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1 Abstract

The field of robotics has developed enormously from the recent decades. Last year, an idea for a concept of building a robot arm to operate was suggested through the organisation, “Mars Institute Student Chapter” (MISC). This year, the idea is to build a robot arm that can operate at different circumstances on Mars. When the robot arm is functioning, it composed to force over the entire arm, and more, and even more forces are applied when the arm has to pick up objects. The calculations are first and foremost made with the help of analytical programs. Conclusions are based on the results, and thereby analyse whether they give satisfying values. If the answers are not satisfying, then a new conclusion can be made on why the errors happened. With that said, the robot arm has great potential for further development.

Preface

This article represents 3 students who have come through 3 years at the University of Stavanger, and can look back to both good and bad times, but still, independent of the moments, prove to be a valuable period. First of all, this thesis presents project about a Robot arm that is supposed to operate at the given conditions on Mars. We would like to thank MISC for giving us the opportunity to be a part of their project. They gave us a big hand to utilise our knowledge and skills within in the field of mechanical engineering. At times it has been difficult for us to solve the problems, which we have faced during these last 5 months. After this period of time, we are now ready for taking a proper degree in our field, and call us officially for engineers.

First of all, we would like to thank our supervisor at the University of Stavanger, Professor Dimitrios Pavlou. He gave us ideas about how we can attack the problems our thesis. Through his experience and knowledge, he showed us the possibilities we had, which we are thnakful to. We wish also to thank our family and friends for giving us motivation and support to perform well in the thesis. Even during difficult times when we met the wall, they told as to work hard and believe in our self.

In conclusion, we would like to mention *"Never regard study as a duty but as an enviable opportunity to learn to know the liberating influence of beauty in the realm of the spirit for your own personal joy and to the profit of the community to which your later works belong"*
- Albert Einstein

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Nomenclature

Acronyms

ALM Advanced Laser Materials

CAD Computer Aided Design

DC Direct Current

DOF Degree Of Freedom

DOF Degrees of freedom

EDL Entry, descent, and landing

EMF Electromotive force

EMI Electromagnetic Interference

ERC European Rover Challenge

ESF European Space Foundation

FDM Fused Deposition Modeling

FEA Finite Element Analysis

FOC Field Oriented Control

FSW Friction Stir Welding

FVF Fibre Volume Fractions

GCR Galactic Cosmic Rays

HMP Haughton Mars Project

HS High strength

IM Intermediate modulus

LDC Life Detection Experiment

MISC Mars Institute Student Chapter

MR Mars Rover

MSL Mars Surface Laboratory

N.D. Not Defined

NASA National Aeronautics and space Administration

PAN Polyacrylonitrile

PID Proportional Integral Derivative

RHU Radioisotope Heater Unit

STF Spread Tow Fabrics

STT Spread Tow Tapes

Tex The weight in grams of 1000 linear metres

UHM Ultra high modulus

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2 Introduction

Robotics is known to be an interdisciplinary branch of science that incorporates several fields of engineering. Mechanical engineering, electrical engineering and computer sciences to name a few. Accordingly, the field of robotics enables a variety of technological and everyday endeavours. From simple manufacturing processes in local businesses, to stem cell research across various living organisms. From dangerous causes of bomb detection and de-activation, to analysis and simulations of complex dynamical systems. In it's totality, the field of robotics can be utilised to solve or simplify any problems that the everyday human being might face. This exactly, was the sole purpose behind the implementation of the field, which dates back to the industrial revolution. [1]

This thesis is written on behalf of the organisation MISC, which works as a link between students, academia and businesses under innovative projects to develop technology development in our region. The project will also make cooperation among industries where students are the main focus. There is also a "European Rover Challenge" (ERC), which is a competition towards technological development specified in the area of space exploration and utilisation. Their goal is to set benchmark within planetary robotic activities with strong professional career development. Hence, the students of engineering project(s) at the Universities organize groups in order to build robots and compete in international challenges for space robotics. Since MISC are participating in the ERC competition held in September 2018, there are requirements set for the tasks purposely shaped to be solved by the means a robot arm. Therefore, members of this team and other teams working on the project with background in computer science, mechanical and/or electrical engineering selected only ideas adequate to meet these requirements, which became the fundamental functions that the arm must be able to do. With that being said, the motivation behind the thought process and as well as the arm itself was to design a concept that could be improved upon, hence being capable to be used for training purposes. As extra, we listed requirements from the preliminary study of Mars and locations similar to the planets environment on Earth. [2]

- The arm has to be of a modular nature, but retain sufficient mobility to perform given tasks
- Chosen motors must provide enough torque needed to perform the tasks at their assign positions in relation to the joints in the arm
- Desired positions needs to be attained through communication between base of the robot to the individually controlled joints expressed by some sort of a trajectory planning
- The arm must be operable in conditions achieved on Earth, such as Devon Island, and on Mars, but also wear and tear by students and teacher alike

On the other hand, there are some obstacles that are taken into consideration, such as climate, temperature, maintenance and other circumstances which are unlike compared with Earth. In conclusion, the thesis require to design a robot arm with the mentioned obstacles are taken into account, and the final results are based on choice of materials, motors, and tools. Figures of the arm will be added, in addition to calculations, which are of analytical programs like Inventor, Anfisnetwork and Matlab to provide meaningful answer to the most relevant mechanical engineering tasks, which will be elaborated in the coming sections.

3 Mars' Atmosphere

3.1 Mars as a planet

Mars, the forth planet from the sun, differs from the Earth by its glowing colour and sudden weather changes. After humankind landed on the moon for the first time in 1969, everyone set their eyes on the red planet to become the first interplanetary explorers. As a result of robotic spacecraft exploration and the observation of permafrost, it is feasible for a colonization of Mars, though it is depended on the water accessible to settlers. Missions suchlike these is one of the reasons behind the ERC and the development of rovers in general, in addition to gathering data for research like LDC and MSL.[3]

Mars is a remote and isolated planet, thereby requiring extreme solution compared to terrestrial standards, for instance drills and other tools specifically engineered for surface deployment. Main physical challenges for the astronauts and rovers in the Martian environment and related requirements are shown in table 2.5 ([3](Table 2.5)). The physical characteristics of the planet is described in table 2.1 ([3](Table 2.1)). As such, these conditions will in like manner apply to the robot arm.

3.2 Challenges and requirements

The robot arm is exposed to physical challenges, mainly because of different states between Mars and Earth. Particularly, Mars needs transportation across interplanetary space, EDL (entry, descent, and landing), and surface deployment solutions by the Earth's point of view. In addition, the martian surface and subsurface environments differ from the Earth's. Main physical challenges for the martian environment and associated requirements are shown in table 2.5. Clearly said, the obstacles are more demanding and complex for a robot arm to perform on Mars than the Earth. In the upcoming sections the challenges will be elaborated. [3]

3.2.1 Remoteness/Isolation

Mars differ from the Earth, mainly because of its extreme environment. Similarly to Earth, Mars rotates around the sun at different velocity, orbit and inclination. For this reason, the distance changes constantly from 56 to 402 million km. As Christopher Hoftun once said: *"light travel time for radio communications ranges from about 4 to 20 min each way. Round trip signal time can therefore reach 40 minutes"*.[3] Consequently, this makes it nearly impossible for telecommunication of complex systems on Mars from Earth.

Nevertheless, rovers called "The Mars Exploration Rovers" (MER) have been closest to present a teleoperated plan from Earth. In this case, a command string was uploaded to the rovers day by day. Since no real time link was set, the decision fell on a software which gave correct path to reach the determined destination. Although the command string was uploaded without any problem, the real time monitoring and interference from the Earth was not possible. It was critical of dynamic real time decision making and as consequence receiving limiting bad result. Nevertheless, there are three options of dealing with the communication setbacks: [3]

1. *"Direct presence of humans physically operating from the surface of Mars."*
2. *"Teleoperated from the surface, orbit or Phobos/Deimos (Mars moons)"*
3. *"Fully automated system with dynamic real time decision making by machines"*

Consciousness must be in place when dealing with advantages and disadvantages. Furthermore, many industries over a long period of time have expanded systems that can go along with new technologies. [3]

3.2.2 Atmospheric Pressure

The atmospheric pressure on Mars is significantly less compared to Earth. It can vary from 6 mbar to 14 mbar compared to Earth´s 1 bar. This causes water to only exist as ice or vapour; in other words ice vaporise into vapor, skipping the liquid phase when heated. As a consequence of the low pressure, the electronics need to have active cooling system to circulate excess heat from the components. This ensured the electronic subsystems to be heated up at low surface temperatures. The pressure also cause core challenges under entering Mars' atmosphere and requires complex EDL and others heat protectors, parachutes, airbags and sky cranes. [3]

3.2.3 Gravity

As a result of Mars´ gravitation being approximately one third of the gravity on Earth, an object needs to have three times the downforce to reach the same value it would have on Earth. This coincides with the ratio between high cost and interplanetary shipment. [3]

3.2.4 Temperature

Normally the surface temperature is approximately 220 K with periods of thermal fluctuations up to 100°C. These variations are some times measured to last up to six hours. These variations in temperatures are unfavourable for both human and robotic explorations. As a consequence the electronics will be forced to operate in extreme conditions [3]

When dealing with electronic subsystems, they have to be located into a Radioisotope Heater Unit (RHU), and the temperature has to be kept below 208 K.[3] Moreover, *"they have to be powered on less than 1 watt from radioactive elements, however, most of the robotics must be designed to operate at temperatures below 173 K (-100 °C)".* [3]

Choice of material is essential with what is being said above. Large temperature variations in a short amount of time cause the materials to expand and contract at sudden rates which again result in discontinuity to the tested material.[3]

3.2.5 Radiation

Mars does not have a stable magnetic territory, which can protect it against radiation from the sun. Additionally, the planet is exposed of radioactivity as a consequence of Galatic Cosmic Rays (GCR) and Solar Energetic Particles. The same problems will occur for electronics on Mars.[3] (For more see [3])

3.2.6 Dust

Mars is mainly exposed to fragments and a slight covering of chemically weathered dust covering rocks. As mentioned in section 3.2.5, the technological instruments are constantly being exposed to dramatic changes in the environment. For instance, sandstorm could cause trouble for the rover where the electric components are exposed to the atmosphere. Rovers usually gets power through solar panels. These panels have to perform through the help of direct sunlight with alteration of constant solar fluxes. However, the dust reduces the efficiency of solar panels, which might lead to a big issue in the future. [3]

3.2.7 Planetary protection

Mainly, missions in solar system are of interest to discover new life by ensuring that there is not anything harmful attached to hardware from Earth, nevertheless, so the new discoveries can avoid pollution and other undesirable effects. The board of Space Research, is responsible for making the requirements for planetary protection and pollution control, as they formed in different categories. Further on, these categories are subdivided into three sections, which are responsible for requirements and procedures as *"1) Target body; 2) Degree of concern; and 3) Representative range of requirements, by reducing the involvement by humans, contamination and sterile environments are induced during the assembly of the hardware."*[3] [3]

4 Devond Island

Devon Island in Baffin Bay belongs to the Canadian Artic Archipelago. It is the largest uninhabited island on Earth. The ground at the island is frozen for almost the entire year. The eastern third of the island is covered by an ice cap, and it is between 500 to 700 meters thick. For a short period between 45 to 50 days in the summer, the ground is snow-free. Summer temperature is only 8°C, but the average temperature on Devon Island is around -16°C. In winter, the temperature can be low as -35°C. Devon Island contains frost rocks and contains nearly without of animals and plants. The Island is very interesting place for science and doing research. The climate and the desert are very similar to conditions on Mars. [4]

Mars and Devon Island are cold and dry, and they both got valleys and canyons. The help of researches for HMP found a new conclusion about the formation of Mars' geology and their climate. They know the climate at Haughton Crater has always been dry and cold. They observed its valleys were formed by melting ground ice, and its valley connections and canyons shaped by the movements of glaciers. Because of that, it means Mars may have been always cold. [5]

4.1 Haughton Mars Project

From 2001, Devon Island has been the summer home for a group called the Haughton Mars Project (HMP).[4] They are people who is working on an international research project. HMP studies how humans can live and work on other planets, in particular on Mars.

Devon Island have rocky terrain, isolation, very low temperature and remoteness which offer NASA scientists and difficult research opportunities. Devon Island is the site of the Exploration program. This evolve new strategies, technologies and operational protocols geared. This support the future exploration missions of the Mars, Moon and different planets. [6]

HMP researches test prototypes with new technologies. For example, K-10. It is a robot which can help humans before, and after human exploration missions. This is because of the environment is very harsh and isolated. [6]

5 Preliminary material studies

It is important to gather some knowledge about carbon, carbon fibre and aluminium before mentioning exact what is been used. Having some awareness about them will make it clear why the choices fell on them.

5.1 Aluminium

Aluminium has thus far been (has been and still is) the preferred material in the development of modern aviation and humanity's exploration of space. This is attributable to its lightweight, about a of steel, and ability to resist the stresses that occurs during operation and launch, as well as exceeding in mechanical stability, dampening and reduced weight compared to other metals, e.g. using aluminium in vehicles for the purpose of dead-weight reduction and energy consumption while increasing load capacity. Although in recent years, the structural and widebody platforms have been replaced with composite materials, suchlike carbon fibre (section CF).

Aluminium has by its nature high corrosion resistant and a protective oxide coating, and using lacquering, paint and such can improve these qualities. Although the metal alterations both mechanical and physical properties, these changes is not as intense as steel and other when exposed to temperature ranging from -195°C to 400°C.

5.1.1 Tempering and aluminium alloys

Whereas pure aluminium is used for foil and conductor cables, due to characteristics suchlike softness, ductility and high electrical conductivity, by alloying with other elements, the metal will have an increment to its strength. Further improvements can be made by the use of tempering, which is divided into two groups namely heat- and non-heat treatable.

Non heat-treatable alloys Work hardening (H14), in some cases strain hardening, is the common classification for processes giving increment in strength and reduction in ductility, e.g. pressing and rolling. Partial annealing (H24), often referred to as temper let-down, describes a process of heat that decreases the strength on the account of increasing ductility after work hardening. The third alternative is introduced during manufacturing as heat or as a thermal treatment with low temperature with the purpose of stabilise the material in order to ease the remaining internal stress. Known as Stabilising (H34), it is made us of with regard of moderately age-soften unstable alloys as well as often improving ductility.

Heat-treatable alloys Heat-treating is defined by the process in which aluminium is heated at prescribed time and temperature, then quenched in water for rapid cooling. This method is separated in two ageing groups. The natural ageing process happen at ordinary temperature until the alloy reach a stable condition, hardening the material in addition to a heat treatment solution. Alloys undergone this process will have the denomination T1, T2, T3 or T4. The artificial process, where the aluminium is heated for a set period at a low temperature until it reaches a stable condition, thus strengthening the alloy quicker than the natural process with the help of heat-treating solution. Aluminium alloys undergone this process will have the denomination T5, T6 or T9.

5.1.2 Surface treatment of aluminium

There are two primary classifications of aluminium alloys, namely wrought and casting alloys. Whereas the wrought alloys are ductile enough to be cold- or hot worked (section HOT AND COLD WORKED), the cast alloys are brittle to an extent that this type of aluminium must be fabricated by casting due to not being able to deform the material by shape. Differentiation in each category is based on specification and the degree of alloy elements. Moreover, several alloys react to phase solubility by exposure to thermal treatment, suchlike heat treatment solution, precipitation, quenching or age hardening.

Similarly, different types of treatment were developed in order to improve the surface characteristics, like reflectivity, wear- and corrosion resistance. These are further divided by their technique, namely electrochemical-, chemical- and coating treatment:

Electrochemical treatment:

- *"Cold impregnation: Treatment of anodic oxidation coatings on metal to plug the pores and reduce the absorption capacity of the coating by chemical processes carried out at low temperatures after anodizing."*
- *"Architectural anodizing: Anodizing to produce an architectural finish to be used in permanent, exterior and static situations where both appearance and long life are important."*
- *"Protective anodizing: Anodizing where protection against corrosion or wear is the primary characteristic and appearance is secondary or of no importance."*

Coating treatment:

- *"Priming: Application of a priming paint often pigmented with a corrosion inhibitor such as zinc chromate, after suitable pretreatment".*
- *"Single coat system: Single coating either with requirements on appearance, malleability, corrosion protection, subsequent painting, etc., or as a primer with special properties regarding adhesion and corrosion protection for post-painting applications."*
- *"Multiple coat system: System comprising a primer or a base coat, possibly intermediate coat(s), and a top coat with particular requirements on appearance, malleability, corrosion protection, etc."*

5.1.3 Fabrication

Fabrication of aluminium can be done in numerous ways, among them being cutting, plastic deformation/-forming and joining with regard to human artisanship or machining. Cutting includes the use of saw and tapping, as well as deburring and milling. Negating problems commonly associated with appearance, alloy used and hardness, in addition to limiting the formation of burrs, is depended on size and amount of teeth, diameter of blade, number of RPM and the feed. Plastic deformation, a.k.a. plastic forming, uses bending methods, including stretch-, roller- and press bending, in order to obtain desired shape. Joining includes, among other approaches, adhesive bonding and weldment e.g. FSW.

5.1.4 Cold- and hot working

With respect of the correlation between the material recrystallization temperature and the processing temperature, there are types of working which can alter the material properties suchlike the methods mentioned before (section Tempering). Materials with compact and high dimensional accuracy can be attained through cold working, along with elimination of errors due to shrinkage and an increase of hardness, yield- and tensile strength, becoming more brittle. The material would need to be exposed to heat during rolling to remove suchlike, undesirable altercations. Cold working will also lead to dislocations in the grain structure, allowing the overall change in shape, in addition to a good surface finish. To be specific, this type of working will produce elongated grains and the metal get good surface. On the other hand, hot working makes the material more ductile and soft due to repeatedly large deformations. The lessened hardness is a result of cooling rate after rolling and chemical composition, thereby requiring lower deformation energy. In light of this, better grains is achievable through this type of working compared to cold working. In short, if the processing temperature of the mechanical deformation of a metal is under the recrystallization temperature, it is defined as cold working and vice versa for hot working.

5.2 Background about Carbon Fibre

5.2.1 What is Carbon?

Carbon is defined as C in the chemical term, and is a well known element in the periodic table which plays a huge role in many engineering application. Materials from the past, like graphite, coal and diamonds all consist of carbon which can be found in nature. Non-renewable energy sources like oil and gas also includes carbon. Generally carbon compounds are crucial for all form for life, whereas organic compounds are characteristic because of the amount of carbon.[7]

5.2.2 C-C bonds

Carbon has three different ways of bounding together, these are listed below:

- Chains and bonds from each carbon atom are bound to two other carbon atoms [7]
- Plane net where every carbon atom is bound to three carbon atoms [7]
- Three dimensional structures where every carbon atom is bound to four carbon atoms [7]

Dependent of how the electrons in a carbon are divided. There are four electrons in the outermost electron shell, which is half full. This freedom gives it many possibilities to bound with others. [7]

5.2.3 Carbon compounds with other substances

Carbon has electronegativity 2.5, which is in the middle among the less electronegative substances, such as alkali metals, which has electronegativity of 1, and the most electronegative substances, as halogens, which has electronegativity of 4. This property makes it possible for carbon to form bonds with almost any substances, with the exception of hydrogen, which makes bonds with all the atoms. [7]

5.2.4 Chemical properties

Carbon does not react properly in normal temperatures, but when the temperature is increased it reacts well with the most atoms. When it is bound with oxygen, dependent of the amount of oxygen and temperature, either carbon monoxide, or carbon dioxide will appear. The ability of carbon to form oxides will lead it to a good reducing agent of metal oxides. [7]

Carbons are used in the form of coal and coke to manufacture metals, for instance iron, copper, and lead, with reduction of the respective oxides. When these reactions happen, carbon monoxide will be formed first. [7]

Equations below show the process of carbons reacting with steam during formation of carbon monoxide, carbon dioxide, and hydrogen gas: [7]

$$C(s) + H_2O(g) \rightleftharpoons CO(g) + H_2(g)$$

or

$$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$$

5.2.5 Where does Carbons come from?

Carbon occurs in the nature as diamond and graphite, and in some form of coal. In petroleum it is chemically bonded, mainly with hydrogen. Petroleum and coal are made of plants and marine animals with slow contamination and heating without air supply. Moreover, in plants and animals, the carbons play a big part in the bindings of organisms. One can find them for instance in organic compounds like carbohydrates, proteins, and fat. With that said, in a human body there is up to 17 weight percent carbon. [7]

The total amount of carbon content in both plants and animals estimate to be 270 billions tons. Carbon is included in several minerals, for the most carbonates. At most, carbon consists of 0.0032 weight percent of the earth crust. In fact, the air consists of 0.04 volume percent carbon dioxide, and the content is still increasing as a result of pollution.[7]

In addition, the water solves huge amounts of carbon dioxide, in the form of carbon dioxide and bicarbonate (HCO^{3-}). The average carbon content in seawater is 0.005 weight percent, equivalent to a total carbon content of 27 000 billions tons. [7]

5.2.6 What is Carbon Fibre?

With that said generally about carbon, one can move on to describe carbon fibre and how it influences the design of robot arm. It looks black and is an artificial fibre which comprises of almost pure carbon. The material is known for its high tensile strength and stiffness, heat- and chemical resistance. Moreover, it has a lower density compared to other competing materials, among others glass fibres. [8]

5.2.7 Application of carbon fibre

The use of carbon fibre has increased in reinforced materials, as a whole or temporary replacement, for instance for glass fibres. These composites are used for technical/engineering purposes such as flight-, ship-, car-, and mechanical parts. Short fibres can be used as filler in simple thermoplastics, e.g. such that is assumed for high temperature applications, but some fibres are crispy for regular thermoplastic processing. Moreover, carbon fibres would suit to reinforcement(elaborated more later) of ceramic and metallic materials. [8]

5.2.8 Carbon fibre manufacture

Carbon fibres are manufactured by coaling the organic fibres, mainly acrylic fibres, but viscose fibres are also used. The procedure of the process is below, and very often the fibres are in tension: [8]

1. Fibres are closely heated up to 220 °C, where polymeric molecules get cyclic structures in the chain, they oxide in the air up to 300 °C. Hence, the fibres will not melt anymore. [8]
2. Fibres will be carbonised in nitrogen up to 1300 °C. [8]
3. In the end a heat treatment happens between 1500-3000 °C, where the carbon gets the desired degree of graphite structure. Temperatures of 1500 °C give a maximum strength (up to $7KN/mm^2$), while

the bigger temperatures give maximum rigidity (elastic modulus up to 500KN/mm^2). The fibres will be treated on the surface to improve adhesion[9] to to plastic.[8]

5.3 Composite materials

Understanding of composite materials are essential for the decision behind the choices. Composite materials are made of two or more different materials, and result in better property, for instance higher strength, rigidity, toughness, compared to just one material.[10] With other words, combining more materials give the composite material an unique property. By combining materials together, the fibres will bind to each other, which is known as reinforcement. [11]

5.3.1 Reinforcement

Reinforcement in a composite material does first and foremost increase the mechanical properties of the neat resin system. All of the different fibres used in composites have different properties and for that reason the properties of the composites will be affected in different ways.[12]

On the other hand, individual fibres or fibre bundles can only be used on their own in a short processes such as filament winding. In most cases, the fibres wish to be arranged into some form of sheet, known as a fabric, to make handling possible. There are many ways of assembling fibres into sheets and the variety of fibre orientations cause to different types of fabrics, where each has its own characteristics.[12]

5.3.2 Modern composites

Fibreglass is seen as the first modern composite. Equipment in sports and car bodies are usually made of it. It is made of a matrix that is plastic, in addition to a reinforcement, which is of glass. These together give a kind of cloth type material. The glass alone is very strong, but have the possibility to be broken when it is bent strongly. On the other hand, the glass fibres are held together by plastic matrix, which shield them from damage of applied forces.[11]

In several contents carbon fibre are more preferred than glass fibre, due its weight and general strength. However, the price could be a disadvantage when choosing carbon fibre instead. This might explain why carbon fibres are more selected for instance in aircraft structures.[11] An example could be the Air buss A380, which tells that *"The new Airbus A380, which is the world´s largest passenger airliner, does use modern composites in their own design. More than 20 % of the A380 is made of composite materials, mainly plastic reinforced with carbon fibres. The design is the first large-scale use of glass-fibre-reinforced aluminium, a new* *composite that is 25 % stronger than conventional airframe aluminium but 20 % lighter."*[11]

5.3.3 Why use composites?

Compared to other materials, modern composite materials have the benefits of being much lighter and stronger at the same time. A wished application can be made through correct combination of matrix and reinforcement material. Modern composite materials provide variations, since they can be changed into advanced shapes, and more qualified product, nevertheless the price will not be in favour.[11]

5.3.4 Fibre properties

Reinforcing fibres have more mechanical properties in comparison to non-reinforced resin systems. Therefore, the fibres of the composites have great importance to the mechanical attributes of fibre. Mainly, the fibres are set through four main factors, which are mentioned:[13]

1. *The basic mechanical properties of the fibre itself"*[13]
2. *"The surface interaction of fibre and resin"*[13]
3. *"The amount of fibre in the composite"*[13]
4. *"The orientation of the fibres in the composite"*[13]

The level of bonding between fibre and resin is determined by the surface interaction. Impact of applied treatment to fibre surface, and a specification is vital for end result.[13]

Fabrication is chosen through the number of fibre in the composites. Accordingly, high Fibre Volume Fractions (FVF) due to reinforcing fabrics will give a laminate of rough fibres. Mainly, having high fibre surface areas come due to fibre diameter, which is an essential part. Admittedly, the instant number of fibre has a relationship with the stiffness and strength in a laminate. Nevertheless, when the laminate's strength has reached the top, it will fell down due to shortage of agreeable resin to bind together the fibres suitably, which comes a result of not so concentrated tensile stiffness. Later on, the factor "anisotropy" plays a part, which makes the reinforcing fibres to work on the load along its length, and neglects the width, and in addition gives a desired orientation for properties in the composite. This factor increases the general design.[13]

5.3.5 Laminate properties

The properties of the fibres only show part of the whole. Hence, the composite will derive from those of the fibre, but also the way it interacts with the resin system used, the resin properties itself, the volume of fibre in the composite and its orientation.[14]

Below there is a diagram which illustrates a simple comparison of the main fibre types used in a typical high-performance undirectional epoxy prepreg, where the fibre volume fractions are normally done in aerospace components.[14]

Graphs below show the strengths and maximum strains of the different composites at failure. Moreover, the gradient of each graph illustrates the stiffness of the composites. The steeper the gradient, the higher its stiffness. In addition, the graphs also show how some fibres, for instance aramid, display very different properties when loaded in compression, compared with loading in tension.[14]

5.3.6 Laminate impact

When laminates are exposed to particularly high stiffness fibres, this could cause harm. It comes as a result of low thickness in the build of laminate. However, orientation of fibre and weave style can also be other affecting factors, which lead to low resistance. Carbon fibre is an example of this problem, since it is very often a product due to other fibres which are involved.[15]

5.3.7 Glass fibre

Glass fibres can be made through quarry products such as limestone and kaolin at 1600°C. In the beginnings it becomes as a glass of liquid, but later on goes through a process to be cooled down to get the desired glass fibre filaments. Due to protection from abrasion, and give cohesion to filament, it will be put into a string and covered. Glass fibres can be produced through various methods. Different variations for producing. Some varieties for structural reinforcements are E-glass, C-glass, R-,S- and T-glass.[16] For more see [16] E-Glass fibre can be made through these named forms:

- Strand: A solid amount of filaments, which are seldom and regularly put together to provide yarns.[16]
- Yarns: Similar to strands, given that a yarn is equivalent to each other, and the filament diameter is usually between 4-13m. Tex (the weight in grams of 1000 linear metres) is used to specify the changeable weight, which is normally between 5 and 400. [16]
- Rovings: Similar to yarns, where per filament diameter normally stays between 13-24m. As a result of

inconsistent weights, the tex value stays in the range of 300 to 4800.[16]

With that said, glass fibres can still be accomplished through long fibres with the help of spinning. Even if they have less structural properties, admittedly, the higher surface areas of yarn are adequate to soak up resin.[16]

5.3.8 Aramid fibre

Aramid fibres are made of the same process as the E-glasses, but due to synthetical mixture they differ from each other. Wide range of properties, especially high strength and low density, give the aramid fibre high specific strength. They are widely used for the purpose of projectiles, rockets and general movement under gravity. Kevlar is the most known material under the name of aramid fibre, and gives different options when it comes to modulus and treatment of the surface. Effect of the ultraviolet light can provide damage to fibre, but on the other side giving protection from abrasion, synthetical and thermal influence. Usually the texes lye between 20 to 800 for the aramid fibres.[17]

5.3.9 Carbon fibre

There are different methods to produce carbon fibre, and polyacrylonitrile (PAN) is a way to follow, because it is be made of cellulose, and provide good fibre properties. The process of graphitization has its advantages in either providing high strength or high modulus fibres in combination with other fibres. When carbon fibre is to be used, its strength becomes vital, therefore the necessity of surface treatment occurs for developing both the matrix and chemical bonding.[18]

The history of carbon fibre dates back to the late sixties.[18] Nowadays the price is down to USD [14000 - 18000/tonnes] range, the huge drop in appraise comes as a result of increased carbon fibre material production. [19] *"By 1996 the annual worldwide capacity had increased to about 7,000 tonnes and the price for the equivalent (high strength) grade was £15-40/kg"*.[19] Usually properties of carbon fibre are sorted in the order of high to low, which are high strength (HS), intermediate modulus (IM) and ultra high modulus (UMH). 5-7µm is a common number for the generally filament diameter. Its big advantages say that *"Carbon fibre has the highest specific stiffness of any commercially available fibre, very high strength in both tension and compression and a high resistance to corrosion, creep and fatigue."*.[18] Nevertheless, both glass- and aramid fibres have greater impact strength compared with carbon fibres.[18]

5.3.10 Fibre comparisons

Considering the different fibres to each other, these have both pros and cons. For that reason, some fibres would fit more than others when it come to specific utilisation. Feedbacks are often determined from letters the "A" and "C", where "A" tells how well the fibre scores, and "C" tells how bad the fibre scores. [20]

5.3.11 Other fibres

Carbon-, glass-, and aramid fibres are familiar in lot of environments, however, there are other options that could be used in the leading composite designs, which have not been well established, such as:[21]

- Polyester[21] (for more, see [21])
- Polyethylene[21] (for more, see [21])
- Boron[21] (for more, see [21])

5.3.12 Fibre finishes

Strengthen the fibres properly provide less damage and increase of chain strength in the form of surface finishes. These can be utilised to glass-, carbon-, and aramid fibres by implementing to the point of fibre fabricate, which last all over the reformation toward fabric.[22]

Glass Fibre Finishes:

"Glass fibre rovings that are to be used in direct fibre processes such as prepregging, pultrusion and filament winding, are treated with a 'dual-function' finish at the point of fibre manufacture".[22] With that said, there are two levels the glass fibre threads can be used to within weaving. During the procedure of weaving, the fibre will be weak, and for that reason, the primary finish will implemented simply to avoid this. Later, some chemical substances are used to purify the surface as a result of weaving. After the process of chemical substances, another treatment will be implemented in form of resin, which creates a solid binding, resilience against water, and provides an excellent physical appearance.[22]

Carbon Fibre Finishes: In the case of carbon fibres, the epoxies are *"Finishes, or sizes, for carbon fibres used in structural composites are generally epoxy based, with varying levels being used depending on the end use of the fibre. For weaving the size level is about 1-2% by weight whereas for tape prepregging or filament winding (or similar single-fibre processes), the size level is about 0.5-1%. The chemistry and level of the size are important not only for protection and matrix compatibility but also because they effect the degree of* *spread of the fibre. Fibres can also be supplied unsized but these will be prone to broken filaments caused by general handling. Most carbon fibre suppliers offer 3-4 levels of size for each grade of fibre"*.[22]

Aramid Fibre Finishes:

"Aramid fibres are treated with a finish at the point of manufacture primarily for matrix compatibility. This happens because aramid fibres need much less protection from damage caused by fibre handling. The main types of fibre treatment are composite finish, rubber compatible finish (belts and tyres) and waterproof finish (ballistic soft armour). Compared with the carbon fibre finishes, there are differing levels of composite application finish depending on the type of process in which the fibre will be used".[22]

5.3.13 Treading methods

The basic methods used by the majority of weavers are *weave and stitch* and *simultaneous stitch*. As As *Net Composites* describes these:

*"With the **'Weave & Stitch'** method the +45° and -45° layers can be made by weaving weft Unidirectionals and then skewing the fabric, on a special machine, to 45°. A warp unidirectional or a weft unidirectional can also be used unskewed to make a 0° and 90° layer If both 0° and 90° layers are present in a multi-layer stitched fabric then this can be provided by a conventional 0/90° woven fabric. Due to the fact that heavy rovings can be used to make each layer the weaving process is relatively fast, as is the subsequent stitching together of the layers via a simple stitching frame"*[...] *"To make a quadraxial (four-layer: +45°, 0°, 90°, -45°) fabric by this method, a weft unidirectional would be woven and skewed in one direction to make the +45° layer, and in the other to make the -45° layer. The 0° and 90° layers would appear as a single woven fabric. These three elements would then be stitched together on a stitching frame to produce the final four-axis fabric."*[...] ***"Simultaneous stitch*** *manufacture is carried out on special machines based on the knitting process, such as those made by Liba, Malimo, Mayer, etc. Each machine varies in the precision with which the fibres are laid down, particularly with reference to keeping the fibres parallel. These types of machine have a frame which simultaneously draws in fibres for each axis/layer, until the required layers have been assembled, and then stitches them together, as shown in the diagram below."*[23]

5.4 Spread Tow Fabrics

First and foremost, k, defines how many filaments(in thousands) there are in per tow. For instance, in 12k, there are 12000 filaments per tow.[24] The concept of STF is about widening carbon fibre tow towards a small STT for a weightless fabric manufacture using tape-weaving technique. By utilising this method, fabricators will have the possibility to reduce the weight-to-area ratio in terms of reinforcement by choosing 12k or higher compared to carbon fibres of 1k to 6k. Benefits of STF are clear, since the properties of the fibres can be developed much in tensile loading, as it comes of ordering the woven structure of fibres in the direction as attainable, both in- and out-plane. Both STF and UD are close to each other when it comes to cross-ply, but STE differs due to the better *"draping ability and delamination resistance."*[25] Normally the carbon fibres of 12k and bigger, are spread to an STT with preferred shape to hinder it going back to its original shape. Through the method of STT, the carbon fibre gets higher *"volume fraction av fewer interlacing points"*[25] , which result in lower frequency and crimp value and angle. The process of STE increases the mechanical enforcement and protection, as well as reducing weight and strengthens durability. [25]

5.5 Filament for 3D-printers

3D-printer is a machine used for manufacturing an physical phenomenon in three dimensional digital model. During this process a material will be in a heat phase, and go through a nozzle, which will be placed on the surface as layer. Powders are used in more advanced printers, which melt before hitting the surface. Some times the material can solidify before completion. Another principal can cause the material to be put in a bath of liquid substances. Different types of materials e.g. metals, alloys, polymers, biological materials, etc have shown good results when the 3D-printer is used. This machine has shown its worth even with geometrical complex materials. Due to its ability, there are great expectations towards specialised components, e.g. within biotechnology.[26]

It all begun back to 1893, where the American engineer, Chuck Hull developed a method, called stereolithography. A laser beam passes through a programmed pattern over a bath with liquid, light sensitive plastic, where the layer at the surface is cured because of photopolymerization. the foundation for the work piece submerges gradually a crack in the bath before applying a new layer. The engineer presented this method the year after, and started the company in 1986. Since then, the company has been on top for the new techniques within 3D-printing.[26]

6 Design choises

6.1 Solenoid

To make the hand/fingers open and closed, a solenoid was chosen to be implemented. This section describes the requirements for the solenoid and which type/size of the solenoid the hand is going to have. Finally the choice of the solenoid will be discussed in the conclusion.

6.1.1 Requirement

For the solenoid there are some several requirements:

- A solenoid need both pull and push actuation
- The solenoid should have a suited stroke length
- The operating voltage should be low as possible
- Minimum weight and space in the hand

The solenoid has the task to make the fingers/hand open and close as same time. These means the solenoid has to deliver enough force/weight to lift all fingers out. If a small solenoid is chosen, this will reduce the force and it will be a problem to lift slightly heavier weights. The solenoid is powered by the general/main battery on the rover.

Solenoids is a cylindrical, tight-wounded electric coil either pulls or pushes a steel or iron plunger. [27] A solenoid works, when voltage is applied to the solenoid coil the electromagnetic force pulls the center plunger in. When the solenoid is not energetic, spring-loaded from the solenoid returns. Solenoids can be used in electric locks, security doors, door bells and many other applications. [28]

These medium solenoids from Trossen Robotics has a weight around 135 gram and have a maximum stroke length of 1.5 mm. Choice of a solenoid have a current of 1.5 A, and the maximum strength is 900 gram. When the solenoid start, it will push all fingers out without any struggling, and have to hold there for a little while. The pull actuation is implemented to make sure the object/green container stays tightly, when the rover moves around. The plunger comes back to its start position when the current is turned off. [28]

6.2 Conclusion

The reason for choosing exactly medium solenoid, is because of the maximum strength, and the weight of it. For the solenoids, they can be chosen with different max strength, operating voltage and current. The large solenoid will take much space, and a motor will be placed beside the solenoid. The solenoid has to have low operating voltage, and voltage of 24V will be too much. The small solenoid has low weight, but have very low force. Therefore to lift all fingers out and pull them back, the medium solenoid is selected.

6.3 Actuator

In this section the actuator will be discussed. First the requirements will be discussed and where the actuator is going to be placed. The options will be compared to each other and finally the choice of it will be explained in the conclusion.

6.3.1 Requirements

- The actuator need to move the robot arm
- An actuator should have enough force to move the arm
- It must stand low temperature, under freezing point
- The stroke length have to be long enough

An actuator is a component of a machine that create motion in a straight line. The actuator has a job to move the first joint with an angle. To make it happened the actuator has to deliver great enough force to lift the first and second joint and the manipulator. If a lightweight actuator is chosen, this will reduce the capacity to lift the arm. The lifetime for the actuator will be reduced. Since the environmental is extremely on Mars/Devon Island, the design of it have to be compact. When the power turned off the actuator have to stop immediately in same position.

6.3.2 Options

To achieve the requirements written above, some different type of actuator will be discussed, like force, different stroke length options and some safety options. The following options will be talked about:

- 10 Inch Stroke 110 LB Linear Actuator with Feedback
- LA22
- LA23 Techline

10 Inch Stroke 110 LB Linear Actuator is a 12V DC actuator. This actuator is well built and reliable linear actuator. The sturdy mounting brackets make them easy to mount and will not break. This actuator have a maximum load capacity of 500 N, and extended length of 0,65 m and retracted length is 0,40 m. 10 Inch Stroke 110 LB Linear Actuator has a built-in potentiometer to sense its position. The metal house is waterproof and sealed against dust, and it has limit switches at both ends to protect against damage .

The LA22 is an in-line actuator and it is designed with a small overall dimension for easy use in industrial and rehabilitation products. The protection class is IP51. It means is protected from limited dust ingress and protected against vertically falling drops of water. The maximum thrust is 400 N, when it is uses 12 V permanent magnet motor, the max force will be 300 N. This actuator is usually used on wheelchairs.

The LA23 Techline is a small and strong push and pull actuator. It can push up to 2500 N. The actuator can be used in different applications where size is important. Some of the qualities LA23 has, are:

- Compact design
- High trust
- Standardized cables
- Available with integrated controller (IC)

[29]

6.4 Conclusion

Because of the selection if this actuator is first of all inexpensive compared to the other actuators. There are many characteristics that come close to Mars or Devon Island environment. Actuator with 0.750 kilos saves the weight of robot arm (manipulator). The weight is important so the rover does not roll over. According to the ESC rules, the total weight of the rover can maximum be 50kg.

7 Lacquer and Insulation

To make the robotic arm more protected and isolated from the harsh climate on Mars/Devon Island, some lacquer and insulation need to be added. This section focuses on lacquer protection and different low temperature insulation. Finally the choice of these objects will be made in the conclusion.

7.1 Requirement

There are divers of surface coating and insulation materials, which has been used e.g. the surface of a car and pipe insulation.

For the protection of the arm the following requirements are found:

- The carbon fibre must be protected from UV
- Less damage to the metal
- The metal temperature should not be very low or high

The motors have the task to move individual joint. When the motor is working and make the arm moves, the heat from the motors will send out. It is important to have foam inside the carbon fibre. This will reduce the heat on the inside of a material to melt. Because of the high compressive strength, the foam can be pressed to make space inside without being destroyed.

The carbon fibre is covered with epoxy/resin. Carbon fibre is not good UV resistance, but the epoxy/resin is immune to UV degradation. The metal will be exposed a lot throughout its lifetime. Therefore it is important to have lacquer protection to have a great shape on surface.

7.2 Options

- Foamglas from Pittsburgh Corning (INDUSTRI)
- Polyisocyanurate (Dyplast's ISO-C1 polyisocyanurate insulation)
- Dytherm Phenolic insulation
- Depron insulation carpet 3mm
- Clear coat (klarlakk for Biltema Utbedringslakk)

- Ditec Original Lacquer protection

FOAMGLAS ONE insulation is made from millions completely sealed glass cells. It is lightweight and is resistant to water in both forms, liquid and vapour. The foam withstand quite low temperature down to -268°C, and has high heat resistance, up to + 482°C. It has some other characteristics than cold and high heat temperature resistance. It is waterproof, resistance to attack, high compressive strength, chemical resistant, is easy to cut and shape it and is solid for extremely weather condition.[30] [31]

ISO-C1 Polyisocyanurate Insulation used for panels, pipe and equipment. This insulation has extremely physical characteristics. It has very good water and moisture resistance. This insulation uses for refrigeration insulation, warehouse insulation, transportation tanks and freezer insulation. This product can withstand temperature between -183° C and 149° C. It is also harmless to the environment.[32]

Dytherm Phenolic insulation is not heavy, it is lightweight, and has the lowest thermal conductivity. Transportation, handling and installation are very easy for this insulation. This product is developed to give good performance with fire resistance, insulation efficiency, high compressive strength, low emissions of smoke, safety, health and price. Dytherm Phenolic insulation used for equipment and pipe, and has the temperature range between -180°C to +120°C.[33]

Depron insulation carpet is an insulation plate that is placed under floor. When Depron is placed under the carbon fibre, the heat will be reflected. The insulation has a double function. It lead the heats and gives effective protection against cold and moisture.

Clear coat has an excellent abrasion resistance. The product is immune to UV degradation, and protect the metal in various forms of dirt, harmful chemicals and acid rain.

Ditec lacquer protection is UV resistance and protect against harsh climate. The protection will stay clean and absorb less tar, asphalt and other particles. This product is a lacquer amplifier. [34]

7.3 Conclusion

The choice for protection inside the carbon fibre is FOAMGLAS ONE insulation. Using this product and not the others is because of it is resistance to attack and have a long lifetime. It will take care of the heat engine without melting from inside, and the low temperature outside of the robot arm. .The main reason is the huge temperature different between FOAMGLAS ONE insulation and the other three insulations. The thickness for this product is between 40 to 180 mm. When the insulation cuts and shape it, it does not get the same temperature range. Therefore the insulation has to have the temperature as high and low as possible. It has to fit inside the robot arm without any collision with the motors and materials.

Ditec lacquer protection is going to be the outside of the robot arm on the carbon fibre. This product will protect the metal very good, and resist wear and lot of dust and gravel on the arm. The metal's lifetime will be longer. By choosing right FOAMGLAS ONE insulation and Ditec lacquer protection for the carbon fibre requirements are met.

8 Implementation

8.1 Kinematic

Kinematic described the motion of bodies without taking into account forces and mass.[35] In kinematics, one can decide the positions given the joint parameters and even joint configurations can be determined if positions are given. To solve problems within kinematic, one can either use forward- or inverse kinematics. Forward kinematics refers to the use of the kinematic equations of a robot to compute the position of the end-effector from the angle values for the different joints. Inverse kinematic is used for finding the angles for the joints for given position.[36]

8.2 Forward kinematic

Forward Kinematic solves the position and orientation of the end-effector of the arm if the angles are known. It is a bipolar stepper motor that move the joints, rotates, provide different angles. The calculation of the forward kinematic is the only way to find the end position.[36] The theta values that has been decided from the arm can find the end-effector's position using the following equations:

$$x = L_1 \cos\theta_1 + L_2(\cos\theta_1 + \theta_2) + (l_3 + d_4)\cos(\theta_1 + \theta_2 + \theta_3)$$

$$y = L_1 \sin\theta_1 + L_2(\sin\theta_1 + \theta_2) + (l_3 + d_4)\sin(\theta_1 + \theta_2 + \theta_3)$$

x1, x2 and x3 + m4 are the lengths for the different parts of the arm. Theta 1, 2 and 3 are the angles made by connection between x1 and x2, x2 and x3. m4 is the length of the hand. These equations are used to find the position for the end-effector using MATLAB. [36]

Figure 1: Block diagram for Forward Kinematic

8.3 Invers Kinematic

Inverse Kinematics is used to finding the joints angles for a specific position of the end-effector.[36] To make the arm move to a given point, feedback of both magnitude and direction of rotation has to be given to motors working on the specific joint controlling the arm at their respective axes. Each joint needs a micro-controller to receive these signals. To calculate the Inverse Kinematic, one takes the co-ordinates end-effector as the input and gives the joint configuration as output." [36]

Figure 2: Block diagram for Invers Kinematic

Equations to find theta 1,2 and 3 are given by:

$$\phi = \theta_1 + \theta_2 + \theta_3$$

$$\phi = \tan^{-1}(\frac{y}{x})$$

$$x' = x - L_3 \cos\phi$$

$$y' = y - L_3 \cos\phi$$

$$\theta_1 = \gamma + \arccos(\frac{x'^2 + y'^2 + l_1^2 - l_2^2}{2l\sqrt{x'^2 + y'^2}})$$

where γ:

$$\gamma = \text{atan2}(\frac{-y'}{\sqrt{x^2 + y^2}}, \frac{-x'}{\sqrt{x^2 + y^2}})$$

$$\theta_2 = \text{atan2}(\frac{Y_i - l_1 \sin\theta_1}{l_2}, \frac{X_i - l_1 \cos\theta_2}{\sqrt{l_2}})$$

$$\theta_3 = \phi - \theta_1 - \theta_2$$

To calculate the Invers Kinematics, one takes the co-ordinates end-effector as the input and gives the joint configuration as output." [36]

9 FIS

FIS stands for Fuzzy Interference System. This type of fuzzy logic is usually applied in robot arm with higher degrees of freedom. With more degrees of freedom, the robot arm's motion will be in greater area. A fuzzy logic control system will guide the arm to locate the object in different ways. [36]

The arm is programmed to move the end-effector from one position to another in a work space. This is why a microcontroller with FIS is calculating the angles using Inverse Kinematics for each joint to achieve wanted positions. The calculations has to be done for the entire arm. The robot arm become intricate with higher DOF systems. *"With increase in complexity of the calculations to be carried out by the controller, the time for computing also increases".* The FIS is the solution for this problem. Fuzzy logic eliminate complex calculations which result in slow reply of the arm. It's create a simple mathematical function having all the values of the arm from a data set, so it becomes easy for the microcontroller. *"The microcontroller now just has to extract the values for a given input from the mathematical funtion created by using some algorithms"* [36]

9.1 ANFIS

ANFIS stands for Adaptive Neuro Fuzzy Interference System. *"An adaptive neuro -Fuzzy Inference System is a cross between an artificial neural network and a fuzzy inference system (FIS)."*[36] The Neural Networks has machine learning features for mathematically solve complex equations for a data set. It first creates a parameterized mathematical model and the data set is created to train the neural engine. Data set here is using the forward kinematics equations.. [36]

It's necesarry to create the data set for training each member. The data set defines all the angles at different joints with a iteration of 0.1 °. MATLAB was used to create all the data sets with forward kinematics which is then imported into ANFIS for training. [36]

For three joints there are three ANFIS networks for each of them to be built. The first joint from the reinforcement 1, is not involved as a function for training the members. Since it is the only axis in Z-direction compared to the others joints. x-coordinat and y-coordinates are used as inputs and the angle of corresponding joint are used as output when the ANSIS networks are trained. The values for number of membership functions use as inputs and outputs, and the number of training epochs are decided. Values are decided by trial and error method manually. One epoch represent one complete presentation of all data points to the ANFIS. The number of membership functions has been decided to be 20 and 300 for the training epochs. [36]

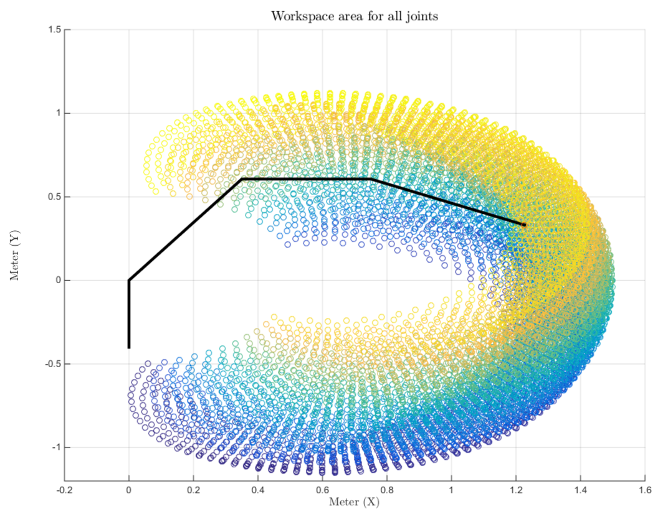


Figure 3: Workspace area

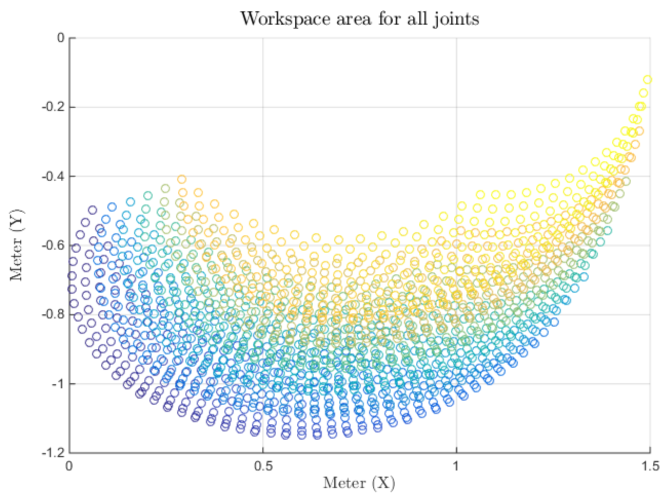


Figure 4: Lower workspace area

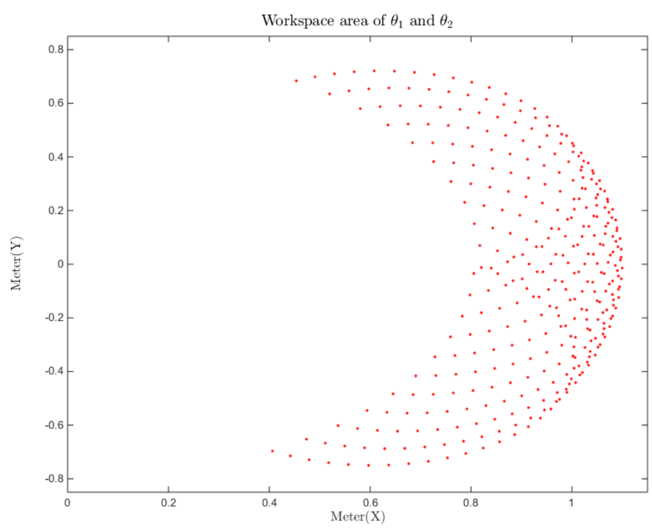


Figure 5: workspace area for theta 1 and theta 2

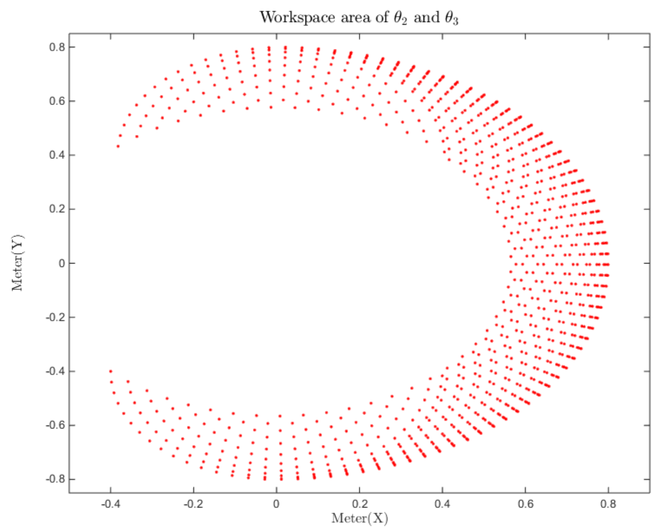


Figure 6: workspace area for theta 2 and theta 3

When the ANFIS has been trained, the model need to be tested to check its operation.*"It gives an idea about the accuracy of the outputs of trained ANFIS model"* .One has to examine accuracy of the outputs from ANFIS to the actual values for the inverse kinematics. Error is the difference between inverse kinematic calculations(that we have done, mathematically) and the values from ANFIS model. [36]

Error is in at all the joints of the robot arm. Th error is the calculation between deduced minus predicted, from the MATLAB coding(SECTION). Formel: deduced - predicted.[36]

9.2 PID

PID Stands for proportional-integral-derative controller.*"It is a control loop feedback mechanism greatly used in industrial control systems and other applications requiring modulated control"*. [37] This controller is greatly used in industrial control processes, because it is very understandable and is quite effective. It is problematic to achieve some points like unknown non- linearities, time delays, constant time disturbances and changing in the system parameters. To achieve this problems, the fuzzy logic control is solution for this problem.[38][37]

P stands for proportional. When increasing the proportional gain (Kp), *"it has effect of proportional increasing the control signal for the same level of error"*. [38] To make the closed-loop react more rapidly the controller will "push" harder for given level of error. Another way to increase Kp is to reduce the steady-state error. Adding derivation for the controller, it has capability to predict error. With only Kp controller the e+

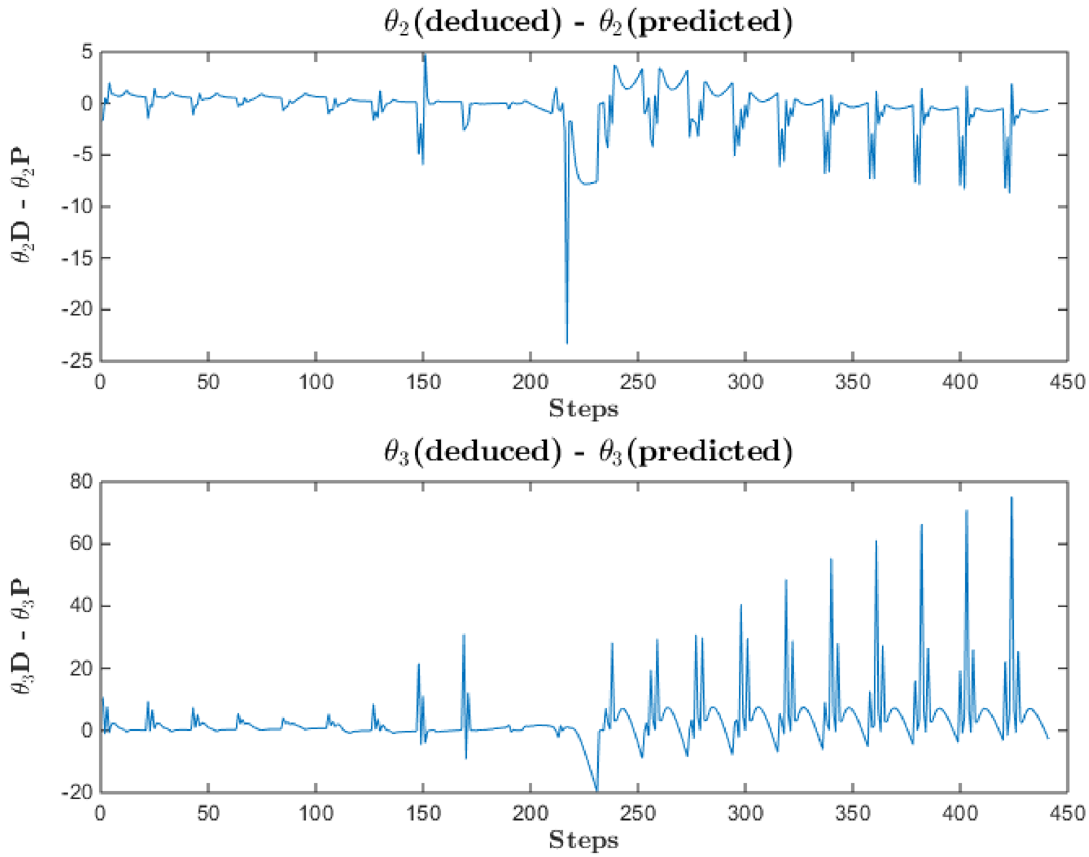


Figure 7: Error in theta2 and theta3

error will increase. When the Kd is included, the control signal become much greater. The error slope upward while the magnitude of the error is still small. This system quiet down the system and reduce the overshoot. Applying derivation of the controller has no effect on the steady-state error. Adding the integral (Ki) helps the steady-state error graph to be minimal. If there is a persistent, steady error, the integrator builds and builds, thereby increasing the control signal and driving the error down." A disadvantage for the integral time is that the system will get slower. Since the error signal changes so will it take time for the integrator to rest. [38]

Fuzzy logic is a technology used for developing intelligent control and information systems. This logic is used too nonlinear to use conventional control. Fuzzy control has the same quality as PID, but has less complexity. [37] Fuzzy logic controller have 4 main parts:

- Fuzzification

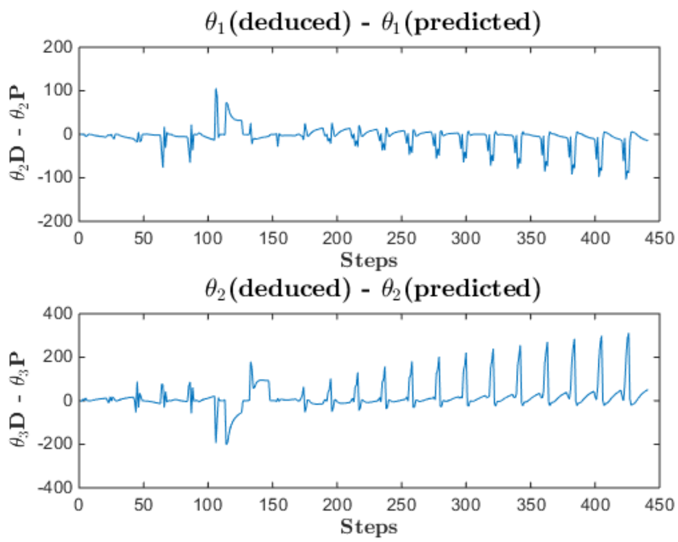


Figure 8: Error in theta1 and theta1

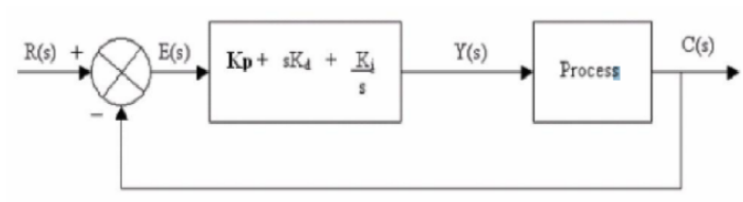


Figure 9: Fuzzy Logic Controller

- Rule base
- Interference
- Defuzzification

Preprocessing: The inputs are complicated measurements from some measuring equipment. Before they enter to the controller, some example of preprocessing are:

- Quantization rounding to whole number
- Normalization is standard range
- Filtering removing the noises

Fuzzification: Inside the controller is the fuzzification, which is the first block (figure FUZZY). This process convert each piece of input data to degress of membership by searching in several membership functions. The fuzzification move on to next block or processes, which is rule base and interference engine. [37]

Rule Base: The rules are picked from the operator

Defuzzification: The result of fuzzy are transformed to a number that send to the process as a control signal (on to the next block (post processing)

Post processing: After defuzzification comes the post processing, its include an output gain that can be tuned. [37]

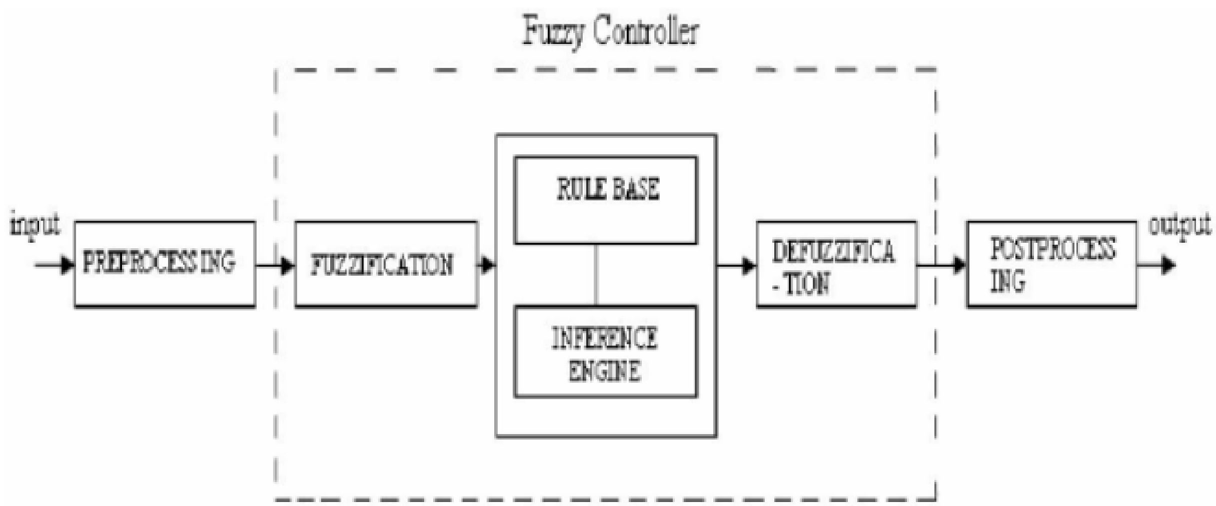


Figure 10: Fuzzy Logic Controller

10 Stress and strain matrix

10.1 General Hooke's law

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{bmatrix} \tag{1}$$

10.2 poissons ratio

$$V_{ij} = -\epsilon_j/\epsilon_i \quad , \quad i = 1,2,3 \quad , \quad j = 1,2,3 \tag{2}$$

10.3 Laminate stresses

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{21}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix} \begin{bmatrix} \epsilon_x^0 + zk_x^0 \\ \epsilon_y^0 + zk_y^0 \\ \gamma_{xy}^0 + zk_{xy}^0 \end{bmatrix} \tag{3}$$

10.4 Laminate stiffness matrix

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \epsilon_x^0 \\ \epsilon_y^0 \\ \gamma_{xy}^0 \\ k_x^0 \\ k_y^0 \\ k_{xy}^0 \end{bmatrix} \tag{4}$$

10.5 Reduced stiffness matrix

$$\begin{bmatrix} Q_{ij} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{bmatrix} \tag{5}$$

where $Q_{11} = \dfrac{E_1}{(1 - v_{12}v_{21}}$
$Q_{22} = \dfrac{E_2}{(1 - v_{12}v_{21}}$
$Q_{12} = \dfrac{E_2 v_{12}}{(1 - v_{12}v_{21}}$

$Q_{66} = G_{12}$
$v_{21} = \dfrac{v_{12}E_2}{E_1}$

10.6 Stiffness Matrices of thin laminates

$$\left[\overline{Q_{ij}}\right] = \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix} \tag{6}$$

$C = \cos\theta,\ S = \sin\theta$

$\overline{Q_{11}} = c^4 Q_{11} + s^4 Q_{22} + 2c^2 s^2 (Q_{12} + 2Q_{66})$

$\overline{Q_{22}} = s^4 Q_{11} + c^4 Q_{22} + 2c^2 s^2 (Q_{12} + 2Q_{66})$

$\overline{Q_{12}} = c^2 s^2 (Q_{11} + Q_{22} - 2Q_{66}) + (c^2 - s^2)^2 Q_{12}$

$\overline{Q_{66}} = c^2 s^2 (Q_{11} + Q_{22} - 2Q_{12}) + (c^2 - s^2)^2 Q_{66}$

$\overline{Q_{66}} = 0$

$\overline{Q_{26}} = 0$

10.7 Stiffness matrix of the laminate

$$A_{ij} = \frac{h}{n} \sum_{k=1}^{n} (\overline{Q}_{ij})_k \tag{7}$$

h = total thickness of a laminate

n = number of layers

10.8 For fiberretning + - 45 grader

$$\left[\overline{Q_{ij}}\right] = \begin{bmatrix} 72,27 & 6,72 & 0 \\ 6,72 & 77,27 & 0 \\ 0 & 0 & 35,48 \end{bmatrix} \tag{8}$$

10.9 The stiffness matrices of the laminate

$$[A] = \int_{-h_b}^{h_t} \overline{[Q]} dz \quad 10^6 \frac{N}{m}$$

$$[D] = \int_{-h_b}^{h_t} z^2 \overline{[Q]} dz \quad 10^6 \frac{N}{m}$$

The elements of these matrices are (i,j=1,2,6)

$$A_{ij} = \int_{-h_b}^{h_t} \overline{Q}_{ij} dz \quad 10^6 \frac{N}{m}$$

$$D_{ij} = \int_{-h_b}^{h_t} z^2 \overline{Q}_{ij} dz \quad Nm$$

Combining them:

$$A_{ij} = \sum_{k=1}^{K} (\overline{Q}_{ij})_k (z_k - z_{k-1})$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{K} (\overline{Q}_{ij})_k (z_k^3 - z_{k-1}^3)$$

k= total number of plies in laminate z_k, z_{k-1}= are the distances from the reference plane to the two surfaces of the $k-th$ ply.

$Q_{ij})_k$= The element of the stiffness matrix og the k-th ply
$a_{11} = \frac{1}{Eh} \qquad a_{12} = -va_{11} \qquad a_{66} = \frac{2(1+v)}{Eh} = \frac{1}{Gh}$
$d_{11} = \frac{12}{Eh^3} \qquad d_{12} = -vd_{11} \qquad d_{66} = \frac{24(1+v)}{Eh^3} = \frac{12}{Gh^3}$

$[a] = 10^-9 \frac{m}{N}$ $[d] = \frac{1}{Nm}$

$E_1 = LongitudinalModulus$

$E_2 = TranverseModulus$

$G_{12} = InplaneshearModulus$

11 Design choices

The collective design choices for the arm follows the requirements set both by us in collaboration with the other members of MISC and for the European Rover Challenge, recall section(AJHI). On the other hand, the structural design choices are primarily based on the ERC requirements [2].

Maintenance Task

- Demonstrates the manipulation devices on the rovers' ability and performance in operating electrical panels located between 0.2m and 1.5m above the ground. To change the state of the switches, handle element will be required to have different forms of translation and/or rotation of the handle element, which in our case will be the end-effector and the corresponding common connection
- *We didn't take the requirements regarding the voltage measurements in consideration on the account of our team leader chose to delegate this aspect of the challenge to the electrical teams of MISC*

Collection Task

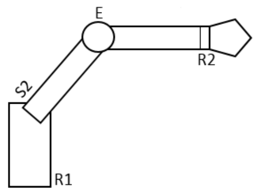
- Demonstrates the ability to perform collection of caches from different locations, more specific the concept of Sample Fetching Rover, or SFR in short
- On-board, detachable container must tolerate forces acted on the rover when traversing through challenging terrain to designated place and/or area, thereby keeping caches in vertical position
- *We are given a schematic view of preliminary cache design, notwithstanding, it could change at the competition*

11.1 Requirements

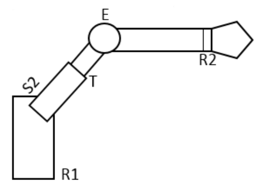
In order to enable execution of the stated tasks, following requirements were set:

1. Have a reach up to 1.2m, measuring from the base of the robot arm to the end-effector
2. Stable end-effector control, which then allows the arm to reach the caches on the rover
3. Movement to flip a switch, scoop and turn a knob, addition to the movement to handle a drill
4. Modular and compact design

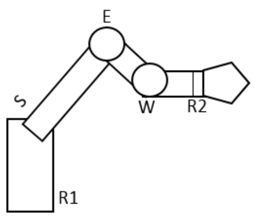
In accordance with the maintenance task requires the arm to have a reach from 0.2m to 1.5m. These numbers include the height of the rover, set to be approximately 0.5m, thus reducing the needed final maximum reach to 1.3m. The arm is also required to have a stable end-effector control, in order to avoid any sudden movements by the arm. In its readiness, sufficient degrees of freedom permits the range to reach all positions. Additionally, a resting position is a necessity to limit the possibility for bringing imbalance to the rover when traversing across the terrain. It is desirable to change end-effectors, parts and electronic components, so modular design is preferable, therewith favouring same controller electronics.



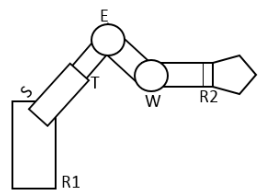
(a) D1



(b) D2



(c) D3



(d) D4

Figure 11: Design Options

	Unit	Design 1	Design 2	Design 3	Design 4
Degrees of freedom		4	5	5	6
Rotational joint 1	Degrees	∞	∞	∞	∞
Shoulder joint	Degrees	120	120	120	120
Telescopic joint	m	-	0.3	-	0.4
Elbow joint	Degrees	180	180	180	180
Wrist joint	Degrees	-	-	180	180
Rotational joint 2	Degrees	∞	∞	∞	∞
Link 1	m	0.4	0.4	0.4	0.4
Link 2	m	0.7	0.4-0.7	0.7	0.3-0.7
Link 3	m	0.6	0.6	0.4	0.4
Link 4	m	-	-	0.4	0.4

Table 1: Design Options

There are multitude of configurations when designing a robot arm. More freedom of movement is attainable by adding more joints. A few options were sketched

Arm design 1 The accumulation of joints shown in the design (figure 11a), subsequently gives four degrees of freedom (DOF). A rotational joint (R1) at the bottom of Link 1 combined with a twisting joint (shoulder joint) make sure that the robot arm itself can revolve around the rover at any height. Then another rotational joint, i.e. elbow joint (E), is placed roughly half way of the total arm-length and offers extra mobility in the vertical movement. Hereafter, another link follows the link before, increasing the range of the arm, which makes it easier to reach the caches without having to rely too much on the movement of the rover. Somewhere on this link, a rotational joint is created to indefinitely rotate the end-effector, consequently a solution to the tasks mentioned before. Although the total length of the robot arm is 1.9m, the limitation in the shoulder joint and Link 1 assembled under the rover at a certain height, depended on the dimensions of modulated house casing, makes the total height from the ground to the end-effector approximately 1.5m. This renders the robot arm ineffective in so-called dead zone areas.

Arm design 2 Identical to the figure (figure 11a, arm design 2 (figure 11b has an extra linear joint, i.e. telescopic joint (T), placed between S and E. The extra DOF increases flexibility and so forth the range of the arm, in addition making it more compact. This solution reduces the torque imperative to the movement of joints. However, the extra motor required will enlarge the total weight and alters the centre of inertia to a position more depended on the posture of the arm. Placing the motor in the first link maintains the torque magnitude in the elbow joint and brings the centre of total mass closer to the base.

Arm design 3 In common with figure 11b, arm design 3 (figure 11c) has the same number of DOF, but the telescopic joint is removed as a rotational one, i.e. wrist joint (W), is attached. Following the gained flexibility, this reduces the effective dead zone meantime/meanwhile enables the possibility to keep the end-effector in a certain angle whilst driving/actuate the robot arm. Nonetheless, as with the figure 11b, the motor necessary for this operation increases the mass of the particular link.

Arm design 4 The last arm design (figure 11d incorporates the features of figure 11b and 11c. Notably, it is a configuration of linear and rotational joints to the base design (figure 11a). Furthermore, it embodies the advantages of the previous layouts, like compactness, extra flexibility and a decrease of dead zones. As a result, the total weight of the arm will increment in addition to an increase of both required torque and power.

11.2 Consideration

The simplest design is the first design as well as the least flexible and has low weight, which then lowers overall power consumption. It is crucial that the arm has the right movements rather than the latter. Therefore, it is justified to include more motors for more versatility, along with being in a resting position when it is not in use, subsequently having zero consumption during traversal. With the increment of complexity taken into account the increase of joints, a larger total amount of torque is required to drive the robot arm attributable to the mass growth. The mandatory height set by the team is not a problem for any of the design, though this is dependent on the house casing, as referred to in Arm design 1, moreover making the centre of mass an issue in certain cases for instance collecting object more than a meter away. We have for that reason used trajectory planning. In terms of the progression between the selections of feasible arm design, an extra joint in link 3 will allow a better positioning of the end-effector, i.e. wrist joint. Further, the linear joint, i.e. telescopic joint, yield/permit a more compact design.

11.3 Conclusion

The logical choice for the primary design were the figure 11d. An advantage to a modular arm is the possibility to remove or add joints based on later iterations of the design. Through the sum of joints in the figure, the requirements 2 to 4 are fulfilled. Although the shoulder- and the elbow joints present a suitable posture of the arm, the telescopic joint is the sine qua non by significantly contribute to the compactness when folding on the rover. Nevertheless, the ability to reach the appropriate height to accomplish the tasks is unaffected by these decisions, achieving requirement 1. However, the telescopic joint was removed during the development of the project as well as the motor in shoulder joint was replaced with an actuator, as the reason for this was it proved difficult to implement from a mechanical point of view; an easy fix by virtue of a modular design.

12 Elecrical choices

The requirements for motors in general come from the electrical teams and the robot design, e.g. torque specifications and power consumption:

5. Movement of a joint is done by one motor with right amount of torque
6. Motor must have a suitable torque-to-weight ratio and provide precise control
7. Power consumption should be as low as possible
8. To keep the system modular, one type of motor is to be chosen

In order to move every joint individually, a motor has to deliver a torque great enough to move the joint in preferred position. Howbeit, a torque-speed gear or other kind of transmission coupled with the motor can lower the desirable torque output. Thus, a valid statement with the aim of lowering the weight of each link in the arm would be to have lightweight motor in each joint. The general battery on-board the rover powers the motors, which consequently makes it important to keep the power consumption low. Additionally, choosing one type of motor keeps the joints modular and simple, along with the possibility to use same controller for every motor. Conjointly, chosen type of motor must have the ability to rotate in two directions or more.

12.1 Options

Brushed DC motors Powered by direct current (DC), this internally electrical commutated type of motor contains a stationary part and a moving part, namely a stator and a rotor. Former generates a stationary magnetic field by fixed or permanent electromagnet that surrounds the latter being an armature of windings, more specifically a configuration of wound wire coils. In order to create an electrical current, an energized rotor will then create a magnetic field that attracts the stators' opposite poles, causing it to turn. This develops a mechanical commutation when the brushes makes mechanical connection with the electrical contact. Subsequently, the contacts and being most prone to wear. A controller is a necessity for speed and torque control for the purpose of protections from factors like under- and over-voltage and current limit, in addition to holding the motor in a certain position and the linearly reduction of torque with increment of speed.[39]

Brushless DC motors While this type of motor is similar brushed DC motor, the replacement of the internal brushed, switching system with an external controller element, or in other terms electronic commutation, is what sets these two types apart. As a result, this exploits the relationship between the magnetic field and the electrical energy flow, additionally improving heat transport to the outside of the motor. Moreover, there is less friction and a diminutive voltage drop produced, thereby ensue a better efficiency in comparison to brushed DC motor. Using a FOC, PID or other advanced algorithms with sensors suchlike hall effect sensors will contribute for better control. [39]

Stepper motors Another type of a synchronous motor, this type of motor uses a certain amount of steps for the rotation, hence the name. Compared to brushless DC motor, it gains a more precise control due to its smaller steps in the rotation, in addition to having a longer life span given that the moving parts comes only in contact with bearings, and be able to create a greater holding torque by using more windings per coil. However, this provides a larger back-EMF in which case reduces the maximum speed. Another possible flaw with the motor loss of a particular cycle if a step is skipped e.g. load on motor is larger than the switching speed of the current. This is preventable by using a feedback controller, or in other terms a drive.[39][40]

Servo motors Self-contained electric devices, servomotor are intended for use in applications that require rapid acceleration and deceleration. Furthermore, it allows precise control of angular positioning and velocity. Given its small size and the armature resistance being fairly high, a short-circuit/"locked rotor" current will have approximately five times the continuously rated current at full armature voltage, ensuring the necessity of choosing a drive amplifier to cope with this condition without complication and consequently a very rapid acceleration from rest. Further, it is typical for the motor to which the full armature voltage reversal is instantaneously at full speed; somewhat the larger DC motors is unable to do.

[39]

12.2 Consideration

While evaluating the choices for the robot arm with regard to size, it was apparent that the torque delivery was not high by solely using a direct drive. Therefore, a gearing system was implemented. This subsequently resulted in a more power consuming, larger, and heavier brushed DC motors compared to brushless DC-, stepper- and servomotors, in other words an undesirable development.

12.2.1 Conclusion

A decision was made to use stepper motors on the account of considerations and requirements. Although the brushless DC motors' capability of holding a steady operating torque satisfies requirement 6, as well as requirement 8 and 9 considering its high efficiency and better torque to size and weight ratio compared to brushed DC motors, so does the stepper motors. This is also true to choosing right stepper motor for each joint, fulfilling requirement 9. Such motors and servomotors offer precise control given which type of drive one use, but in terms of rotating the joint in a combination with a gearbox with low rotational speed, the stepper motor is the better choice, while the brushless DC motor is preferable if higher rotational speed is desirable. The team leader requested also these motors, inasmuch that other electrical teams are using stepper motors, thereby allowing a common code structure/recipe for the whole team. Servomotors is a viable option, given that these motors are favourable in application where high RPM is necessary, yet the generated amount of torque at safe voltage is advantageous for the stepper motor. Note that former are more flexible than the latter. On the other hand, brushed DC motor are the least-attractive choice due to its unreliability in terms of brush wear-out, maintenance and electrical noise (EMI)

13 Mechanical choices

13.1 Materials

A preliminary study was conducted to gather a selection of materials able to withstand conditions such as Devon Island (section 4) in order to formulate requirements based on information from sources such as ESF and *Background on Mars* [3] by Christopher Hoftun.

9. The physical properties of the material must tolerate sub-zero temperatures and other weather elements, for instance wind and dust, during traversal and task execution
10. Motor must have a suitable torque-to-weight ratio and provide precise control
11. Protection against UV radiation
12. Although being able to manage forces and pressure acted on the system, it is imperative that the sum of arm mass is kept low as possible

Considering the large thermal fluctuations and the cold environment on Mars, materials chosen based on the preliminary study is required to have a high probability to endure these temperatures, thereby coinciding with the shear strength of that material. In other words, these variations will induce fracture or delaminate by expansion and contraction at different rates due to stresses. Additionally, the material must have some type of protection against UV radiation inasmuch that the atmosphere around Mars is not composed of the same layers of gas as Earth's. The reader should note that the traits attributable to environment used in simulation and calculations is limited to the weather and climate on Devon Island.

13.2 Option

13.2.1 Aluminium

As mentioned in (section 5.1), aluminium has a wide variety of possible application depended on which type of environment the material is exposed to. These alloys were selected because of the requirements: [41] [42] [43]

6061 T6 Aluminium 6061 T6 is a medium-to-high strength, heat-treatable alloy. In addition to have a wide range of mechanical properties and good workability, "it is the least expensive, yet most versatile of the heat-treatable alloys according to ASM Aerospace Specification Metals Inc" [44] It offers weld-ability as well as corrosion resistance, consequently being a sought-after aluminium type, along with other alloy types like 2024 T6. 6061 T6 is often considered for low- and sub-zero temperatures due to its fracture toughness and cold formability (section HOT AND COLD WORKING). Tensile Yield Strength for 6061 T6 is 276 MPa and the elongation at the break is 12%, thereby possessing high elastic deformation. [45] [46]

3003 H14 3003 H14 is a medium strength alloy, non-heat treatable aluminium alloy. A compound with a high concentration of the manganese, it has a tensile yield strength from 140 to 180 MPa and elongation value between 1-8%, both depended on thickness, thereby retain features suchlike excellent workability, weldability and good corrosion resistance. Furthermore, 3003 H14 is one of the widely used alloys as it can be deep drawn, spun, welded or brazed, although this alloy can only be strengthened by cold working as a result of its alloy type. [47] [48] [49] [50]

2017 T4 Utilized in current work, 2017-T4 alloy is suitable for machining automatics, milling machines, lathers and so forth. Its physical properties allows good workability with great formability and ductility, though it is harder to machine. The heat treatable alloy has a tensile strength of 240 MPa and allows elongation from 12 to 14%. Similarly to the alloys mentioned, 2017-T4 is has satisfactory qualities for sub-zero applications. [48] [51]

13.2.2 Carbon Fiber

Unidirectional Fabric Unidirectional fabric (UD) is a type of carbon fibre lamina in which the majority of fibres run in a predetermined direction. Minor amount of fibres or other material may run in other directions in order to hold the primary fibres in position, albeit other materials might modify the structural properties of the lamina. As such, weavers tend to use the term UD for fabric with the number of unidirectional fibres at 75% or more. Further, the two classification of this type of lamina is *warp UD* because of the predetermined angle of 0°(primary angle) whereas the angle of 90°is defined as *weft UD*. Fabrics regarded as *true unidirectional fabrics* grant positioning of the fibres with precision at an optimum quantity, thus resulting in uppermost possible lamina properties compared to other composite layers. Additionally, the structure of fabrics determines the drape, stability and surface smoothness, and the combination of number of fibres per cm and fibre tex regulate the *wet out*, area weight and porosity. Note that these fabrics can only be improved upon by prepreg with resin, as there is no secondary material to keep the fabrics in place. [52].

Multiaxial Fabrics In construction of components by composite materials, the carbon fibre type favoured for implementation is multiaxial fabrics. These fabrics are based on a laminate which consist of long fibres kept by a secondary, non-structural stitching tread, whereas the main fibres can be of any combination structurally speaking. Polyester is often used as binding fibres as a result of its properties and cost. The stitching process allow the fabric to combined by a variation of fibres in orientations besides the 0°and 90°(section 5.3.13). [23]

13.3 Forward kinematics

X og Y is the coordinates of the end-effector

$$x = L_1 \cos\theta_1 + L_2(\cos\theta_1 + \theta_2) + (l_3 + d_4)\cos(\theta_1 + \theta_2 + \theta_3)$$

$$y = L_1 \sin\theta_1 + L_2(\sin\theta_1 + \theta_2) + (l_3 + d_4)\sin(\theta_1 + \theta_2 + \theta_3)$$

13.4 Inverse kinematics

$$\phi = \theta_1 + \theta_2 + \theta_3$$

$$x' = x - L_3 \cos\phi$$

$$y' = y - L_3 \cos\phi$$

$$\gamma = \text{atan2}(\frac{-y^{'}}{\sqrt{x^2 + y^2}}, \frac{-x^{'}}{\sqrt{x^2 + y^2}})$$

$$\theta_1 = \gamma + \arccos(\frac{x'^2 + y'^2 + l_1^2 - l_2^2}{2l\sqrt{x'^2 + y'^2}})$$

$\sin 1 = \sin\theta_1$

$\cos 1 = \cos\theta_1$

$$\theta_2 = \text{atan2}(\frac{Y_i - l_1 \sin\theta_1}{l_2}, \frac{X_i - l_1 \cos\theta_2}{\sqrt{l_2}})$$

$$\theta_3 = \phi - \theta_1 - \theta_2$$

14

In the recent years have organizations taken advantage of 3D printing to aid their mission for space travel to Mars and other interplanetary *and interstellar* travels. Additionally, NASA have experimented with solutions suchlike building rovers and construct building using Martian resources, for instance dirt, as filament. This concept was adapted as a solution to obstacles like physical components that were highly prone to wear and tear, specifically the end-effector. As 3D filament materials have a broad utilization possibility limited only by the physical challenges, the preliminary study was restricted to these requirements: [53] [54]

- The filament must have high strength and durability in low temperatures and rugged end-uses
- Imperative for the solid model to have a low weight

ABS plastic Also known as "Acrylonitrile Butadiene Styrene", ABS is a thermoplastic-based filament. This is widely used in engineering due to its low cost and multifunctional properties and is resistant to factors such as chemicals, heat and impact. As a consequence, the ABS is widely used in everyday usable items, e.g. cars, phones, and technical items, in addition to being recycleable. Even so, the ABS has restrictions, suchlike being highly flammable, low UV resistance, limited applications in the food industry, tolerant against solvents, and higher price compared to polystyrene and polyethylene based materials.

PLA Polylactic Acid, PLA in short, is also a thermoplastic, but more beneficial for environment compared to other plastics. The filament is favourable considering it is made of bioplastic, whereas other plastics are made of non-renewable material. As its production method is the same as counterparts, it is relatively cost efficient to produce. [55]

Nylon12/PA12 Nylon 12 or Polyamide 12, PA12 in short, is known for its physical properties that are suited for almost any mechanical products, e.g. nozzles, sealing rings, wire insulation, ski boots, and etc. Moreover, it is used in architectural and other engineering projects, thereby replacing ABS when in need of higher tolerances. Additionally, the material is utilised in injection moulding process of engineering applications. With the ALM technology, also known as selective laser sintering, it is possible to produce strong components. Models made of PA12 will retain its form, even if exposed to moisture, in addition to relative absorbent towards impact- and non-impact strength due to its fatigue, stress and abrasion resistance, even at low temperatures. However, this is depended on the printing method. Moreover, the material have minor coefficient of friction when it is dry run against other materials such as steel. In consequence of these reasons, the PA12 has a higher cost compared to PLA and ABS. [56][57] [58]

14.1 Consideration

PLA is favourable for bendable solid models, whereas ABS is a better choice in terms of elongation. ABS has the most rigid printed models compared to Nylon12 and PLA. All of this is good for the end “fit and finish” of the station. It is also case components for something like a Chatty Beetle. Temperature for the printing of PLA is lower than other filaments. This means using solid models of this material will result to warping, melting and/or cracking due to temperature and similar conditions. It will flow without inducing warp and is not prone to blobbing or stringing during print. The finished solid model is modified for its implementation in terms of task relevance. The plastic is harmless to the environment and will biodegrade due to its bioplastic properties. ABS and PLA are used to create accurate parts, and have the printing details down to 0.8 mm and minimum features down to 1.2 mm. The tolerance is 0.5 mm by connecting parts, the lowest wall thickness is 1-2 mm, and will have strength in wall elements. Because of its low printing temperature, the PLA will be cooled down, which makes it less likely to warp and print effectively at the corners and makes it more rigid than ABS. Although they are different, the PLA provides better tensile strength, but when it breaks, the elongation gets extended at maximum 6%. The elongation for ABS is between 3.5%-50% , for this reason it is preferred more for its improved ductility, high flexural strength and better elongation. On the other hand, ABS is preferred when it comes to high temperature applications. Both are usually FDM-based printed materials, and are similiar in price. ABS is more difficult to print than PLA due to necessary extrution temperature, but has better mechanical properties, as well as suited for applications where ductility, strength, thermal stability and machinability are required.[59] [60] [61] [62]

As a result of its composition of polyamides, Nylon12 is a greater versatile material than ABS and PLA. Due to its self-supporting powder, it can be constructed by support-walls of lesser thickness. Additionally, it may have higher density and lower porosity, though this is depended on method of print, e.g. laser sintering, and type of printer (SLS vs SLM). It should be taken into account that PA12s’ value of E’modulus grows as temperature decreases beyond 0°C, more so than the compared materials, along with increased strength and elasticity. Furthermore, as a consequence of its flexibility and lightweight, it is favoured for models or parts associated with continual wear and tear use. To put it in layman terms, PA12 is used in applications in which it is necessary to use a plastic material with high melting temperature. Moreover, the physical and mechanical properties of Nylon12 can be greatly improved by merging with other materials, e.g. carbon fibre [63] [64] [65] [66] [67]

http://www.performance-plastics.co.uk/product/classification/nylon-12-pa12/

(

It is also possible to increase the properties of Nylon 12 by implementing carbon, e.g. "carbon fibre 20%", the data sheet is here

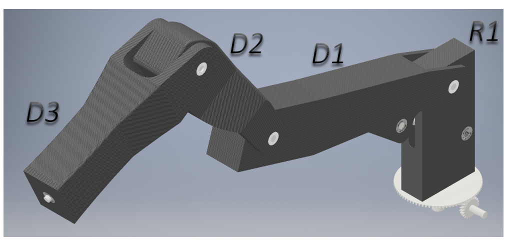
http://web.rtpcompany.com/info/data/0200F/index.htm

http://crdm.co.uk/pdf/LS-PA12.pdf

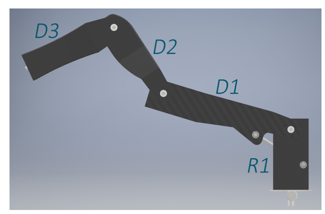
15 Mechanical results

Inventor 2018 was utilised for the stress analysis of the different parts and components in the assembly. The simulations are divided into two categories, the first being simulations run through the *Design Accelerator*. This generator allows the user to input values in order to get the minimum values to cope with the forces acted upon the component. These values are then calculated using the formulas in the handbook provided by the CAD program.

The second simulation method is the FEA stress analysis. The direction stresses is acted upon the system defines which type of stress is being calculated. In other words, multidirectonal stresses will be summarized to the Von Mises stress, whereas unidirectional stresses equals a singular equicalent stress relate to the real stress system. The physical displacements and stresses are calculated relative to the global coordinate system in the part or assembly.



(a) The robot arm (without end-effector)



(b) Sideview of the arm

The FEA analysis can be modified to obtain a more accurate stress simulation and convergence compared to using the standard values. In the first iterations of the analysis, only the p-refinements (polynomial formula to describe displacements) is used, whereas h-refinements (h is the size of the circumscribed circle of the triangle) is used to calculate in terms of the part or assembly's mesh. The convergence settings give the user to alter the Maximum Number of H refinement, thereby determine the total number of iterations that it will be attempted. These iterations will then stop if either the Stop Criteria or Maximum Number is met. The threshold parameter controls how the system progression correlate to positions in order to refining the mesh geometry, determing where the refining process is focused around singularities- and concentration areas of stress.

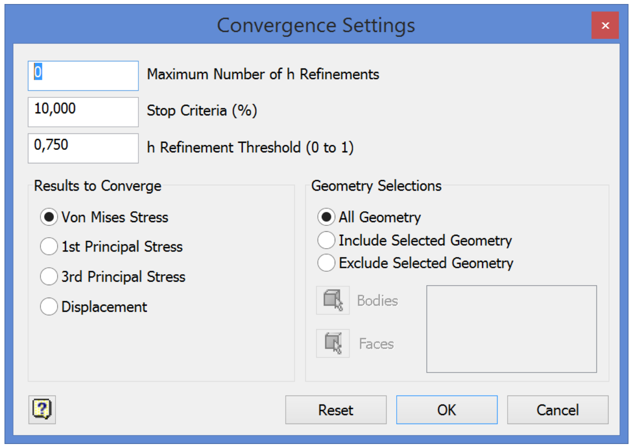


Figure 13: Convergence Settings in FEA Analysis

15.1 Design Accelerator

In order to simulate properly, we required some predetermined values. Since the majority of results were depended on the movement of the arm, we used the specifications of NEMA 23 and NEMA 17 to drive the worm gears and the bevel gear, in addition to the shaft connecting the end-effector to the arm. All mechanical components are *standard parts* to keep the modular nature, for instance all shafts have Ø20mm in diameter.

15.1.1 Reinforcement 1

The bevel gear connected to NEMA 23 translates 40,780 Nm at 1.69 rpm through a gear ratio at 4ul to 159.857 Nm at 0.42 rpm, giving the arm a fully rotational limb, as mentioned in section 11. The helix angle is 20°in order to reduce slip. The shaft connected to the bevel gear shows a large number in shear force at the second support. This is a product of bending moment from the robot arm carrying maximum load of 160N, therefore also contributing to the deflection around 100mm. The shaft connecting *Reinforcement 1* and *Detachable 1* will most of the shear force be acted upon between the ends and the supports. Bending moment between the supports remain the same, while deflection values at approximately 7 micrometers are at the tips of the shaft.

15.1.2 Detachable 1

The shaft connected between the actuator and *Detachable 1* is only subjected to forces acted on the bearings and the actuator itself. As a result, the bending moment is at its peak around the middle of the shaft. Since there is only one major force, the maximum number of deflection and bending stress at the acting point. The shaft connecting *Detachable 1* and *Detachable 2* is constrained by the placement of the worm gear. Forces acting on the shaft is a result of the connection forces between the parts. As a consequence, the bending moment is rather fixed at approximately 1.2 Nm. The deflection angle results to deflection being near 6 micrometers at the end, again where the *Detachable 2* is connected to the system. With the gear ratio of 25ul, the worm gear connected to NEMA 23 translates 5.730 Nm at 12 rpm to 90.732 Nm at 0.48 Nm. The transalated torque is one the reasons for the high values of deflections on the *connecting shaft*.

15.1.3 Detachable 2

The shaft connecting *Detachable 2* and *Detachable 3* has similar results compared to the connecting shaft in 15.1.2. Although, as a result of lower torque value given by the worm gear, the most noticeable differences are the rugged shear force diagrams and the curve in the graph of deflection. This particular worm gear has 28ul in gear ratio, thereby producing 73.715 Nm at 0.54 rpm of an efficiency 0.633 ul, same as the other worm gear. Both have same values for the worm, however values for each worm gear is different due to size and load difference.

15.1.4 Detachable 3

The shaft between the *end-effector* is *subjected* to 160N due to an attachment in accordance to MISC. This results into peak values at the end where the connection is made, except for the area of deflection being between the bearing supports. In this system, the forces acted upon the bearing close to the connection is the largest compared to other systems, e.g. *Detachable 1*.

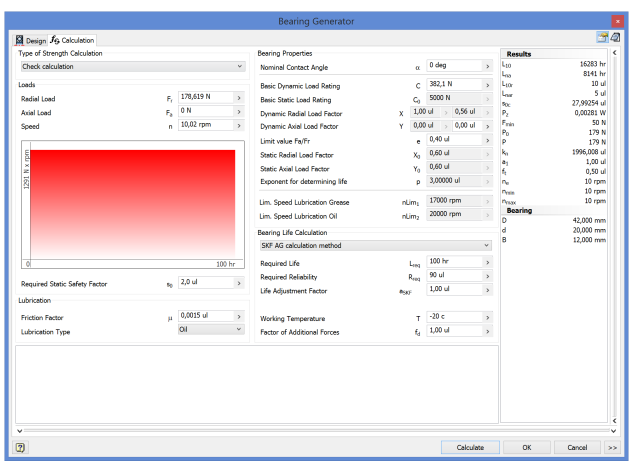


Figure 14: Bearing calculation in terms of forces acted upon

15.2 FEA Analysis

The simulations were set to 15 iterations, 0.5 in h Refinement Threshold and 0.05 iterations. As the figures in section **??** illustrates, one could get a high accuracy if the settings are set to right configuration. All solutions needed at least 10 steps except the unforeseen result for Detachable 2. The values ranges from 402.283 MPa to 2.246 MPa in the Von Mises stresses, while the displacements for each system is relatively the same, except Reinforcement 1.

The end-effector was intended to be designed by us, but was given to a student at Stavanger Offshore Technical College

16 Discussion

As elaborated earlier, in order to get the results we wished, the worm is to be made of steel while the material for the worm gear is aluminium. The shaft as expected to be of aluminium. We tried the using 3D filament as material, but it resulted in failure. The reader should also know that the highest values in terms of the FEA analysis is at the bearings. The carbon fibre bodies was able to withstand the forced of stresses and strain, as seen in the calculation for the simulations in appendix.

The ANFIS needs to be more adapted, as it became erratic after approximately 200 steps. This might be of a reason to the code we made and used, or the epoch and/or membership functions. The inverse kinematic equations could have been wrong which gave us these graphs. The input could changed or increased the number of training samples. Because of the high numbers of epochs and function numbers, it too long time to get the each graph. One epochs represent one complete presentation of all data points to the ANFIS. We decided to have a membership functions at 20 and for the training epochs 300.

References

[1] N.D. *Robotics*. 2018. URL: https://en.wikipedia.org/wiki/Robotics.

[2] European Space Foundation. *ERC, Student Rules European Rover Challenge*. 2018. URL: http://roverchallenge.eu/wp-content/uploads/2018/03/ERCStudent_rules_official.pdf.

[3] Christopher Hoftun. *Background on Mars, Mars as a Planet, Mars Institute Student Chapter.*

[4] Kaushik. *Devon Island: Mars on Earth.* 2016. URL: http://www.amusingplanet.com/2016/05/devon-island-mars-on-earth.html.

[5] Leonard David. *Aluminum Goes to Mars NASA's Grotzinger on the Essential Element for Space Travel.* 2015. URL: https://www.space.com/31312-mock-mars-mission-devon-island.html.

[6] N.D. *Haughton Mars Project (HMP)*. URL: https://www.marsinstitute.no/hmp.

[7] Bjørn pettersen. *Karbon*. 2018. URL: https://snl.no/karbon.

[8] Sven Ore. *Karbonfiber*. 2009. URL: https://snl.no/karbonfiber.

[9] Øyvind Grøn. *adhesjon*. 2018. URL: https://snl.no/adhesjon.

[10] Bjørn pettersen. *komposittmaterialer*. 2017. URL: https://snl.no/komposittmaterialer.

[11] N.D. *Composite materials*. URL: http://www.rsc.org/Education/Teachers/Resources/Inspirational/resources/4.3.1.pdf.

[12] N.D. *Reinforcements*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/.

[13] N.D. *Fibre Properties*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/fibre-properties/.

[14] N.D. *Laminate Properties*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/laminate-properties/.

[15] N.D. *Laminate Properties*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/laminate-impact/.

[16] N.D. *Glass fibre*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/glass-fibrefiber/.

[17] N.D. *Aramid fibre*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/aramid-fibrefiber/.

[18] N.D. *Carbon fibre*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/carbon-fibrefiber/.

[19] Dimitros G.Pavlou. *Composite Materials in Piping Applications*. Vol. 395. Reading, Massachusetts: DEStech Publications, Inc, 2013, p. xiv.

[20] N.D. *Fibre Comparisons*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/fibre-comparisons/.

[21] N.D. *Other fibres*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/other-fibres/.

[22] N.D. *Fibre Finishes*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/fibre-finishes/.

[23] N.D. *Multiaxial Fabrics*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/multiaxial-fabrics/.

[24] N.D. *Carbon Fiber- What is K?* 2015. URL: http://www.carbon.ee/en/n/carbon-fiber-what-is-k.

[25] N.D. *Spread Tow Fabrics*. URL: https://netcomposites.com/guide-tools/guide/reinforcements/spread-tow-fabrics/.

[26] Lars Mæhlum. *3D-printing*. 2017. URL: https://snl.no/3D-printing.

[27] N.D. *Solenoid*. 2018. URL: https://en.wikipedia.org/wiki/Solenoid.

[28] N.D. *Medium Solenoid*. URL: http://www.trossenrobotics.com/p/medium-solenoid.aspx.

[29] N.D. *Actuator LA23 Data sheet*. N.D.

[30] N.D. *INDUSTRIAL PIPE EQUIPMENT INSULATION*. 2017. URL: https://industry.foamglas.com/-/media/industry/files/en/products/pds-us/pds-us/fg-one-pdsusa110117.pdf.

[31] N.D. *FOAMGLAS® ONE*. 2012. URL: https://industry.foamglas.com/-/media/industry/files/en/products/migrated-data-sheets/1066foamglas-one-insulation-en-14305-pds.pdf.

[32] N.D. *ISO-C1® Polyisocyanurate Pipe and Panel Insulation*. URL: https://www.dyplastproducts.com/iso-c1-polyiso.

[33] N.D. *Phenolic Insulation*. URL: http://extolohio.com/info/?category_name=phenolic-insulation&data-types=prod-data-sheet.

[34] N.D. *Ditec Orginal Lakkbeskyttelse*. URL: http://www.ditec.no/bilpleietjenester/lakkbeskyttelse.

[35] N.D. *Kinematics*. 2018. URL: https://en.wikipedia.org/wiki/Kinematics.

[36] Karna Patel. 'Adaptive Neuro Fuzzy Inference System for Kinematics of 6 DOF Robotic Arm'. thesis. N.D, 2016. URL: https://www.ijser.org/researchpaper/Adaptive-Neuro-Fuzzy-Inference-System-for-Kinematics-of-6-DOF-Robotic-Arm.pdf.

[37] Guru Nanak Asim Ali Khan. 'Fuzzy PID Controller: Design, Tuning and Comparison with Conventional PID Controller'. thesis. Islamabad, Pakistan: N.D, 2006. URL: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1703213.

[38] N.D. *Introduction: PID Controller Design.* URL: http://ctms.engin.umich.edu/CTMS/index.php?example=Introduction&section=ControlPID.

[39] Austin Hughes. *Electric Motors and Drivers, Fundamentals, types and Applications.* Vol. Third edition. Elsevier Ltd, 2006. URL: N.D.

[40] Dr. Douglas W. Jones Reston Condit. *Stepping Motors Fundamentals.* 2004. URL: http://www.microchip.com/wwwAppNotes/AppNotes.aspx?appnote=en012151.

[41] N.D. *Hot Cold Working and the Rolling Process.* URL: https://www.leonghuat.com/articles/hot&cold.htm.

[42] N.D. *Properties of Aluminum Alloys at Cryogenic and Elevated Temperatures.* 2001. URL: http://www.totalmateria.com/Article23.htm.

[43] Duaa Amer Kadhim Dr. Hussain J.M. Alalkawi Dr. Fikrat Abdulkareem Fattah. *Fatigue Performance of 2017-T4 AL. Alloy Under sub-zero Temperature by Using Electromechanical Freezing System.* 2016. URL: https://www.iasj.net/iasj?func=fulltext&aId=123693.

[44] N.D. *Aerospace Aluminum Distributor.* URL: http://www.aerospacemetals.com/aluminum-distributor.html.

[45] N.D. *Aluminum 6061-T6; 6061-T651.* URL: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061T6.

[46] Samuel J. Rosenberg. *EFFECT OF LOW TEMPERATURES ON THE PROPERTIES OF AIRCRAFT METALS.* 1940. URL: https://nvlpubs.nist.gov/nistpubs/jres/25/jresv25n6p673_A1b.pdf.

[47] N.D. *3003-H14 Aluminum.* URL: https://www.makeitfrom.com/material-properties/3003-H14-Aluminum.

[48] N.D. *Aluminium Alloy Data Sheet 3003.* 2013. URL: http://www.atlassteels.com.au/documents/Atlas_Aluminium_datasheet_3003_rev_Oct_2013.pdf.

[49] N.D. *Aluminum 3003.* URL: https://www.metalsupermarkets.com/metals/aluminum/aluminum-3003/.

[50] N.D. *3003-H14 Aluminum.* URL: https://www.speedymetals.com/information/Material21.html.

[51] Duaa Amer Kadhim Dr. Hussain J.M. Alalkawi Dr. Fikrat Abdulkareem Fattah. 'Fatigue Performance of 2017-T4 AL. Alloy Under sub-zero Temperature by Using Electromechanical Freezing System'. In: (2016). ISSN: 16816900 24120758,

[52] N.D. *Unidirectional Fabric*. URL: `https://netcomposites.com/guide-tools/guide/reinforcements/unidirectional-fabric/`.

[53] N.D. *NASA's 'Mars Rover' Has Many 3D Printed Parts*. 2012. URL: `https://www.ptonline.com/articles/nasas-mars-rover-has-many-3d-printed-parts`.

[54] Neil Savage. *To build settlements on Mars, we'll need materials chemistry, Scientists explore ways to use martian soil to build habitats on the red planet*. 2017. URL: `https://cen.acs.org/articles/96/i1/build-settlements-Mars-ll-need.html`.

[55] N.D. *Everything You Need To Know About Polylactic Acid (PLA)*. URL: `https://www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes`.

[56] N.D. *NYLON 12 (PA) — POLYAMIDE 12*. URL: `http://www.rtpcompany.com/products/product-guide/nylon-12-pa-polyamide-12/`.

[57] Christina Hansen. *Materials Spotlight: The Properties of Nylon 12*. URL: `https://www.cableorganizer.com/learning-center/articles/materials-nylon12.html`.

[58] N.D. *MATERIAL DATA SHEETLS – PA12*. 2011. URL: `http://crdm.co.uk/pdf/LS-PA12.pdf`.

[59] N.D. *Chatty Beetle: A Rugged Iridium Satellite Terminal for Short Burst Data (SBD) sevice*. URL: `http://www.wernerlabsinc.com/rist.htm`.

[60] N.D. *ABS or PLA: Which 3D printing filament should you use?* 2015. URL: `https://www.digitaltrends.com/cool-tech/abs-vs-pla-3d-printing-materials-comparison/`.

[61] N.D. *ABS or PLA: Which 3D printing filament should you use?* 2016. URL: `https://rigid.ink/blogs/news/3d-printing-basics-how-to-get-the-best-results-with-pla-filament`.

[62] Ken Giang. *PLA vs. ABS: What's the difference?* URL: `https://www.3dhubs.com/knowledge-base/pla-vs-abs-whats-difference`.

[63] P.J. Hine, M. Bonner, I.M. Ward et al. 'Hybrid carbon fibre/nylon 12 single polymer composites'. In: *Composites Part A: Applied Science and Manufacturing* (2014). ISSN: 1359-835X. DOI: `https://doi.org/10.1016/j.compositesa.2014.05.020`. URL: `http://www.sciencedirect.com/science/article/pii/S1359835X14001626`.

[64] G.V. Salmoria, J.L. Leite, L.F. Vieira et al. 'Mechanical properties of PA6/PA12 blend specimens prepared by selective laser sintering'. In: *Polymer Testing* (2012). ISSN: 0142-9418. DOI: `https://doi.org/10.1016/j.polymertesting.2011.12.006`. URL: `https://www.sciencedirect.com/science/article/pii/S0142941811002108`.

[65] Michael Armani. 'What's the Difference Between PLA, ABS, and Nylon?' In: (2017). URL: `http://www.machinedesign.com/consideration/what-s-difference-between-pla-abs-and-nylon`.

[66] 'Everything You Need To Know About Nylon (PA)'. In: (). URL: `https://www.creativemechanisms.com/blog/3d-printing-injection-molding-cnc-nylon-plastic-pa`.

[67] 'Fiber Force Nylforce Carbon Fiber 2.85'. In: (). URL: `https://3dnet.no/products/fiber-force-nylon-carbon-2-85`.

Detachable 1.pdf.pdf Detachable 1.pdf Detachable 1.pdf.pdf Detachable 1.pdf

MATLAB function code

```
function q=fk(theta1,theta2,theta3)
%Forward kinematic
l1=0.7;%lenght of the first arm
l2=0.4;%lenght of the second arm
l3=0.4;%lenght of the third arm
d4=0.150; %lenght of the manipulator
thetax1=theta1+pi/2;

X=l1*cos(thetax1)+l2*cos(thetax1+theta2)+(l3+d4)*cos(thetax1+theta2+
    theta3); %finding x coordinate
Y=l1*sin(thetax1)+l2*sin(thetax1+theta2)+(l3+d4)*sin(thetax1+theta2+
    theta3);% finding y coordinate

d=ones(2,4);
n=1
d(1,n)=0;
d(2,n)=-0.4;
d(1,n+1)=0;
d(2,n+1)=0;
d(1,n+2)=-(l1*cos(thetax1));
d(1,n+3)=-(l1*cos(thetax1)+l2*cos(thetax1+theta2));
d(1,n+4)=-(l1*cos(thetax1)+l2*cos(thetax1+theta2)+(l3+d4)*cos(thetax1
    +theta2+theta3));
d(2,n+2)=l1*sin(thetax1);
d(2,n+3)=l1*sin(thetax1)+l2*sin(thetax1+theta2);
d(2,n+4)=l1*sin(thetax1)+l2*sin(thetax1+theta2)+(l3+d4)*sin(thetax1+
    theta2+theta3);
q=[X Y]; %End-effectors position in meters

figure(1)
plot(d(1,:),d(2,:),'-',...
    'LineWidth',3,...
    'Color','k') %Figure of the arm
hold on
plot(-X,Y,'o')
hold off
end
```

MATLAB function code

```

clc
```

```
clear all
close all

l1 = .7; % length of the second arm in meter
l2 = .4; % length of the third arm in meter

theta1 = -pi/6:0.1:pi/6; % all possible theta1 values
theta2 = -pi/2:0.1:pi/2; % all possible theta2 values

[THETA1, THETA2] = meshgrid(theta1, theta2); % generate a grid of
    theta1 and theta2 values

X = l1 * cos(THETA1) + l2 * cos(THETA1 + THETA2); % finding x
    coordinate
Y = l1 * sin(THETA1) + l2 * sin(THETA1 + THETA2); %  finding y
    coordinate

data1 = [X(:) Y(:) THETA1(:)]; % creating data set 1
data2 = [X(:) Y(:) THETA2(:)]; % creating data set 2


fprintf('-->%s\n','Start training first ANFIS network. It may take
    one minute depending on your computer system.')
anfis1 = anfis(data1, 20, 300, [0,0,0,0]); % Training the first ANFIS
     network
fprintf('-->%s\n','Start training second ANFIS network. It may take
    one minute depending on your computer system.')
anfis2 = anfis(data2, 20, 300, [0,0,0,0]); % Training the second
    ANFIS netweok



x = 0:0.1:2; % x coordinates for validation
y = 0:0.1:2; % y coordinates for validation

[X, Y] = meshgrid(x,y);

c2 = (X.^2 + Y.^2 - l1^2 - l2^2)/(2*l1*l2);
s2 = sqrt(1 - c2.^2);
s2f=find((imag(s2) ~= 0));
[rowi,coli]=find(imag(s2));
matrixi=ones(4);
matrixc=ones(2);
p=1;
for a=1:length(coli)
        [cTheta,cRho]=cart2pol(real(s2(rowi(p,1),coli(a,1))),imag(s2(
```

```
   rowi(p,1),coli(a,1))));
        s2(rowi(p,1),coli(a,1))=cRho*cos(cTheta)+cRho*sin(cTheta);
        p=p+1;
end


THETA2D = atan2(s2, c2); % Deduced in theta2

k1 = l1 + l2.*c2;
k2 = l2*s2;
THETA1D = atan2(Y, X) - atan2(k2, k1); % Deduced in theta1

XY = [X(:) Y(:)];

% theta2 predicted by ANFIS 1
THETA1P = evalfis(XY, anfis1);

%theta 3 predicted by ANFIS 2
THETA2P = evalfis(XY, anfis2);


% ERROR for second joint
theta1diff = THETA1D(:) - THETA1P;

% ERROR for third joint
theta2diff = THETA2D(:) - THETA2P;


figure(7)
subplot(2,1,1);
plot(theta1diff);
title('\bf{ $$\theta_{1}$$(deduced) -  $$\theta_{1}$$(predicted)}','
   Interpreter', 'latex','FontSize', 14);
u=xlabel('\bf{Steps}', 'Interpreter', 'latex', 'FontSize', 12);
set(u, 'Units', 'Normalized');
v=ylabel('\bf{$$\theta_{1}$$D - $$\theta_{1}$$}P','Interpreter','
   latex','FontSize', 12);
set(v, 'Units', 'Normalized');
pos = get(v, 'Position');
set(v, 'Position', pos + [0, 0, 0]);

subplot(2,1,2);
plot(theta2diff);
title('\bf{ $$\theta_{2}$$(deduced) -  $$\theta_{2}$$(predicted)}','
   Interpreter', 'latex','FontSize', 14);
u=xlabel('\bf{Steps}', 'Interpreter', 'latex', 'FontSize', 12);
```

```
v=ylabel('\bf{$$\theta_{2}$$D - $$\theta_{2}$$P}','Interpreter','
    latex','FontSize', 12);
set(v, 'Units', 'Normalized');
pos = get(v, 'Position');
set(v, 'Position', pos + [0, 0, 0]);
```

MATLAB function code

```

clc
clear all
close all

l1 = .4; % length of the first arm in meter
l2 = .4; % length of the second arm in meter

theta2 = -pi/2:0.1:pi/2; % all possible theta1 values
theta3 = -pi/2:0.1:pi/2; % all possible theta2 values

[THETA3, THETA3] = meshgrid(theta2, theta3); % generate a grid of
    theta1 and theta2 values

X = l1 * cos(THETA3) + l2 * cos(THETA3 + THETA3); % finding x
    coordinate
Y = l1 * sin(THETA3) + l2 * sin(THETA3 + THETA3); %  finding y
    coordinate

data1 = [X(:) Y(:) THETA3(:)]; % creating data set 1
data2 = [X(:) Y(:) THETA3(:)]; % creating data set 2


fprintf('-->%s\n','Start training first ANFIS network. It may take
    one minute depending on your computer system.')
anfis1 = anfis(data1, 20, 300, [0,0,0,0]); % Training the first ANFIS
     network
fprintf('-->%s\n','Start training second ANFIS network. It may take
    one minute depending on your computer system.')
anfis2 = anfis(data2, 20, 300, [0,0,0,0]); % Training the second
    ANFIS netweok



x = 0:0.1:2; % x coordinates for validation
y = 0:0.1:2; % y coordinates for validation

[X, Y] = meshgrid(x,y);
```

```
c2 = (X.^2 + Y.^2 - l1^2 - l2^2)/(2*l1*l2);
s2 = sqrt(1 - c2.^2);
s2f=find((imag(s2) ~= 0));
[rowi,coli]=find(imag(s2));
matrixi=ones(4);
matrixc=ones(2);
p=1;
for a=1:length(coli)
        [cTheta,cRho]=cart2pol(real(s2(rowi(p,1),coli(a,1))),imag(s2(rowi(p,1),coli(a,1))));
        s2(rowi(p,1),coli(a,1))=cRho*cos(cTheta)+cRho*sin(cTheta);
        p=p+1;
end


THETA3D = atan2(s2, c2); % Deduced in theta3

k1 = l1 + l2.*c2;
k2 = l2*s2;
THETA2D = atan2(Y, X) - atan2(k2, k1); % Deduced in theta2

XY = [X(:) Y(:)];

%theta2 predicted by ANFIS 1
THETA2P = evalfis(XY, anfis1);

%theta 3 predicted ny ANFIS 2
THETA3P = evalfis(XY, anfis2);


% ERROR for second joint
theta1diff = THETA2D(:) - THETA2P;

% ERROR for third joint
theta2diff = THETA3D(:) - THETA3P;


figure(7)
subplot(2,1,1);
plot(theta1diff);
title('\bf{ $$\theta_{2}$$(deduced) -  $$\theta_{2}$$(predicted)}','Interpreter', 'latex','FontSize', 14);
u=xlabel('\bf{Steps}', 'Interpreter', 'latex', 'FontSize', 12);
set(u, 'Units', 'Normalized');
v=ylabel('\bf{$$\theta_{2}$$D - $$\theta_{2}$$}P','Interpreter','
```

```
    latex','FontSize', 12);
set(v, 'Units', 'Normalized');
pos = get(v, 'Position');
set(v, 'Position', pos + [0, 0, 0]);

subplot(2,1,2);
plot(theta2diff);
title('\bf{ $$\theta_{3}$$(deduced) -  $$\theta_{3}$$(predicted)}','
    Interpreter', 'latex','FontSize', 14);
u=xlabel('\bf{Steps}', 'Interpreter', 'latex', 'FontSize', 12);
v=ylabel('\bf{$$\theta_{3}$$D - $$\theta_{3}$$P}','Interpreter','
    latex','FontSize', 12);
set(v, 'Units', 'Normalized');
pos = get(v, 'Position');
set(v, 'Position', pos + [0, 0, 0]);
```

MATLAB function code

```
clc
clear all
close all
l1 = 0.7;%lenght of the first arm
l2 = 0.4;%lenght of the second arm
l3 = 0.4;%lenght og the third arm

THETA1 = -pi/6:0.1:pi/6;% all possible theta1 values
THETA2 = -pi/2:0.1:pi/2;% all possible theta2 values
THETA3 = -pi/2:0.1:pi/2;% all possible theta3 values
full=length(THETA1)*length(THETA2)*length(THETA3);

data1 = [];
data2 = [];
data3 = [];
matrix=ones(full,2);
n=1;
for i=1:length(THETA1)
    for j=1:length(THETA2)
        for k=1:length(THETA3)
X =l1*cos(THETA1(i))+l2*cos(THETA1(i)+THETA2(j))+l3*cos(THETA1(i)+
    THETA2(j)+THETA3(k));
Y =l1*sin(THETA1(i))+l2*sin(THETA1(i)+THETA2(j))+l3*sin(THETA1(i)+
    THETA2(j)+THETA3(k));
            data1 = [data1; X Y THETA1(i)];
            data2 = [data2; X Y THETA2(j)];
            data3 = [data3; X Y THETA3(k)];
            matrix(n,1)=X;
```

```
            matrix(n,2)=Y;
            n=n+1;
        end
    end
end
figure(1)
scatter(matrix(:,1),matrix(:,2),[],1:length(matrix))
hold on
fk(pi/6,pi/3,pi/6)
grid on
axis([-0.2 1.6 -1.2 1.5])
title('{Workspace area for all joints}','Interpreter', 'latex','FontSize', 14);
u=xlabel('Meter (X)', 'Interpreter', 'latex', 'FontSize', 12);
set(u, 'Units', 'Normalized');
% pos = get(u,'Position');
% set(u,'Position', pos + [0.41, 0, 0]);
v=ylabel('Meter (Y)','Interpreter','latex','FontSize', 12);
set(v, 'Units', 'Normalized');
pos = get(v, 'Position');
set(v, 'Position', pos + [0, 0, 0]);
% lh = legend({},'Location','northwest','FontSize', 8);
hold off

fprintf('-->%s\n','Start training first ANFIS network. It may take one minute depending on your computer system.')
anfis1 = anfis(data1, 7, 150, [0,0,0,0]); % train first ANFIS network
fprintf('-->%s\n','Start training second ANFIS network. It may take one minute depending on your computer system.')
anfis2 = anfis(data2, 6, 150, [0,0,0,0]); % train second ANFIS network
fprintf('-->%s\n','Start training third ANFIS network. It may take one minute depending on your computer system.')
anfis3 = anfis(data3, 6, 150, [0,0,0,0]); % train first ANFIS network
```

MATLAB function code

```
clc
clear all
close all
l1 = 0.7;%lenght of the first arm
l2 = 0.4;%lenght of the second arm
l3 = 0.4;%lenght of the third arm

THETA1 = -pi/6:0.1:0;% all possible theta1 values
THETA2 = -pi/2:0.1:0;% all possible theta2 values
```

```
THETA3 = -pi/2:0.1:0;% all possible theta3 values
full=length(THETA1)*length(THETA2)*length(THETA3);

data1 = [];
data2 = [];
data3 = [];
matrix=ones(full,2);
n=1;
for i=1:length(THETA1)
    for j=1:length(THETA2)
        for k=1:length(THETA3)
X =l1*cos(THETA1(i))+l2*cos(THETA1(i)+THETA2(j))+l3*cos(THETA1(i)+
    THETA2(j)+THETA3(k));
Y =l1*sin(THETA1(i))+l2*sin(THETA1(i)+THETA2(j))+l3*sin(THETA1(i)+
    THETA2(j)+THETA3(k));
            data1 = [data1; X Y THETA1(i)];
            data2 = [data2; X Y THETA2(j)];
            data3 = [data3; X Y THETA3(k)];
            matrix(n,1)=X;
            matrix(n,2)=Y;
            n=n+1;
        end
    end
end
figure(1)
scatter(matrix(:,1),matrix(:,2),[],1:length(matrix))%Lower workspace
    area for the robot arm
hold on


axis([-0.5 1.55 -1 1.5])
title('{Workspace area for all joints}','Interpreter', 'latex','
    FontSize', 14);
u=xlabel('Meter (X)', 'Interpreter', 'latex', 'FontSize', 12);
set(u, 'Units', 'Normalized');

v=ylabel('Meter (Y)','Interpreter','latex','FontSize', 12);
set(v, 'Units', 'Normalized');
pos = get(v, 'Position');
set(v, 'Position', pos + [0, 0, 0]);

hold off

fprintf('-->%s\n','Start training first ANFIS network. It may take
    one minute depending on your computer system.')
anfis1 = anfis(data1, 7, 150, [0,0,0,0]); % train first ANFIS network
```

```
fprintf('-->%s\n','Start training second ANFIS network. It may take
    one minute depending on your computer system.')
anfis2 = anfis(data2, 6, 150, [0,0,0,0]); % train second ANFIS
    network
fprintf('-->%s\n','Start training third ANFIS network. It may take
    one minute depending on your computer system.')
anfis3 = anfis(data3, 6, 150, [0,0,0,0]); % train first ANFIS network
```

MATLAB function code

```
clear
clc

syms q1 d1 q2 d2 a2 q3 a3 q4 q5 d5 %Denavit-Hartenberg parameters


% rotz: rotation about the z-axis
% tranz: displacement along z-axis
% transx: displaement along x-axis
% rotx: rotation about the x-axis

rotz1 = [cos(q1) -sin(q1) 0 0; sin(q1) cos(q1) 0 0; 0 0 1 0; 0 0 0
    1];
tranz1 = [1 0 0 0; 0 1 0 0; 0 0 1 d1; 0 0 0 1];
transx1 = [1 0 0 0; 0 1 0 0; 0 0 1 0 ; 0 0 0 1];
rotx1 = [1 0 0 0; 0 0 1 0; 0 -1 0 0; 0 0 0 1];

A1 = rotz1*tranz1*transx1*rotx1


rotz2 = [cos(q2) -sin(q2) 0 0; sin(q2) cos(q2) 0 0; 0 0 1 0; 0 0 0
    1];
tranz2 = [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1];
transx2 = [1 0 0 a2; 0 1 0 0; 0 0 1 0; 0 0 0 1];
rotx2 = [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1];

A2 = rotz2*tranz2*transx2*rotx2


rotz3 = [cos(q3) -sin(q3) 0 0; sin(q3) cos(q3) 0 0; 0 0 1 0; 0 0 0
    1];
tranz3 = [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1];
transx3 = [1 0 0 a3; 0 1 0 0; 0 0 1 0; 0 0 0 1];
rotx3 = [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1];

A3 = rotz3*tranz3*transx3*rotx3
```

```
rotz4 = [cos(q4) -sin(q4) 0 0; sin(q4) cos(q4) 0 0; 0 0 1 0; 0 0 0
    1];
tranz4 = [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1];
transx4 = [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1];
rotx4 = [1 0 0 0; 0 0 -1 0; 0 1 0 0; 0 0 0 1];

A4 = rotz4*tranz4*transx4*rotx4


rotz5 = [cos(q5) -sin(q5) 0 0; sin(q5) cos(q5) 0 0; 0 0 1 0; 0 0 0
    1];
tranz5 = [1 0 0 0; 0 1 0 0; 0 0 1 d5; 0 0 0 1];
transx5 = [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1];
rotx5 = [1 0 0 0; 0 1 0 0; 0 0 1 0; 0 0 0 1];

A5 = rotz5*tranz5*transx5*rotx5


T=A1*A2*A3*A4*A5; % homogeneous transformation matrix
disp(T);
```