contact between the two solids. Four variables must be defined, namely stiffness, force exponent, damping and penetration depth. The Impact function is described as follow within Adams: $IMPACT(q, \dot{q}, q_o, k, e, c_{max}, d)$ where q is the actual distance between the objects, $\dot{q}$ is the time rate of change of the variable q, q_0 is the trigger distance used to determine when the contact force turns on or off respectively and it is recommended to be a real and constant value, k is the stiffness coefficient, e is the stiffness force exponent, c_{max} is the damping coefficient and finally d is the damping ramp-up distance and defines where the maximum dampening occurs. The equations used to calculate the impact force are as follows:

$$F = 0 if q > q_0 \tag{3.1}$$

$$F = k(q_0 - q)^e - c_{max}\dot{q} \cdot STEP(q, q_0 - d, 1, q_0, 0) if q < q_0 \tag{3.2}$$

The $STEP$ function is used approximate an ideal mathematical step function but discontinuous function is not acceptable. The benefits of the IMPACT function for the analysis is that it is better suited for analysing the contact forces that are of great importance of the design [12] compared to the Restitution function.

The method to determine parameters was by inspecting behaviour of a simulation that one would not expect to happen in the real world. To achieve this each and every parameter was altered from the default values and the effect noted by plotting the movement of the center of mass of the upper platform against time. The case used for this analysis was when the upper platform was dropped from the height of H_{max} aligned with the lower platform and horizontal. To determine the coefficients the default parameters within MSC. Adams were used. First the force exponent e was varied. Recommended values for the force exponent are $1.1 < e < 2.2$ [14] [3] since lower values of the force

exponent could cause discontinuities. To compare the position of center of mass was plotted against time to represent any vibration that would occur. Figure A.1 in the appendix A shows that at $e = 1.8$ little vibration occurs and this happens as well for $e = 2.2$. It was noted that at high values of the force exponent that unrealistic oscillation occurred over longer time periods. Figure A.1 in appendix A was made with simulation time of $0.5[s]$ and with 200 steps. It was also noted that with low resolution (few steps) the results changed considerably and that large movements did not occur but the smaller oscillation was still noticeable. By a recommendation, soft materials (rubber) should have lower exponent of $e = 1.1$, soft metals have exponent of $e = 1.5$ and hard material to have exponent of $e = 2.2$ [14]. The damping ramp up distance was chosen to be $0.1[mm]$ This was based upon a recommended value of $0.01[mm]$ [3] in the Adams solver documentations that was assumed to be suited for metals. Since a Nylon polymer was to be used the assumption was used to increase the depth were the maximum dampening occurs. Considering the results from the test the force exponent used for nylon was determined to be $e = 1.6$. The stiffness, k can not be simply determined from the material properties since the geometry and therefore the contact area plays a crucial role in determining its value. Adding complexity to determine the stiffness was the fact that the upper platform is designed to be over damped. This makes determining, when the stiffness levels are to high causing great oscillation, impossible with the current set-up. It can be noted that too low stiffness causes the upper platform to penetrate through the lower platform. The analysis was done by having the damping coefficient, c_{max} to be equal to $1[\%]$ [14] of the stiffness and then changing the value of the stiffness. The results can be found in figure A.2. From this figure the value of the stiffness was determined to be about $1e^5$ $[N/mm]$ and was this used for all dynamic simulations. For further investigation of the chosen values the HertzWin software was used. The HertzWin software is a Hertzian stress calculator and with it one can calculate all the resulting stresses, contact area size, Hertz contact stiffness, the damping ramp up distance and other parameters of interest for elliptical contact [15] [16] [17] as well as Line contact. Further literature for the equation and method used can be found in the software that is free to download.

3.3.2 Contact friction

Frictional forces were included in all the simulations and a Coulomb frictional model was used for the analysis. The friction force function is set within the "create contact" function within MSC Adams and it can be set to none, Coulomb or user defined. The Coulomb model is relatively simple and is based on velocity. A graphical representation of the frictional forces is represented on figure 3.12.

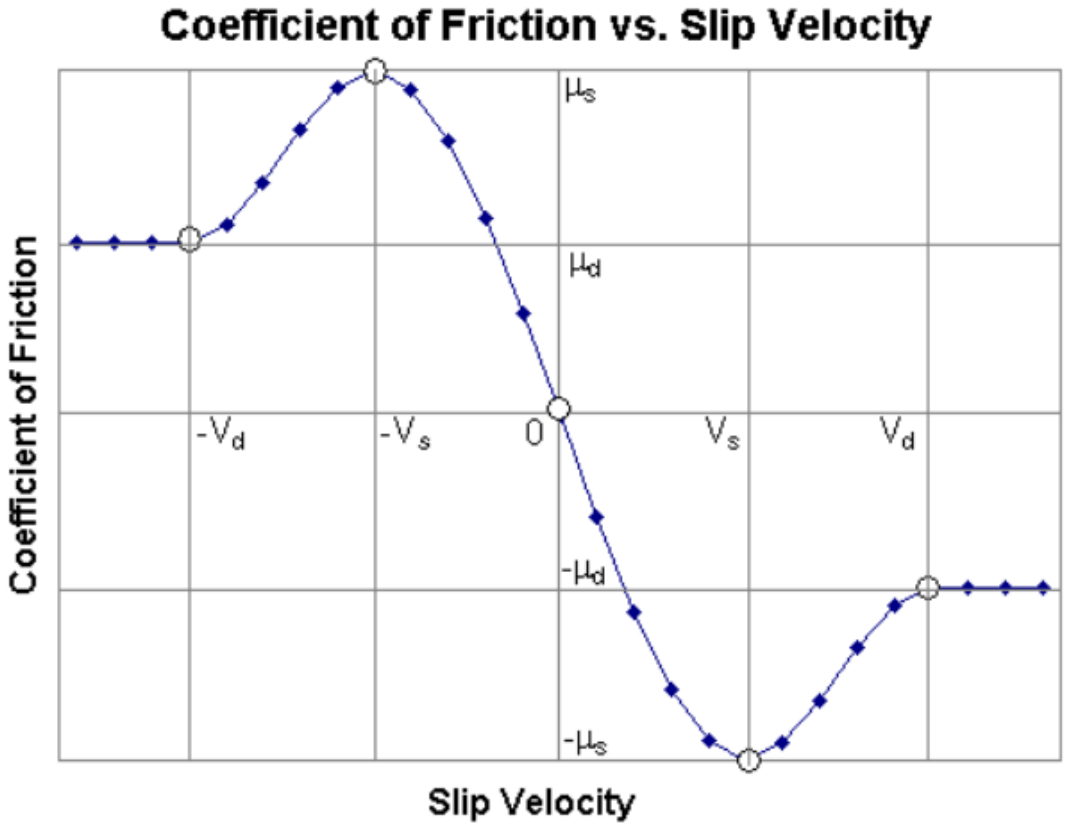

FIGURE 3.12: Representation of how the coefficient of friction is calculated within the Coulomb friction force function in MSC. Adams. Image courtesy of MSC. Software [3]

On figure 3.12 μ_s is the coefficient of static friction, μ_d is the coefficient of dynamic friction, V_s and V_s represents the velocity when μ_s is used and when μ_d is used. V represents the stiction velocity at a contact point. The function is therefore a cubic step function that defines the coefficient of friction. Although contact is fundamentally a discontinuous event as the acceleration of the two geometries is discontinuous and therefore generates a large spike that represents large force or impulse at the moment contact occurs. This function within Adams however uses a continuous function except at zero stiction velocity the coefficient of friction is not defined [3]. The values used for the Coulumb friction force can be found in table 3.2. The coefficients of friction are an assumption of how they can vary over their lifetime and are based on multiple material data-sheets from different manufacturers that manufacture Nylon plastic. The stiction and friction transition velocity were kept at their default value since no better estimation could be generated for this analysis.

TABLE 3.2: Settings for the Couloumb friction force function in MSC. Adams

Coefficient of static friction μ_s	0.2-0.35
Coefficient of dynamic friction [N-sec/mm]	0.05-0.2
Stiction transition Velocity [mm/s]	100
Friction transition Velocity[mm/s]	1000

3.4 Materials

Based on the PDS it is a demand to achieve a lightweight product with a very low cost. Those two criteria are the two most critical ones. Since the product is to be designed for mass production and it is intended to carry low weights, plastic materials are very feasible. Based on those criteria it was therefore determined that Nylon would be a good choice for the material. More specifically a Zytel® nylon resin was chosen as the material for the design.

3.5 Concept evaluation

Total of eight concepts, thereof four variations of one concept were developed to solve the problem of autonomous landing and transportation of cargo. A detailed analysis of all the concepts would require great amount of time and would greatly exceed the time-scope given for this project. Rough sketches were made of all the concepts so that each concept could be evaluated against each other. This was done by using a table where the most important design parameters were weighted and each concept given a score ranging from one to five where 5 is the highest score achievable.

TABLE 3.3: The Pugh matrix, one concept stands out as an obvious winner

		Concept															
		Concept 1 - A		Concept 1 - B		Concept 1 - C		Concept 1 - D		Concept 2		Concept 3		Concept 4		Concept 5	
Selection criteria	Weight	Rating	Weight. score	Rating	Weight. score	Rating	Weight. score	Rating	Weight. score	Rating	Weight. score	Rating	Weight. score	Rating	Weight. score	Rating	Weighted score
Total weight	25%	2	0,5	2	0,5	1	0,25	4	1	2	0,5	3	0,75	1	0,25	5	1,25
Robustness	15%	2	0,3	1	0,15	3	0,45	4	0,6	2	0,3	2	0,3	3	0,45	3	0,45
# Of components	20%	3	0,6	3	0,6	2	0,4	5	1	5	1	1	0,2	4	0,8	1	0,2
Cost	15%	2	0,3	2	0,3	2	0,3	4	0,6	2	0,3	3	0,45	1	0,15	5	0,75
Environment	10%	2	0,2	2	0,2	3	0,3	4	0,4	3	0,3	1	0,1	3	0,3	1	0,1
Sensor/electrics	10%	2	0,2	2	0,2	2	0,2	4	0,4	2	0,2	3	0,3	1	0,1	5	0,5
Servicability	5%	1	0,05	1	0,05	2	0,1	4	0,2	2	0,1	2	0,1	2	0,1	5	0,25
Total score		2,15		2		2		4,2		2,7		2,2		2,15		3,5	
Rank		5/6		7/8		7/8		1		3		4		5/6		2	
Continue?		No		No		No		Continue		Continue		No		No		Continue	

The number of parts was chosen to be the most important criteria since it contributes greatly to almost all the selection criteria except the sensor/electric and environment criteria. The weight is determined by the material of the component required as well as the number of components. Robustness is determined from the number of parts as well as the complexity of the locking mechanism where contact mechanisms like cams was determined to greatly reduce robustness of the design. Cost was determined from the number of components, manufacturing methods required to manufacture the concept as well, materials required and assembly time. Environment is used to determine how well the concepts can cope with dust build up, different temperatures, water and how

that affects their performance. Sensor/electrics determines how easily sensors and other required electrics can be fitted to the concept and great concern was given to if a sensor could be located in the center position of each concept. Serviceability was determined from the number of components, especially moving parts as well as the complexity for example of the locking mechanism.

3.6 Design cases for concept evaluation

For better comparison of the performance of each of the three remaining concepts (Concepts 1-D, 2 and 5) three different cases were developed. All the remaining concepts have in common the same geometrical shapes which greatly simplified simulations. The aim was to check the performance of the different concepts for better comparison and evaluation. The performance parameters evaluated were the contact forces on impact, the average distance between the upper and lower platform measured from the center of the smaller diameter of each cone and finally a visual inspection of the docking. The cases developed can be seen on figure 3.13.

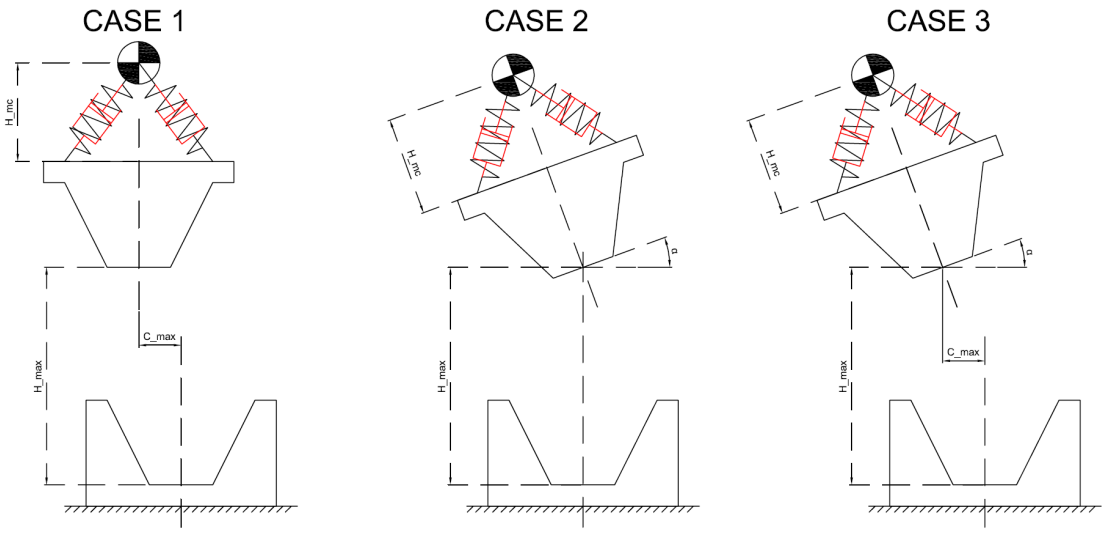

FIGURE 3.13: Three different cases were developed to test different concepts within the MSC. Adams software

The cases were made to represent the design's worst cases. Furthermore they represent a free fall of the upper platform from the height of $H_{max}200[mm]$ above the lower platform. Case 1 represents a case where the upper platform's center line is offset by $20[mm]$ with respect to the lower platform's center line. The upper platform is furthermore completely horizontal with respect to the lower platform. In Case 2 there is no offset between the centrelines but the upper platform has been rotated by $20[°]$ with respect to the lower platform. Case 3 is a combination of Case 1 and 2. Cases 2 and 3 can be expected when

the multirotor vehicle is flying in winds and the angular rotation is to counteract the drag forces caused by a wind as represented in chapter 1. It is predicted that Case 1 and Case 3 are more likely to happen in the real world but are highly dependant on the layout of electrical sensors. If the electrical sensors are located in the center the sensors would have better overview of the lower platform in Cases 1 and 3 than in Case 2. The parameters used for those cases are $C_{max} = 20[mm]$, $H_{max} = 200[mm]$, $H_{mc} = 30[mm]$ and $\alpha = 20[^{\circ}]$. The lower platform on figure 3.13 is grounded with no degrees of freedom. The upper platform has six degrees of freedom and initial velocity was zero with respect to the lower platform. Gravitational acceleration is applied downwards causing the motion of the upper platform toward the lower stationary platform. To simulate the effect of the multirotor vehicle a point mass representing the mass of the vehicle was constructed at $30[mm]$ above the upper platform connected by three dampeners-springs. The coefficient for the springs were kept the same at all times for all of the cases and both of the concepts.

3.7 Parameter optimization

For the design to be successful a great consideration needs to be given to multiple parameters of the product. For many design cases the number of parameters can seem to be overwhelmingly many and very hard to determine how or where to start. As described in the product design specification the main purpose of the parameter optimization was to achieve a design that performed in the best manner possible within the constrains from the PDS and to strive to achieve all of the requirements within the PDS. The design described in this thesis had a great number of different parameters, some independent and some related. Some of those parameters could be determined from the PDS while others were not as easily determined whereas others are uncontrollable. To better understand the design and the parameters involved a list of all parameters describing the design, shape and properties of product. Those parameters were then used to create a parametric CAD model within Autodesk Inventor and MSC Adams view. This parametrization saved a tremendous amount of time, especially since multiple simulation runs could be done within Adams were a specific constrains or limits were set to each and every design parameter. From initial simulation studies within ADAMS it could be understood by visual inspection as well as by looking at the simulation results the desired value for some of the parameters. Some parameters were needed to be maximized or minimized and therefore their values could be set according to constrains within the PDS or simply from the geometrical constrains. Figure 3.14 shows the geometry of the upper (Cone) and lower (Drogue) platform and how the shape is parametrised. Table 3.4 shows a list of those parameters and their constraints.

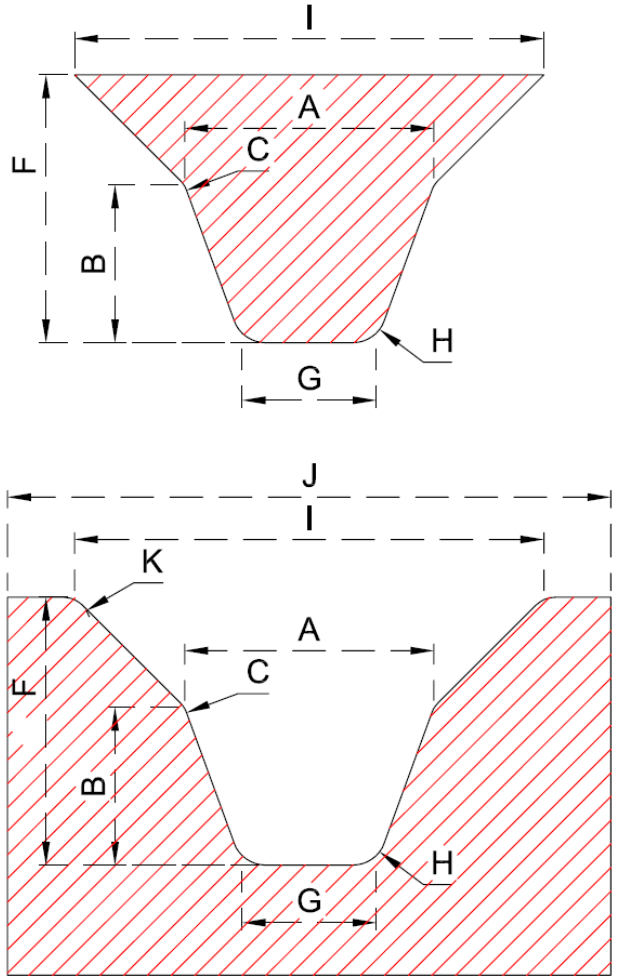

FIGURE 3.14: The geometry of the Cone (upper part) and the Drogue (lower part)and the definition of all the parameters for referencing the name of each parameter see table 3.4

TABLE 3.4: List of all the parameters used to describe the shape of the Cone and the Drogue

Sign	Parameters	Constrains	Units	Comment
A	Drogue mid diameter	$G \leq A \leq J - 30$	$[mm]$	Controllable
B	Drogue mid height	$10 \leq B \leq F - 10$	$[mm]$	Controllable
C	Drogue fillet	$10 \leq C \leq 28$	$[mm]$	Controllable
F	Drogue height	$F5 \geq 0$	$[mm]$	Maximize
G	Drogue bottom diameter	$G \geq 22$	$[mm]$	Minimize
H	Cone fillet	$H \leq 10$	$[mm]$	Maximize
I	Drogue diameter	$I \leq J - 10$	$[mm]$	Maximize
J	Drogue edge diameter	$J \leq 110$	$[mm]$	Maximize
K	Drogue edge fillet	$F \leq 10$	$[mm]$	Maximize
D	Coefficient of kinetic friction	$0.05 \leq D \leq 0.2$	NA	Uncoontrollable
E	Coefficient of static friction	$0.2 \leq E \leq 0.35$	NA	Uncontrollable

The constrains on some parameters in table 3.4 could be defined by maximizing the allowed offset from the centres between the centrelines of the Drogue and Cone (C_{max}) and using the constrains from the PDS. Also maximizing the fillets on possible contact surfaces would distribute the impact forces better and reduce the likelihood of failure due to plastic deformation. Bigger radius on fillets also increased the allowable C_{max}. Three controllable parameters (A, B, C) remained and could not be determined with this method and required further investigation. The uncontrollable parameters were included in this investigation and the effort was to find their effect on performance and see how the design could be made to be as insensitive to variation for those uncontrollable parameters as possible.

3.7.1 Performance

To find how the remaining parameters would effect the design a Design of experiments (DOE) was conducted. A factorial experiment was carried out for Case 1 and Case 2 since initial tests showed that the current design was not able to perform as required in Case 3 as described in Chapter 4. The parameters used in the experiment can be seen in table 3.4, marked as controllable or uncontrollable.
The results from the DOE can be found in table B.1 and B.2. It can be noted what parameters (Main effects) contribute the most to the performance. It is obvious from this table that parameters A (Cone mid diameter) and B (Cone mid diameter) contribute the most and it also interesting to note that their contribution is very much related to each other from the combined main effect. Parameter C (Cone fillet) furthermore shows that it effects the performance very little and especially for Case 1. The table B.1 and B.2 also shows how the uncontrollable factors that contribute to the performance. Parameter D (Dynamic friction coefficient) contributes very little but parameter E (Static friction coefficient) does greatly effect the performance. From this analysis it can therefore be determined that controllable parameters A and B need to be investigated further as well as the effect of the uncontrollable parameter E. This DOE therefore greatly reduced the number of parameters making further investigation much simpler. To investigate the three parameters considered to have greatest effect on the performance a new DOE was carried out within Adams. Three different DOE were carried out where the coefficient of friction was kept at a fixed value for each experiment. Table 3.5 shows the setting for this DOE.

TABLE 3.5: DOE set-up for Case 1 and 2 to determine robust parameter values

# of run	st coeff.	A (Cone mid diameter)	B (Cone mid height)
1	0.2	Full factorial, 10 levels, range $22 - 80$ $[mm]$	Full factorial, 10 levels, range $20 - 40$ $[mm]$
2	0.275	Full factorial, 10 levels, range $22 - 80$ $[mm]$	Full factorial, 10 levels, range $20 - 40$ $[mm]$
3	0.35	Full factorial, 10 levels, range $22 - 80$ $[mm]$	Full factorial, 10 levels, range $20 - 40$ $[mm]$

From this three DOE the resulting values were plotted as a surface within Matlab. The results can be seen on figure 3.15.

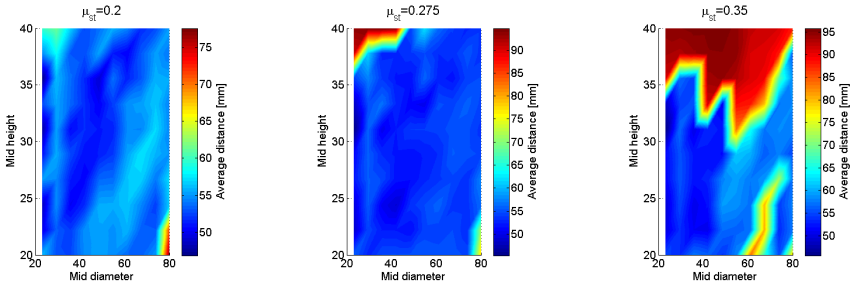

FIGURE 3.15: The results from the DOE for Case 1 for different values for the coefficient of static friction

The plots give an indication on what areas the combined parameters give the lowest average distance and therefore the time it takes to achieve successful docking. Even more interesting result can be interpreted from the plots that the static coefficient of friction plays big role in the docking as predicted from the first DOE. By combining all the results with a plot showing the average values from the simulation a clearer picture can be attained on a preferred value for the parameters. This plot can be seen on figure 3.16.

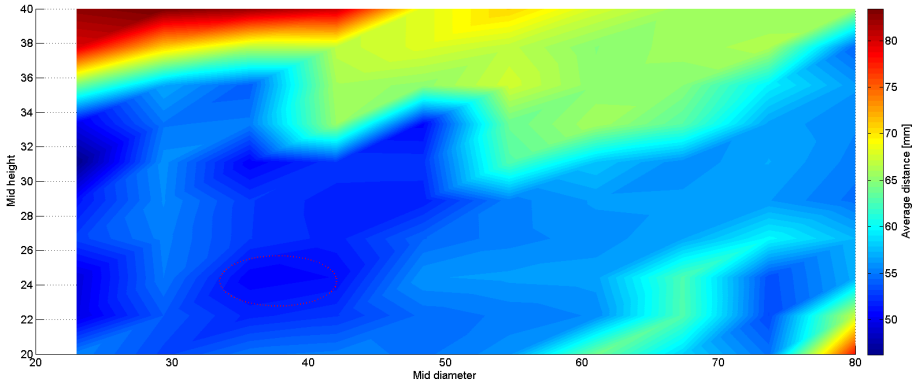

FIGURE 3.16: The average results resulting from merging the plots on figure 3.15 together. A red ellipse is drawn around an area with feasible values for the parameters

One particular spot on figure 3.16 (shown with a red ellipse) is very interesting it seems both on the combined plot on figure 3.16 as well as on the three different plots on figure 3.15 that all show a successful docking. And what is even more important is that this area seems to be not sensitive (Low gradient around it). For the smallest mid radius and a mid height of about 31 $[mm]$ it can be noted that this is configuration produces the lowest result with a average distance of about 46 $[mm]$. This configuration is very

sensitive though (very high gradients around the area) and therefore it can be said that it is not as robust and for higher coefficients of friction than tested for here it might not achieve a successful docking. On top on that having a small diameter for the parameter, cone mid diameter is not feasible since it both could make manufacturing harder (Plastic injection moulding) and also there is less room for sensors inside or other equipment that might be required. From the resulting plots it was therefore determined a range for the parameters. This range can be found in table 3.6 and is represented approximately by the red ellipse on figure 3.16.

TABLE 3.6: The range of the parameters chosen from figure 3.16

Parameter	Min. value	Max value
Cone mid diameter	35	42
Cone mid height	23	26

The same was done for Case 2 as for Case 1. the results from the DOE can be found in appendix B. The results there show a similar pattern for the coefficients of frictions, that is coefficient of kinetic friction has negligible effect on the performance on docking between the two platforms but the coefficient of static friction has some effect but much less effect than noted in the DOE for Case 1. On the other hand the drogue fillet parameter has much more effect on the performance and all the three controllable parameters seem to effect the performance. Very important fact is that although for Case 2 that for all cases tried out successful docking occurs within the given time frame. This gives the results for Case 1 higher importance since not all set-ups result in a successful docking within the given time frame. Although Case 2 is not of the same importance the same three DOE were carried out as for Case 1 with different values for the coefficient of static friction and by keeping the drogue fillet parameter fixed to value of 20 $[mm]$. The results are shown in figures 3.17 and 3.18.

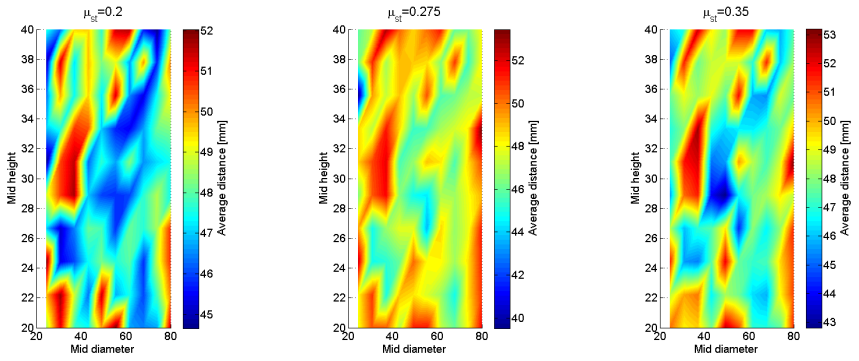

FIGURE 3.17: The results from the DOE for Case 2 for different values for the coefficient of static friction, cone fillet radius is kept constant at 20 $[mm]$

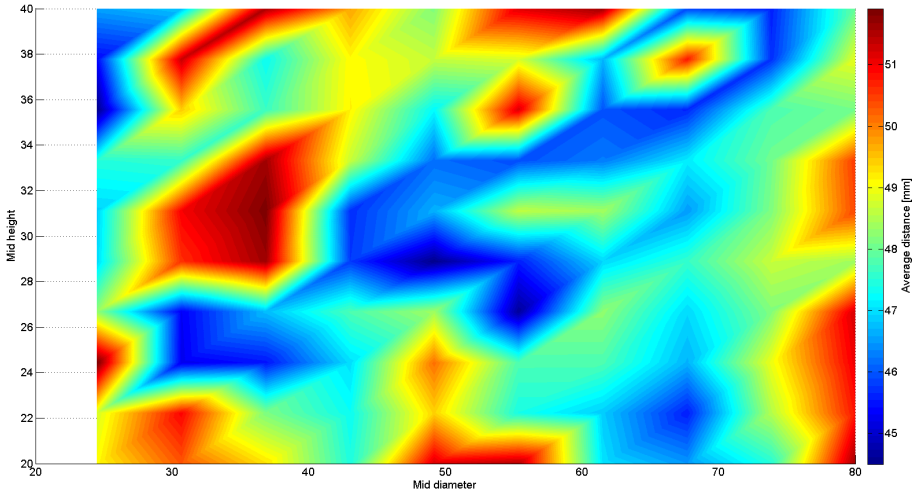

FIGURE 3.18: The average results resulting from merging the plots on figure 3.17 together

From those plots it can be noted that the values determined for the parameters cone mid height and cone mid diameter previously for Case 1 the result also produce a good performance. It is important to note that the range of the average distance is considerably less for Case 2 as mentioned before meaning that for all set-ups a successful docking did occur. Since the value of the drogue fillet had very little effect on results for Case 1 but considerable effect on Case 2, Case 2 was used to determine a good value for that parameter. This was done with a design study with 10 and 100 levels respectively for the value of the drogue fillet radius. The coefficient of static friction, μ_s was kept at a constant value of 0.275 and the parameters cone mid diameter and cone mid height were also kept at a fixed value of 38.5 $[mm]$ and 24.5 $[mm]$ respectively. The results are shown in figure 3.19.

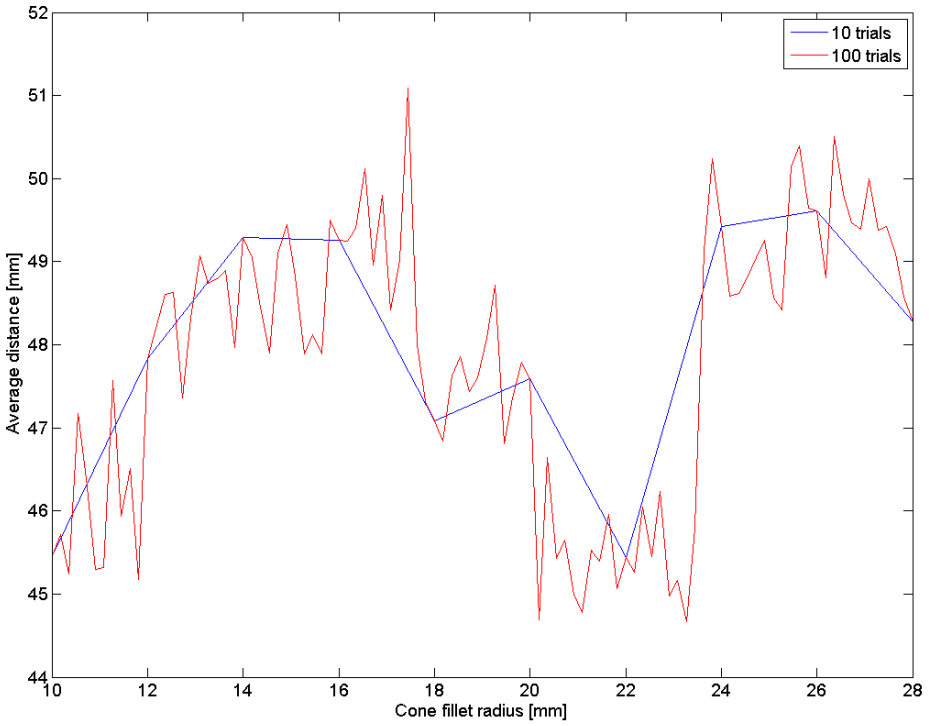

FIGURE 3.19: The results from the design study by testing 100 values of the cone radius between 10 $[mm]$ and 28/$[mm]$

According to the PDS it is desirable to increase the volume inside the cone to be able to better fit sensors or other electronics it is good to have the drogue fillet radius relatively large. Therefore the value of the drogue fillet radius was determined to be 22$[mm]$ from the result shown in figure 3.19 and with the PDS. This gave a decent performance compared to other values although performance difference could be neglected.
It should be pointed out here that since it is very hard to determine the contact forces without experimental data that some inaccuracy is expected in the results of the average distance. This is due to the fact that the frictional forces are highly dependant on the contact forces. The simulation above are therefore merely a way to show how the frictional forces impact the performance and to find the trend of how the frictional forces affect the performance and to come up with a product that is insensitive to the frictional forces. This is important since the coefficient of friction will change with use and under different environmental conditions.

3.8 Visual comparison

In all the dynamic simulation described earlier the shape of the cone and drogue was analysed. Those simulations therefore did not include the arms shown in the multiple

variations of Concept 1. To accommodate for this multiple dynamic simulations were carried out including those arms. The model was made within Autodesk Inventor and exported to the MSC. Adams View environment and can be seen on figure 3.20.

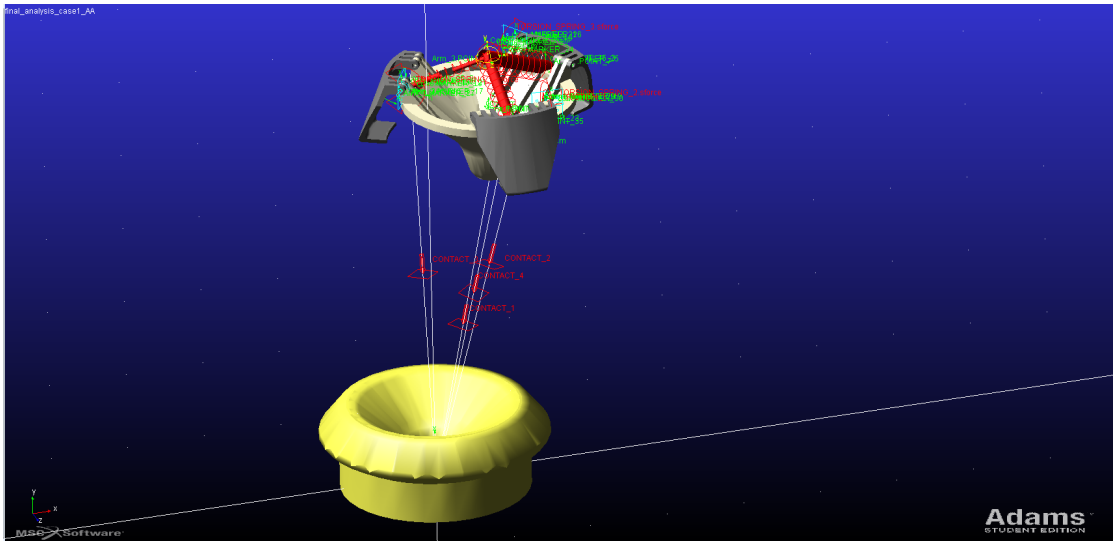

FIGURE 3.20: Simulation of Concept 1 for all variations.

The cone and drogue had the optimum shape that was determined from earlier simulations. The arms have a torsional spring located at their revolute joints. The values for the torsional spring were attained from a documentations from manufacturers to attain reasonable estimation on stiffness of the spring that could be fitted at the joints. The springs furthermore had no pre-load and their stiffness was set to 0.256 $[Nmm/deg]$. The effect of locking the arms were not included in the simulation.

Chapter 4

RESULTS

4.0.1 Concept evaluation results

For Case 3 all concepts failed to achieve successful docking. Figure 4.1 illustrates why successful docking is hard to achieve with the proposed concepts.

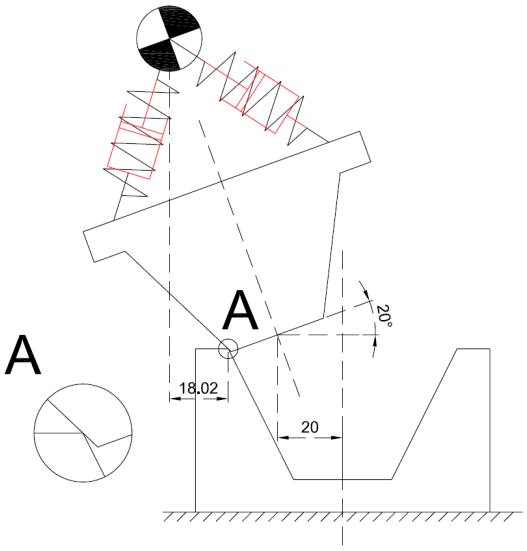

FIGURE 4.1: The center of mass of the multi-copter (represented by a center of mass icon) is off-setted from the point of contact that causes a moment that results in a rotation of the multi-copter from the lower platform.

To be able to achieve docking under those extreme conditions represented in Case 3 concepts 1,2 and 5 can be enlarged so they will be able to accommodate for the offset of 20$[mm]$. By doing so the design of concepts 1,2 and 5 would be larger than the initial size requirements of this product according to the PDS. To accommodate for this, dynamic simulations with concept 1 were carried out hoping that the arms could counteract the moment caused by the center of mass of the multi-copter but such results were not achieved. Therefore a successful docking for Case 3 was not achieved. It should

be pointed out that simulation including the control circuit of the multi-copter could allow for a successful docking.

4.1 Optimum shape

By using table 3.4 and the results from the DOE a shape of the two platforms could be determined to be the optimum shape with the given constrains of the PDS. The final shape of the cone and drogue can be seen on figure 4.2.

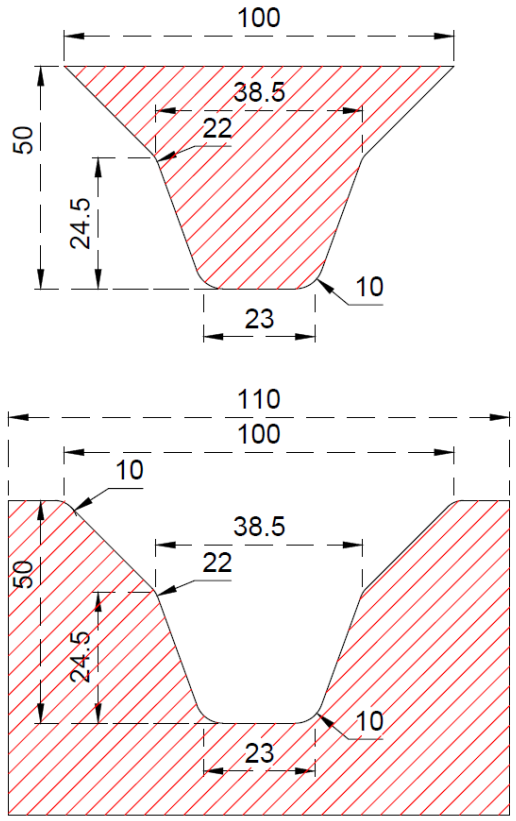

FIGURE 4.2: The final shape of the two platforms, determined with DOE and detailed analysis

This shape of the two platforms was therefore found to perform best under varying coefficient of friction and be within the given size boundaries described in the PDS. For Design cases 1 and 2 the proposed design did perform as required but not for Design case 3.

4.2 Results from visual comparison

From visual inspection it was concluded that Concept 1 with arms included performed better since it reduced the rebound of the upper platform. This did not greatly influence

the average distance but once the larger diameter of the drogue and the cone touched they were not separated again. This result therefore could greatly help in docking, especially in windy conditions that could otherwise blow the multi-copter off the lower platform before the two parts could be locked together.

4.3 Final result

As a final result concept 1-D was considered to outperform all other concepts. This result is therefore both based on the Pugh matrix, DOE and visual inspection. In all of those analyses Concept 1-D performed as good or better than all the other concepts. Furthermore all variations of Concept 1 do have a potential to be able to dock for Case 3, by utilizing the arms as a support and counteract the moment caused by the center of mass of the multi-copter. Finally the concept proposed therefore was capable of achieving most of the requirements defined in the PDS. As mentioned before the concept did not achieve successful docking for Case 3 and therefore could not achieve the demand to be able to dock with horizontal misalignment of 20 $[mm]$ and angular misalignment of 20 $[°]$ both at the same time. All other demands of the PDS were otherwise achieved as well as some of the wishes in the PDS and the weight of the upper platform is assumed from the CAD model to be around 200 $[g]$ And therefore only about 10% of the assumed weight of the multi-copter.

Chapter 5

DISCUSSION AND CONCLUSION

5.1 Discussion

To set-up a realistic contact mechanism with the impact function in Adams it can be said that experimental data can greatly increase the accuracy of the dynamic simulation and is extremely important to validate the results. This thesis is therefore a tool to identify any trends that arise between the coefficients of friction and the contact forces between the geometry of the two platforms. Much of the background research and inspiration for this thesis was from docking mechanism developed for space exploration. Mainly this was due to extensive information available on those systems and decades of experience in such systems. Those systems were considered to be a good source partly because they rely on one stationary platform while the other is platform is guided in place very similar to the application in this thesis. Although those systems are used in almost zero gravity it was assumed that a system as proposed within this system the presence of gravity would only aid in successful engagement of the two platforms since the lack of gravity in space makes such system more challenging to design.

A major consideration was given not to make the optimum system with unlimited cost but rather a feasible solution for mass production that could be used for transportation of goods worldwide with low cost as well as reducing the weight of the system as much as possible, but cost and weight often go hand in hand. The weight of the upper platform is 50% lighter than the initial demand and the weight could furthermore be decreased by further analysis of force distribution over the platforms with finite element analysis. In this thesis very little consideration was given to the weight carrying capability of actuators and the structure itself for simplification. The weight carrying capacity was nevertheless kept to minimum by adding restraints on the movement of the lower

platform with respect to the upper platform when they were engaged. For example forces generated by horizontal movements of the lower platform where not carried by the actuator but the geometry of the platforms instead, therefore forces generated by horizontal movements do not have to be considered in calculation on maximum forces expected on actuators.

Having the PDS made at the beginning of the project helped greatly by serving as a document for desirable results of the design and was frequently looked at in the design process and it helped in keeping a good overview of feasible solutions. The PDS also helped greatly in organizing and simplifying the decision process of determining multiple parameter values when it was down to determining the shape of the platforms. In the end only three controllable parameters were left that could not be determined from the PDS.

5.2 Conclusions

It can be noted that the kinetic coefficient of friction has very little effect on the performance compared to the static coefficient of friction. Therefore it can be concluded that further design would not require detailed analysis of the kinetic friction if both kinetic and static coefficients of frictions are within the boundaries given in this thesis. Although a more thorough analysis of the stiction and friction velocities along with the normal force could give better understanding on the effect of the two coefficients of friction.

The diameter of the cone greatly contributes to the required accuracy of the electronics and software for automatic landing and therefore can be increased to accommodate for lower accuracy of electronic sensors than assumed in this thesis.

This thesis work and the analysis described in it are based upon multiple assumptions. Most of those assumptions were regarding the contact mechanics. No complete guidelines could be found for method to determine the correct parameters within MSC. Adams without doing physical testing. Only vague recommendation and guidelines could be found. Therefore it is important to point out that the results from the dynamic simulation should be read with precaution. A good model has therefore been created for testing different parameters of the design and changing the parameters of the impact function within MSC. Adams can be quickly and easily done as better estimation of their values is attained.

The thesis findings are therefore that the best method to align two platforms is to use a cone on the upper platform and a drogue on the lower platform. For maximized robustness the number of components and especially the number of moving components are minimized and all sensitive areas are enclosed and therefore protected against the environment. Therefore Concept 1-D is the best method for autonomous landing and transportation of cargo with a UAV.

Chapter 6

RECOMMENDATIONS AND FUTURE WORK

6.1 Recommendations

Further verification of the contact mechanism is recommended. This thesis is mainly a tool to identify the parameters that have the most impact on performance under varying coefficient of friction as well as to reduce the impact forces. To determine those exact values multiple parameters of the material used need to be known in details and it is recommended that the coefficient of friction is to be measured under different temperatures and with different surface roughness since the material will wear with use.

Further verification of this thesis work could be done in MSC. Adams by using the contact feature Poission restitution model where the coefficient of restitutions can be attained from physical testing.

It is recommended to increase the Hertz contact stiffness as later results with calculation based on the HertzWin software showed that the stiffness used could be to low for some of the design cases. Also, the effect of the stiffness parameter in the impact function within MSC. Adams should be increased and the effect on the simulation be compared to the simulations done within this thesis.

Validation for all of the multiple parameters used in the impact function within Adams is therefore highly recommended both with physical testing and also by changing different parameters to see how they influence the simulations.

6.2 Future work

Future work includes further testing of a prototype of the two platforms to compare to the analyses done in this thesis. By being able to predict the forces in the dynamic simulation by validation of the multiple parameters required for the contact mechanism as well as being able to better measure the range of the coefficient of friction especially the static coefficient of friction it is possible to use those results to do a finite element analysis to reduce the weight of the platforms.

The geometry proposed here could be made more complex by introducing spline curves or other similar geometrical curves, this would greatly increase the number of controllable parameters and therefore making simulations and or DOE more difficult and time consuming.

For simplification in this thesis, it was assumed that all actuators would be able to carry the given load, further analysis is required to determine if the size of the required actuator is sufficient and if not it could greatly alter the size of the proposed platforms.

Furthermore, analysis should be done by including the control circuit of the multi-copter. This could perhaps be done with integration of Matlab Simulink and MSC Adams and analysis carried out on the resistance of the multi-copter to forces applied trough the two platforms when they come in contact. By also adding the inertia of the multi-copter one could therefore validate the assumptions made within the thesis when inertia is not included since it is assumed to have neglectful effect on the result compared to the control circuit of the multi-copter that contributes greatly to the final result.

Another effect that could be considered is the ground effect generated by the pressure difference on the propellers that will greatly contribute to the behaviour of the multi-copter when it gets closer to the ground. Further analysis as described here are very complex and might require extensive physical testing to fully validate assumptions required to carry out further more detailed analyses than done in this thesis.

A very important work needs to be done in computer vision hardware and algorithms to fully validate if automatic landing is possible with the accuracy required of the platform proposed in this thesis and also analysis of the robustness of such a system is required to be able to fully solve the problem of autonomous pick up and transportation of cargo with UAVs. To fully complete the design concept proposed in this thesis electrical sensors need to be integrated to the design and to make sure they can fit within the space in the concept.

Further work of this platform would greatly benefit from more detailed analysis and design of the dampeners. Optimization of the best dampening characteristics would benefit the design but it is recommended that those analyses would be carried out after determining the contact forces and frictional forces as well as after the control system of the multi-copter is included in the analysis. By including all those factors a very realistic behaviour could be attained and further simulation could be carried out for example by incorporating the environmental effects like wind and the affect it has on the performance of the system.

A very helpful tool could be the creation of an extensive guide for MSC. Adams where results of analysis of contact and impact of different materials and shapes and sizes are periodically tested and the result measured under different conditions, for example impacts at different velocities. All this data could then be used for carrying out dynamic simulation where parameters could be adjusted to attain similar results as in the experimental analysis. This guide could therefore serve as a guideline for future simulations although it would never replace physical testing for comparison.

Appendix A

Impact parameters, MSC. Adams

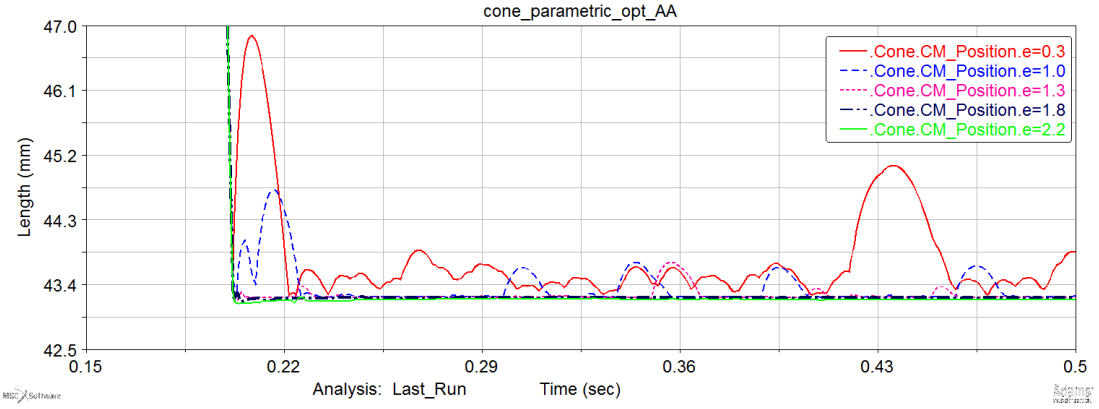

FIGURE A.1: The effect of varying the stiffness force exponent, e while other parameters are kept fixed at their default values.

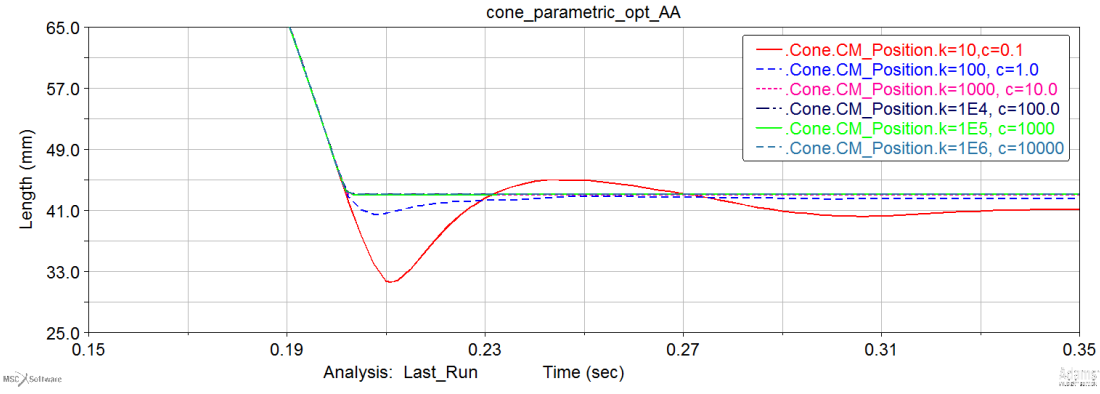

FIGURE A.2: The effect of varying the stiffness coefficient, k while other parameters are kept fixed at their default values except the damping coefficient, c_{max} was determined to be 1[%] of the stiffness value

Appendix B

Design of experiments

Table B.1: The results from the DOE for Case 1

Run						D	μ_{dy}	-	-	+	+						
						E	μ_{st}	-	+	-	+						
	A	B	C	AB	AC	BC	ABC					Average	Range	STD	Main effect	Average	STD
1	-	-	-	+	+	+	-	48,58	47,37	48,58	47,37	47,97	1,21	0,60	A	38,18	0,75
2	-	-	+	+	-	-	+	56,03	54,66	56,03	54,66	55,34	1,37	0,69	B	42,79	14,59
3	-	+	-	-	+	-	+	72,57	94,75	72,57	94,75	83,66		11,09	C	1,02	1,59
4	-	+	+	-	-	+	-	59,65	94,62	59,65	94,62	77,13	34,97	17,48	AB	-72,17	0,95
5	+	-	-	-	-	+	+	78,71	79,60	78,71	79,60	79,15	0,88	0,44	AC	-0,67	-1,65
6	+	-	+	-	+	-	-	78,89	79,78	78,89	79,78	79,33	0,89	0,45	BC	-14,08	1,54
7	+	+	-	+	-	-	-	55,85	87,95	55,85	87,95	71,90	32,10	16,05	ABC	13,72	-1,61
8	+	+	+	+	+	+	+	55,99	87,81	55,99	87,81	71,90	31,82	15,91	D	0,00	0,00
							Average	63,28	78,32	63,28	78,32				E	34,14	5,79
							Range	30,31	47,38	30,31	47,38						
							STD	10,95	16,73	10,95	16,73						

Table B.2: The results from the DOE for Case 2

Run						D	μ_{dy}	-	-	+	+						
						E	μ_{st}	-	+	-	+						
	A	B	C	AB	AC	BC	ABC					Average	Range	STD	Main effect	Average	STD
1	-	-	-	+	+	+	-	46,51	47,19	46,51	47,19	46,85	0,68	0,34	A	-13,26	-0,35
2	-	-	+	+	-	-	+	48,60	50,67	48,60	50,67	49,63	2,08	1,04	B	12,90	-0,11
3	-	+	-	-	+	-	+	68,97	69,33	68,97	69,33	69,15	0,36	0,18	C	-19,77	0,31
4	-	+	+	-	-	+	-	47,59	46,12	47,59	46,12	46,86	1,48	0,74	AB	-26,15	0,12
5	+	-	-	-	-	+	+	50,92	51,75	50,92	51,75	51,34	0,84	0,42	AC	19,24	-0,31
6	+	-	+	-	+	-	-	51,62	51,57	51,62	51,57	51,60	0,05	0,03	BC	-25,87	0,16
7	+	+	-	+	-	-	-	48,37	48,45	48,37	48,45	48,41	0,08	0,04	ABC	24,30	0,23
8	+	+	+	+	+	+	+	48,32	47,45	48,32	47,45	47,89	0,87	0,43	D	0	0
							Average	51,36	51,57	51,36	51,567				E	0,41	0,16
							Range	22,46	23,21	22,46	23,21						
							STD	6,84	7,00	6,84	7,00						

Appendix C

PDS

Specification for autonomous docking platform

Rev. AB
01/10/2014

D/W	Requirements	Changes (Date)
	Performance	
D	Centerline misalignment between platform and copter can be up to 20 [mm]	19.03.14
W	Centerline misalignment between platform and copter can be up to 80 [mm]	19.03.14
D	Angular misalignment beetween platform and copter can be up to 20 [°]	19.03.14
W	Angular misalignment beetween platform and copter can be up to 30 [°]	19.03.14
D	Rotational misalignment around vertical axes (Yaw) inensitive	
D	Maximum joining velocity to be up to 0,63 [m/s], calculated from fall form 0,2 [m] height	19.03.14
W	Maximum joining velocity to be up to 0,76 [m/s], calculated from fall form 0,3 [m] height	19.03.14
D	Attachment of docking unit to quadrocopter requires maximum three bolts	
D	Docking platform with small enough footprint so ground effect is not expereienced	
D	Maximum horizontal velocity to be 0,4 [m/s], regardless of vertical velocity	28.04.14
	Weight	
D	Weight to be less than 400 [g]	19.03.14
W	Weight to be less than 20% of the copter total weight	
	Quality reliability	
D	Reduce the number of components to maximum 20 components	20.05.14
D	Be normally closed without requiring energy	
D	Opens when electric current is applied	
D	Design must be done to prevent dust buildup that can render the product not to work	
	Size	
D	Product to fit inside a bounding box of size 120x150x50 [mm]	19.03.14
D	Product to fit all necessery electric sensors and circuits	
	Time scale	
D	Fully designed product in end of June 2014, mechanical	
D	Fully tested prototype end of August 2014	
D	Production ready product end of January 2015	
	Product cost	
D	Mechanical parts maximum cost 150$	
D	Electrical parts maximum cost 150$	19.03.14
D	Total product maximum cost 300$	19.03.14
W	Total product cost below 200$	
	Patents	
D	Product not to violate any current patents	
W	Parts of product to be patented for protection against competition	
	Processes	
D	80% of parts to be plastic injection molded	
W	Now circuits for the equipment	

Specification for autonomous docking platform

Rev. AB
01/10/2014

D/W	Requirements	Changes (Date)
	Materials	
D	Reduce the use of metals to be less than 5% of total material usage	
D	80% or more of parts to be plastic injection molded	
	Installation	
D	Installation of platform to copter to take less than 5 minutes	
D	Installation of platform to cargo to take less than 5 minutes	
	Maintenance	
D	Cleaning to be done after 1000 docking	01.10.14
D	Inspection on platform carried out every 500 dockings, looked for failures or cracks	01.10.14
	Quantity	
D	Manufacured quantity >2000 units	01.10.14
	Life in service	
D	>2 years	
	Testing	
	Verification of simulated results done trough testing on a prototype	
	Safety	
D	No sharp edges on product that can cause injury to people on impact	
	Product life span	
D	Minimum life time 5 year without any usage	
	Disposal	
W	No parts made from different materials glued together	
	Competition	
D	Extensive search for granted patents on similar solutions	
	Standard specification	
D	Product to be CE marked	
	Documentation	
D	User guide with warnings	
D	Assembly guide	
	Environment	
D	Dust and other contiminants can not accumulate on platform so they effect performance	
D	Not effected by altitudes/air pressures	
D	Working temperature 0°C to 40°C	

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