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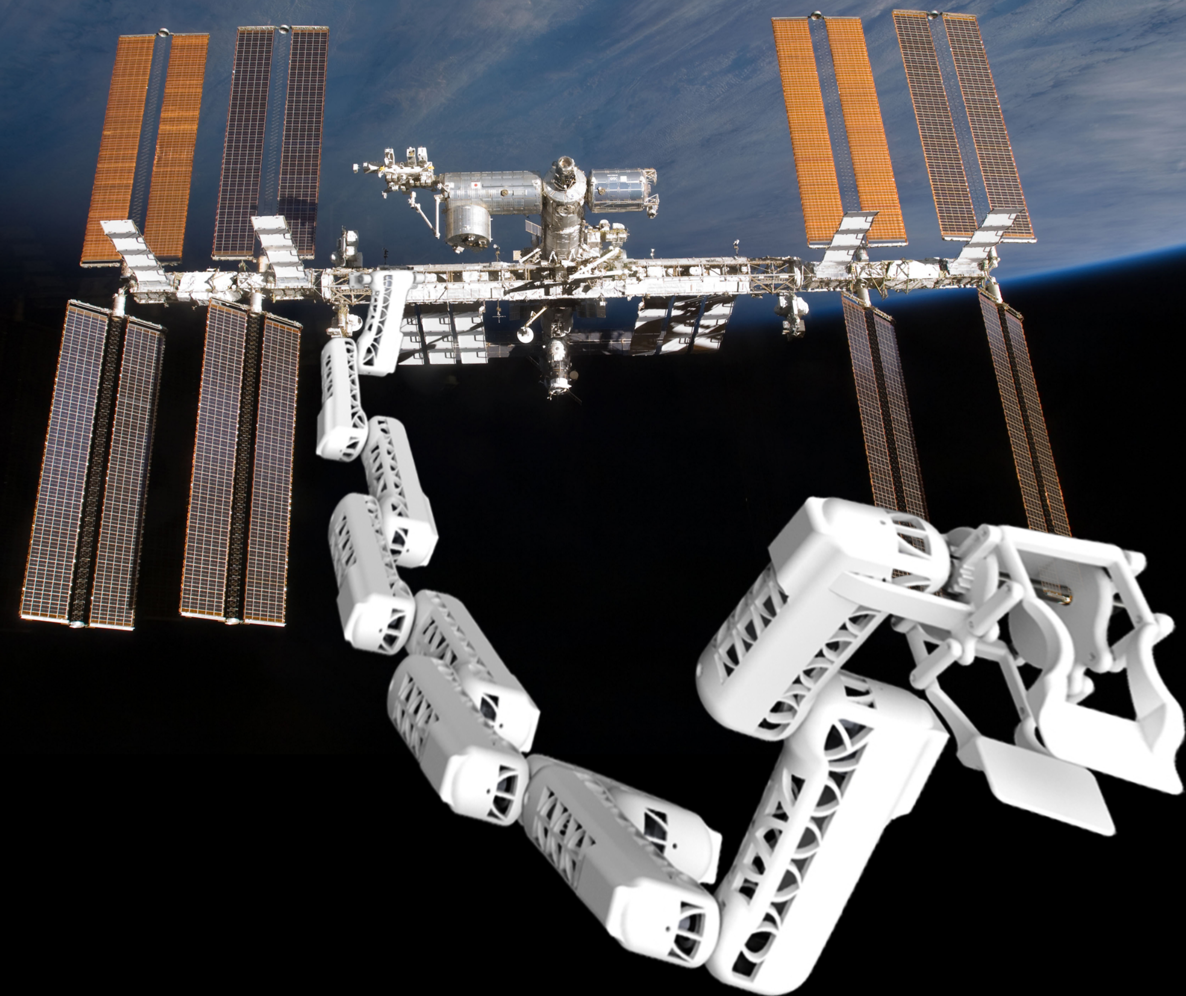

SPACE MANIPULATOR

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Executive Summary

The aim of this design make and test project was to develop a proof of concept for a remotely operated, innovative, manipulator. The manipulator would be able to conduct a variety of applications in space. These applications include: mitigating the space debris problem through mounting to a satellite, or assisting astronauts in extra-vehicular activities on the International space station.

This report describes how each aspect of the manipulator has been created and how they have been combined to produce a finished proof of concept. The project was a success, with 85% of the product requirements achieved. Four prototypes have been generated, with the last one demonstrating wireless control of the arm, enabling it to mimic human movement through an X-Box Kinect. Various tests were conducted such as wireless range testing and positional accuracy. The results obtained showed that the system was responsive up to a range of 14m, meeting PDS requirements. The positional accuracy tests confirmed that the manipulator was able to map the motion of the user to with an average of 10.32 degree accuracy in the shoulder joint, and 24.27 degrees in the elbow joint. This inaccuracy stems from anomalies that arose as a result of manufacturing techniques used, and could be greatly reduced in a further iteration.

Various stretch goals have been achieved such as adding further degrees of freedom and a separate control box to increase the accuracy of the movement and to be used as a safety backup.

Future developments are discussed in order to generate further prototypes and bring the project closer to constructing a space-ready manipulator design.

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1 Introduction

Space is an inherently dangerous environment to conduct operations, however work is regularly conducted to repair and install components to the exterior of the space station. One way to mitigate this risk is through the use of robotic arms as it frees astronauts from having to leave the relative safety of the station and embark on a spacewalk.

Current evolutions in human-machine interface technologies have not yet fully translated to applications in space robotics. As such the premise behind this design, make and test project (DMT) is to use a Microsoft Xbox Kinect and develop an intuitive interface system that will be able to control a robotic arm through mimicking human movement.

This report begins with stating the project aims and objectives, a literature review to summarise the research conducted for the project and the project overview. The design development process is then discussed before introducing the arm and gripper prototype stages in more detail, including rational behind key design decisions. This is then followed by a section on control system design. Testing occured at each prototype stage and was a large component of this project. The testing section is then followed by an outline of how the team used the budget, and a section outlining how risks and challenges were managed. Finally potential developments are discussed and conclusions drawn.

1.1 Project Aims

The project aim was to have a functional robotic arm of modular design, incorporating at least 2 degrees of freedom (DOF). The outcome should be seen as a proof of concept. A space-ready manipulator would be a future development, with increased budget and time. In order for the design to work on Earth, the number of arm segments is restricted to two, with scope for more segments to be added in future iterations of the project. The arm will be controlled wirelessly via X-Box Kinect, with as little bandwidth as possible to replicate the conditions required to transmit data into space. Figure 1 summarises the ideal scenario that the team aims to achieve.

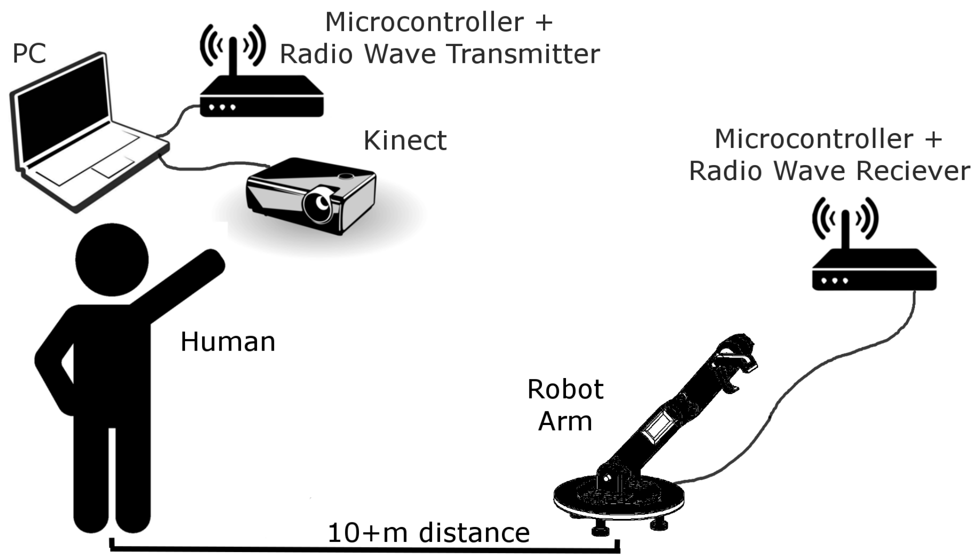


Figure 1: Summary of end goals

1.2 Project Objectives

The project objectives can be split into three; the mechanical design of the manipulator, the control of it, and general stretch goals.

1.2.1 Mechanical design objectives

- Create a progression of arm prototypes starting with a "looks-like" prototype, to envisage the physical design of the manipulator. (Prototype 1).
- Create a basic "works-like" prototype that is motorized to enable the software team to develop the control of the manipulator. (Prototype 2).
- Design and build the first functional "works and looks-like" prototype. (Prototype 3).
- Generate a final prototype to demonstrate the proof of concept specified in the Aims section. (Prototype 4).

1.2.2 Control system and interface objectives

- Produce a basic control system where the motors move through written angle commands sent through an Arduino via the serial port.
- Use the Kinect to develop a program that can print angle commands based on the user's movement with the arm.
- Connect the Kinect program to the Arduino end that moves the servo motors.
- Test on Prototype 3, smoothing any movement necessary and fine tuning the control.
- Migrate the programs to a wireless configuration.

1.2.3 Stretch Goals

1. Implement a secondary control system, using a dial configuration providing an alternative method of controlling the manipulator should the kinect input fail.
2. Add further degrees of freedom, allowing a greater range of movement.
3. Design the manipulator to be able to function if mounted sideways, showing that the mechanical components are not dependent on gravity.

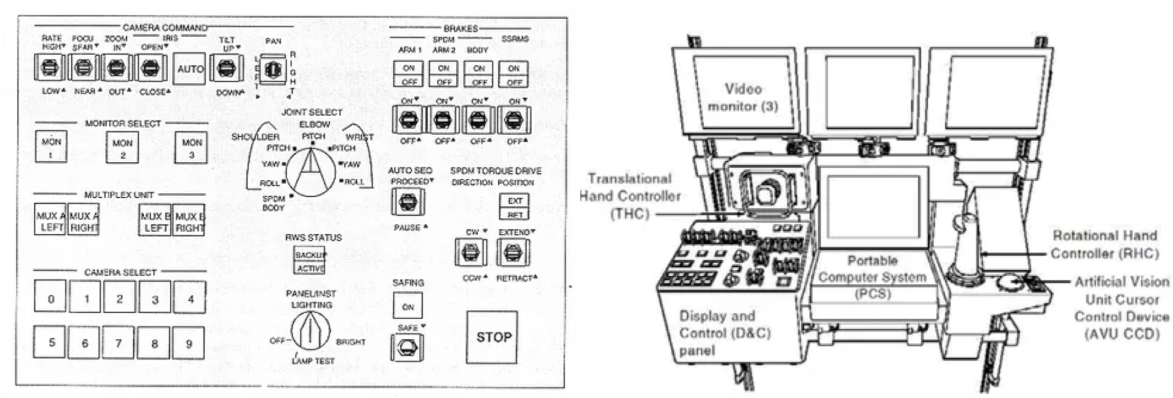
1.3 Background

An analysis of existing space manipulators has been conducted in order to better understand the advantages in their designs, what makes them applicable specifically to a space environment and aspects of their designs which could be improved. Aspects of the design relating to high temperature extremes for instance, have not been analyzed in this project as the focus is in creating a proof of concept.

1.3.1 Existing Robotic Manipulators in Space

Canadarm

The Shuttle Remote Manipulator System (SRMS), also known as Canadarm is a large robotic arm currently installed on the ISS for the deployment and retrieval of hardware from the payload bay. Astronauts control the arm via the use of one translational and one rotational hand controller that work in conjuction with a joint selector, as illustrated in Figure 2. This system means that the arm can only ever be controlled one degree of freedom at a time which is tedious and cumbersome. Canadarm is extremely large at 15m, and it consists of a rotating shoulder, elbow and wrist joint separated by long booms giving it 6 degrees of freedom driven by brushless DC servomotors. Canadarm features two close circuit television (CCTV) cameras at the elbow and wrist joints [2]. Figure 3 shows a schematic of Canadarm. On the top left is the control set up and on the far right the position of the camera can be seen.



a) Control Panel with Joint Selector knob middle center *b) Overall System*

Figure 2: Schematic of Canadarm Joint Selection and Control system. [1].

AMODS: RSat

Figure 4 shows a model of RSat, a cubesat designed by the US Naval Academy (USNA) with the goal of performing diagnostics on existing satellites and executing repairs. This correlates closely with our objectives. The RSat's 3 main goals are:

1. Locomote: The RSat should be able to interact with every critical area of the spacecraft to be repaired.
2. Investigate: The data gathered must be useful to facilitate maintenance, failure

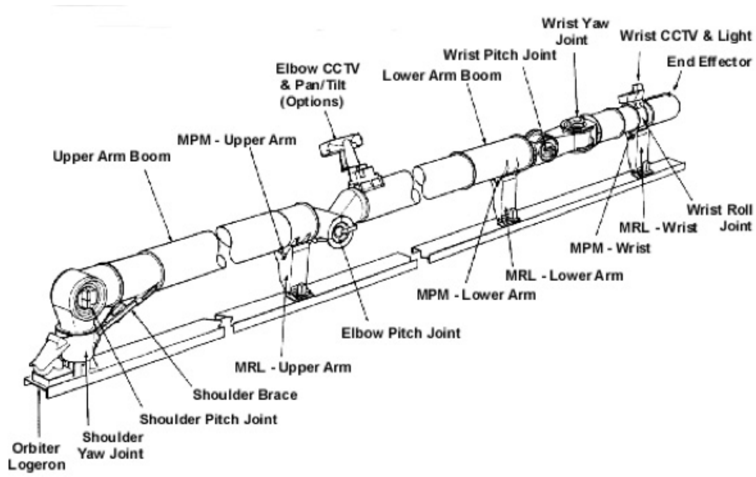


Figure 3: Schematic of Canadarm [2].

analysis, possible salvageability and otherwise increase the understanding of material degradation.

3. “Do no harm”: RSat manipulators should be accurate enough, so as not to damage the spacecraft being repaired.

To fulfill requirement one, RSat is equipped with 2, 60cm robotic arms, each with a total of 7 degrees of freedom. It uses the arms not only for repair, but to "spider" along the outside of the host spacecraft (the spacecraft being repaired) allowing access to all external surfaces of the host.
It is worth noting the design considerations for the material selection and manufacturing choices of the arm design of the RSat. For space minimisation and design efficiency, the arms and claws were constructed using rapid prototyping. The

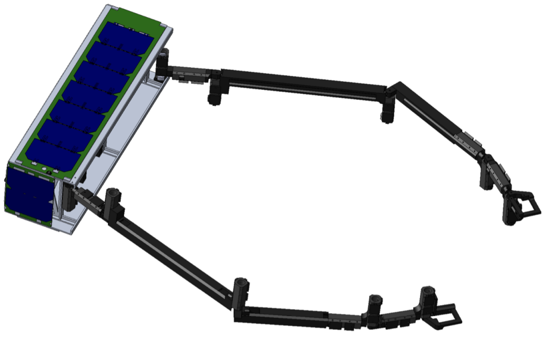


Figure 4: Solidworks model of RSat [3].

team behind RSat used a space-rated plastic material manufactured by selective laser sintering (SLS).
The claw design is particularly relevant to the project, as it is the first satellite to incorporate robotic manipulators of this kind. It is due for launch this year as part of the ELaNa XIX on a RocketLab Electron rocket from New Zealand [10].

1.3.2 Servo Motors and Pulse Width Modulation

Servo motors are comprised of a DC or AC motor, potentiometer, gears, and control circuit. As the rotor rotates, the potentiometers resistance changes and the control circuit regulates how much movement occurs and in what direction. This type of motor has proportional control which means that if the motor is at rest in the desired position, no power is supplied. If the motor is close to the desired position it turns slowly, and if its further away from the desired position it moves faster. Hence, the motor speed is proportional to the distance between the desired and actual positions [11].

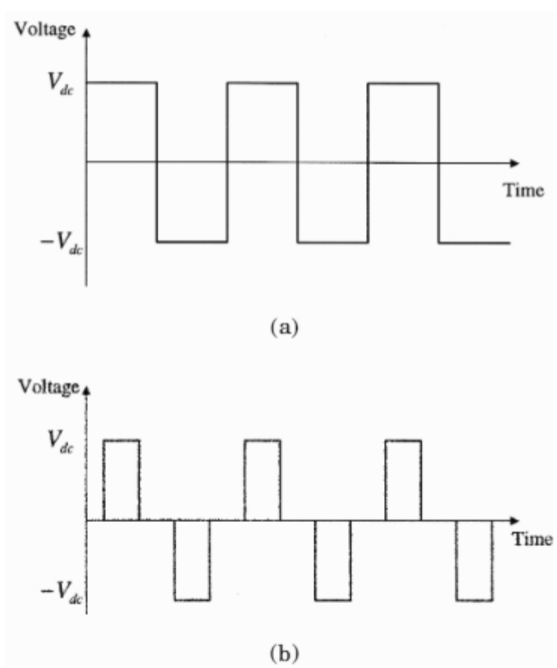


Figure 5: Example of PWM signals with different widths [4].

The control is done via pulse width modulation through a control wire, the motor expects a pulse at a set time interval and the length of the pulse determines how far it turns. After moving, the motor holds the commanded position and resists some external forces pushing it away. The maximum force it can withstand is accounted for in the torque reading, servo motors also only maintain the commanded position for a certain amount of time.

It is also worth noting that there is a difference between baud rates and bit rates. Both are a measure of data transfer speeds, however the bit rate represents the number of binary digits (bits) that can be transferred whereas the baud rate represents the ’actual’ data transfer. This ’actual’ transfer accounts for bits that aren’t part of the desired data transfer such as those intended for redundancy checks and for timing.

1.4 Applications

As mentioned in Section 1.3.1, there is more than one application for a space manipulator. Whilst the current International Space Station has a number of mechanical manipulators mounted to its exterior, the next space station envisaged for cis-lunar orbit will likely include a new generation of robotic manipulation devices [12].

In addition, a growing problem for the space industry is the amount of space debris, as shown in Figure 6. Many solutions are being conceived to solve this problem, including satellites equipped with nets, or harpoons [13] to remove older satellites from orbit and send them down to land in the Pacific Ocean. An alternative idea is to repair existing satellites, and possibly re-purpose them for new projects [14]. This not only reduces the amount of space junk but provides an excellent reduction in the cost of missions, as most of the cost of a space mission is in the launch. For example, building a satellite for data collection would cost approximately 200 million dollars. The projected cost of the AMODS mission (the project including several RSat cubesats) is projected to cost less than 300,000 dollars.

Creating a space manipulator that is modular enables multiple uses for the technology, be that in the form of a cubesat project, utilising perhaps only 4 arm segments as shown in Figure 7, or far more segments to scale up the manipulator for

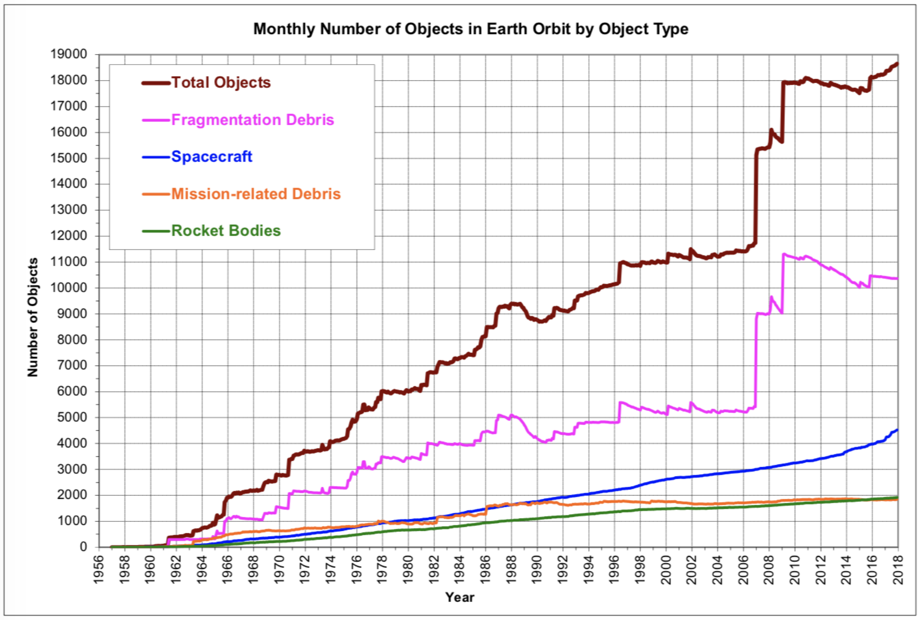


Figure 6: Graph of orbital debris per year [5].

larger projects such as use on a future space station. The advantage of using more modules (thus increasing the degrees of freedom) means that the robot has a greater degree of maneuverability compared to arms such as the Canadarm. This would allow it to reach places that would previously have been unreachable due to size constraints and awkward angles. This is discussed further in the Potential Development section.

Figure 7: Conceptual render of a Cubesat utilising the Space Manipulator, original image courtesy of Clyde Space [6].

2 Project Overview

2.1 Gantt Chart

At the start of the project a Gantt chart (Figure 8) was created to be used as a plan for timekeeping the deadlines and components of the project. The Gantt chart was kept to acceptably high standards, and all the set project deadlines (notated in orange) were met. However, due to the nature of the prototyping process, it was unknown at the conception of the Gantt chart how many iterations of the Arm would be required to satisfy all critical components of the PDS. Therefore, an expanded retrospective Gantt chart was produced at the end. What was initially "Prototype iteration" has been divided across the four arm iterations.

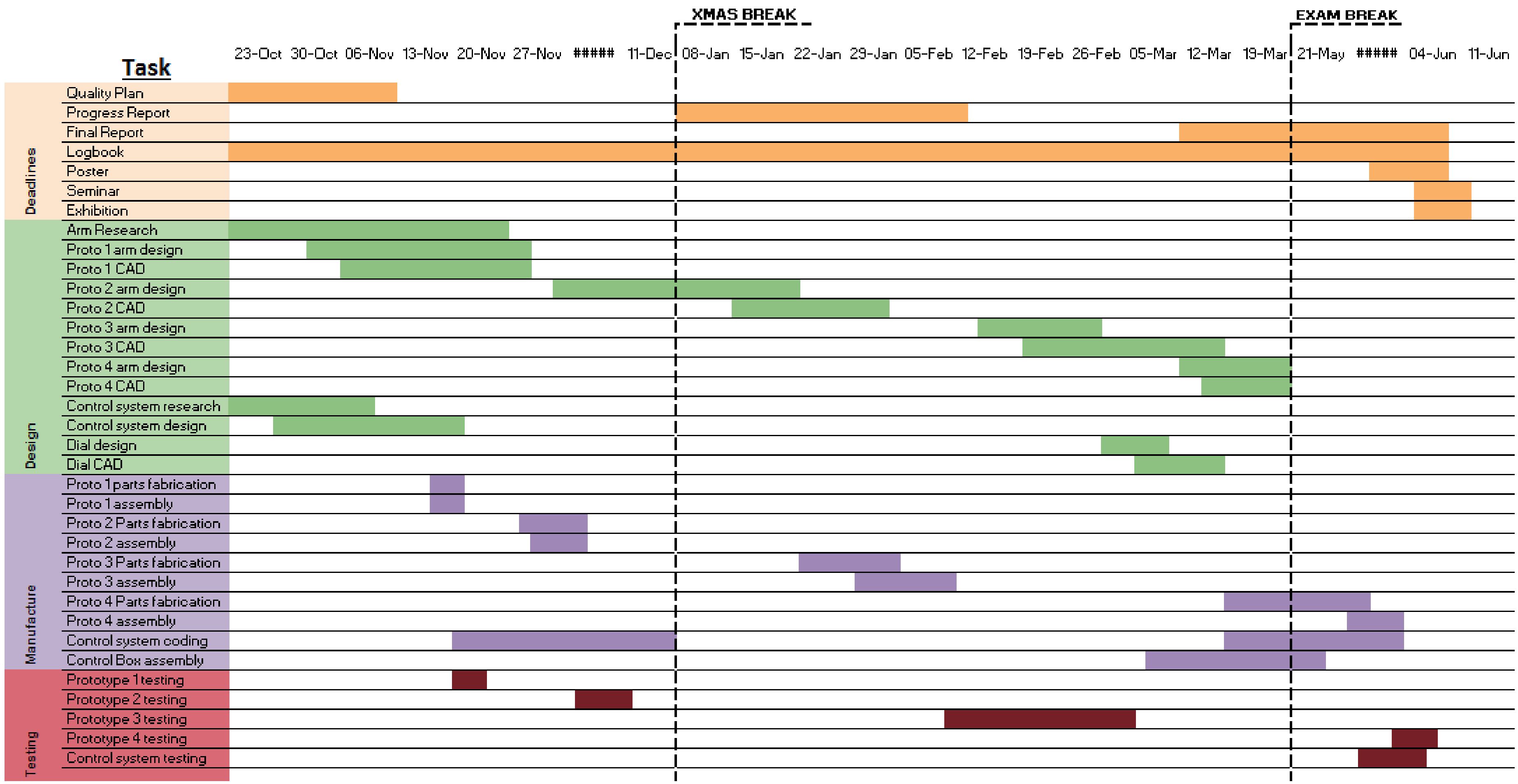


Figure 8: Finalized Gantt Chart

3 Design Development

3.1 PDS

The PDS has been amended since the quality plan to remove out-of-scope requirements. Table 1 shows the revised PDS in accordance with the changes specified in the progress report. Qualitative requirements are divided corresponding to the 3 main project goals: the physical mechanical arm, the control interface and the data link between the two. The requirements were then categorised further into performance, dimensions, safety, and resources. These requirements were then rated on their importance to satisfying the final project goals.

- High - Critical to project success.
- Mid - Desired for project completion. Not design critical, and are estimated targets.
- Low - Non essential, to be achieved after High/Mid priority specifications have been met.

3.1.1 Canadarm Operational Specifications

A summary of requirements for Canadarm [2] was found during research and was used as a reference for creating our own PDS:

1. Performance
    - Provide arm tip velocity of 2ft/s (0.6m/s)
    - Maneuvre and hold tip of arm within $\pm 2 in.$ (0.05m) and $\pm 1°$
    - Capture a payload moving at 0.1ft/s relative to orbiter
    - Stop a 3200 lb (14500 kg) payload moving at 0.2ft/s within 2 ft.
    - Deploy/retrive 65000 lb (29500 kg), 15 x 60ft (4.6 x 18.3m) payload
    - Release 65kg payload within $\pm 5°$ of specified attitude and with angular rates below $0.015°/s$

2. Other Capabilities
    - Place payloads on a suitably configured & stabilized body
    - Inspect orbiter and payloads via closed circuit television (CCTV)
    - Assist crew in extravehicular activities (EVA)
3. Required features
    - Six degrees of freedom and 50 ft (15.2m) reach envelope
    - Brakes, mechanical stops, software stops, CCTV, spotlight
    - Fail safe
    - Built-in test equipment ("BITE")
    - 100 mission / 10 year life
4. Required components
    - Two identical manipulator arms (Serial operation)
    - Display and control panel
    - Translation and rotation hand controllers
    - Manipulator controller interface unit
    - RMS software for orbiter general purpose computer
5. Weight and power budget
    - 994 lb (450 kg) (one-arm system)
    - 1000 W operating power, 1050 W for heaters

Some requirements were found to be directly translateable, such as the product life, while others such as the weight and degrees of freedom were scaled down to match the scope of our project.

	Objective	Criteria	Test conditions	Priority
Arm	**Performance**			
	High precision	±2cm positional accuracy	Measure input movements and compare final motion achieved by arm	High
	Appropriate Dexterity	Has minimum 2 DOF	Use device with human interface to test if all device DOFs respond	High
	Speed	60cm/s unloaded 6cm/s loaded	Use sensor system to calculate if desired speed is achieved	Mid
	Small Reaction Time	Reaction speed of 0.25s	Measure time taken for motions	Mid
	Quick and easy assembly	Assemble in no more than a day using no more than 2 astronauts	Measure time and effort taken for assembly	Low
	Power draw	<1000W Operational, <500W Keep Alive	Use Cumulative Kilowatt-Hour Monitor to detect power usage	Low
	Operating Life	10 years or 100 missions	Calculate operating life time factoring in fatigue life and material properties	Mid
	Dimensions			
	Take-off Volume	Packable for minimal take-off volume (1.5m cubed)	Measure dimensions to be under desired volume	Low
	Reach	Minimum reach of 0.5m	Measure arm length with a ruler	Mid
	Scalable Design	Modular design	Test machine without all features	Mid
	Safety			
	Spatial Awareness	Breaking distance of 10cm from when obstacle is detected.	Test if device stops within breaking distance	Mid
	No Short Circuits	All wires properly insulated	Inspect circuit for failiure	High
	Minimal maintenance	Require maintenance once a year	Calculate operating life time before maintenance	Mid
	Resources			
	Budget	< £500 spend on prototyping iteration	Checking financial records regularly and sum at the end of project	High
	Manufacturability	Manufactured in house	Check if only in-house tools and machines are used	High
Control Interface	**Performance**			
	Minimal Lag	Response delay of 0.25s	Measure time taken for motions	Mid
	High Precision	±2cm positional accuracy	Measure input movements and compare final motion achieved by arm	High
	Quick and Easy set up (plug and play)	Can be set up in room in an hour	Test within an operating space	Mid
	Dimensions			
	Portable	Can be set up in room in an hour	Assemble in a room	Mid
	Small operating space	Only requires a 5x5m empty space for operation	Test within an operating space of 5x5m	High
	Safety			
	Operational Instructions	Easy to use instructions must be provided	Test instructions with sample group	Mid
Data Link	**Performance**			
	Low Bandwidth (information)	Less than 250 Mbit/s	Calculate bandwidth transferred	High
	Minimal Interference	System guarded using relevant materials	Can perform under simulated noise	Mid
	Suitable Range	Minimum operation distance of 10m	Test device with signals from a unit 10m away	Mid
	Resources			
	Budget	<£100 spend during data link development	Checking financial records regularly and sum at the end of project	High

Table 1: Product Design Specification

3.2 Design Process

The first stage of a design process is to ideate solutions to the problem outlined. The team researched possible design approaches and decided to employ the design thinking approach. This is a five step process that is based on prototype iteration, and is illustrated in Figure 9. The five steps are as follows:

Empathise: Research and learn about existing solutions and how the user will interact with the product. From this we identified that current robotic arms have quite a steep learning curve and are not very intuitive to use.

Define: Create a more intuitive autonomous control system for a robotic arm designed for space applications, and design a scaled down robotic arm with design features specifically beneficial for operation in space. These key design features are listed in the PDS and include:

- Simple Modular design, to allow for easy addition of degrees of freedom.
- Lightweight construction to emulate conditions in space as best as possible, as weight is not an issue in space the casing was designed to be as lightweight as possible to better replicate the conditions on the motors. The second motivator was the idea that eventual prototypes would be launched to space and so the launch weight would need to be minimised to save costs.
- Simple construction and assembly, allows to be packable for launch and easily fixable for maintenance in space.
- Low bandwidth communication to reduce control lag when transmitting over vast distances.
- Remote, wireless operation, enabled through the use of visual feedback.

Ideate: The ideate stage initially comes up with multiple solutions which are then whittled down to one design that shows promise. This initial design is then refined enough to produce a very early prototype to test physical attributes.

Prototype: A prototype is produced with the aim to learn as much as possible from its short-comings .

Test: The prototypes were then tested and potential improvements were able to be identified, thus the team would return to the ideation stage.

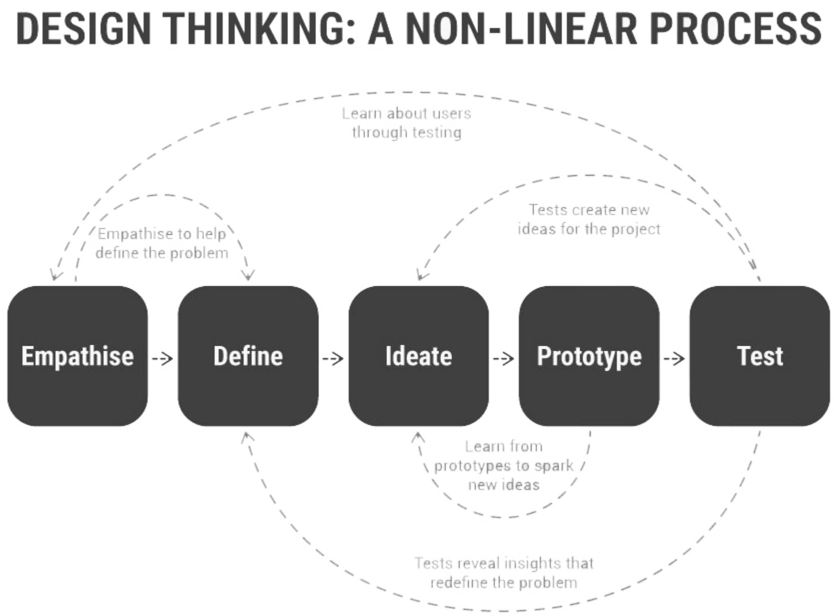


Figure 9: The process of design thinking [7]

3.3 Ideation

The goals section in Figure 12 lists the criteria that each stage of ideation was based around. At each stage of ideation the team would brainstorm potential ideas in their logbooks independently and then come together for a design review to decide on which ideas to carry forward.

Initial Ideation:

Before further design of the arm could continue the team had to decide upon which degrees of freedom would be necessary to approximate the natural motion and dexterity of a human arm. To facilitate this a quick prototype was needed that could be used as a visual aid for the direction the design could take. Figure 10 shows some of the ideas the team brainstormed.

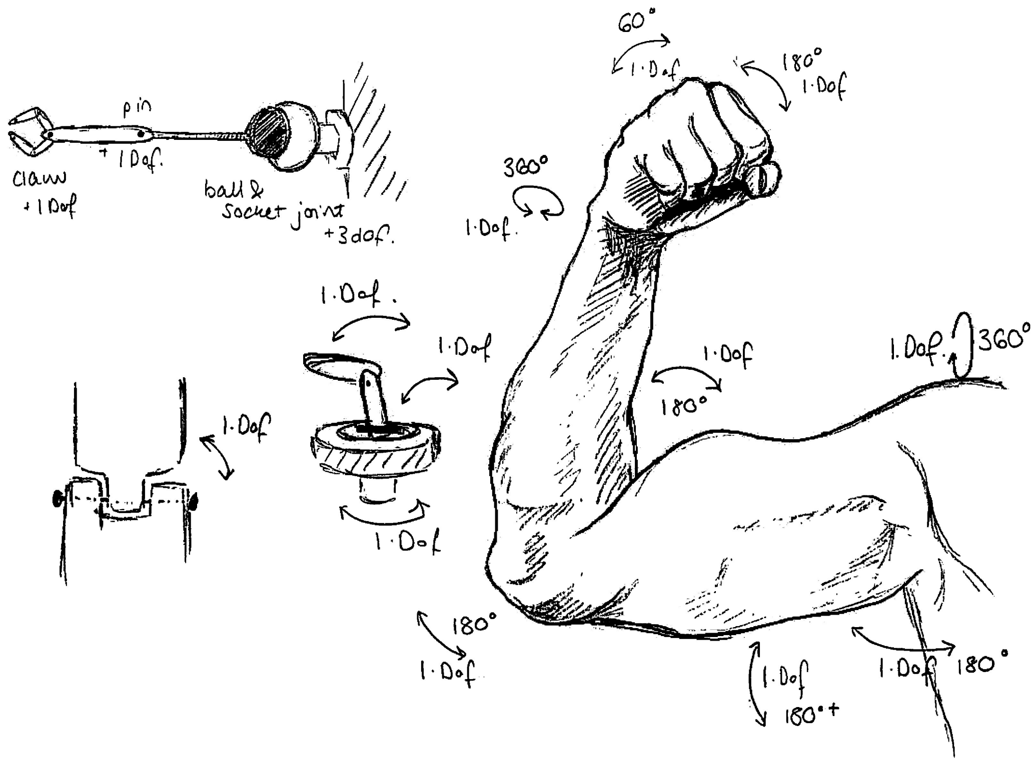


Figure 10: Initial Ideation Sketches

Secondary Ideation In the secondary ideation stage the team's main objective was to create a prototype that could be used to test code for the control interface and data link on. As the project scope included the use of sophisticated electronics and coding it was imperative that the team could start working on this aspect as early as possible. As such cheaper, low torque motors were used due to availability and so the design of the arm needed to be light enough to not stall the motors. Designs at this stage predominantly centered around laser cut, 2D structures.

Tertiary Ideation The tertiary ideation stage recognized the need to begin to develop a casing that would be more in line functionally with a final product that could be sent into space. As such the only strict requirement at this stage of ideation was that any potential designs needed to house the motors and provide the necessary reach. Once one of the casing design's from Figure 11 was agreed upon, the team used CAD software to estimate the casing mass to use with motor calculations as shown in Section 4.3.2 (Motor Selection).

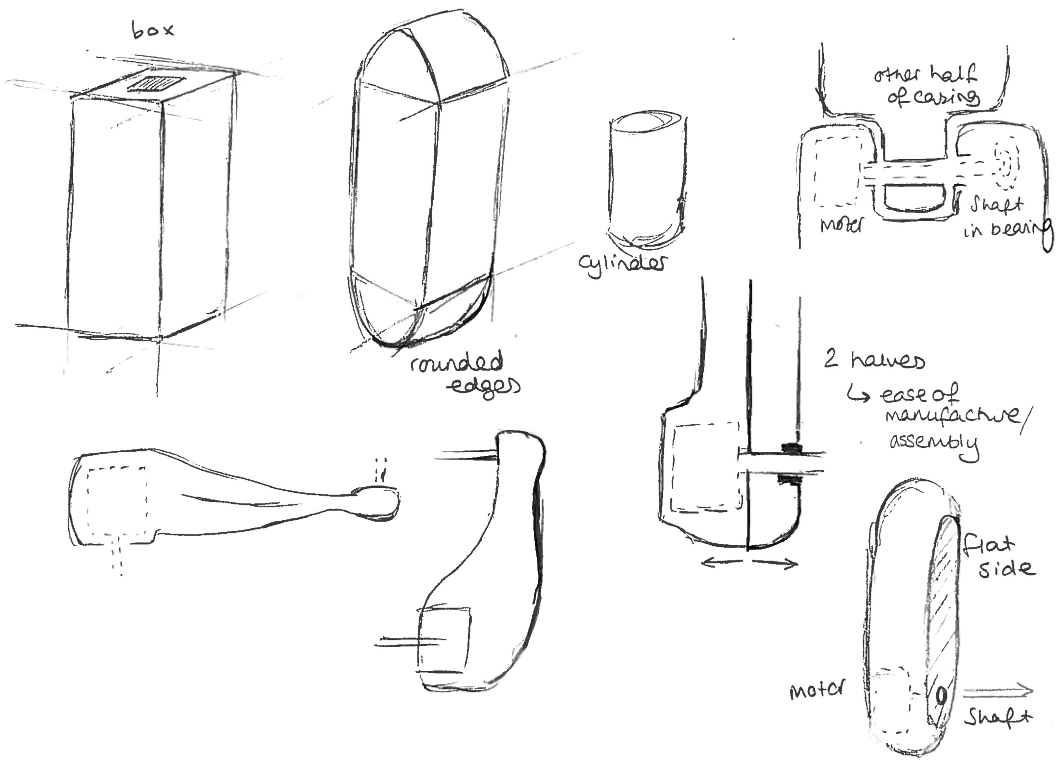
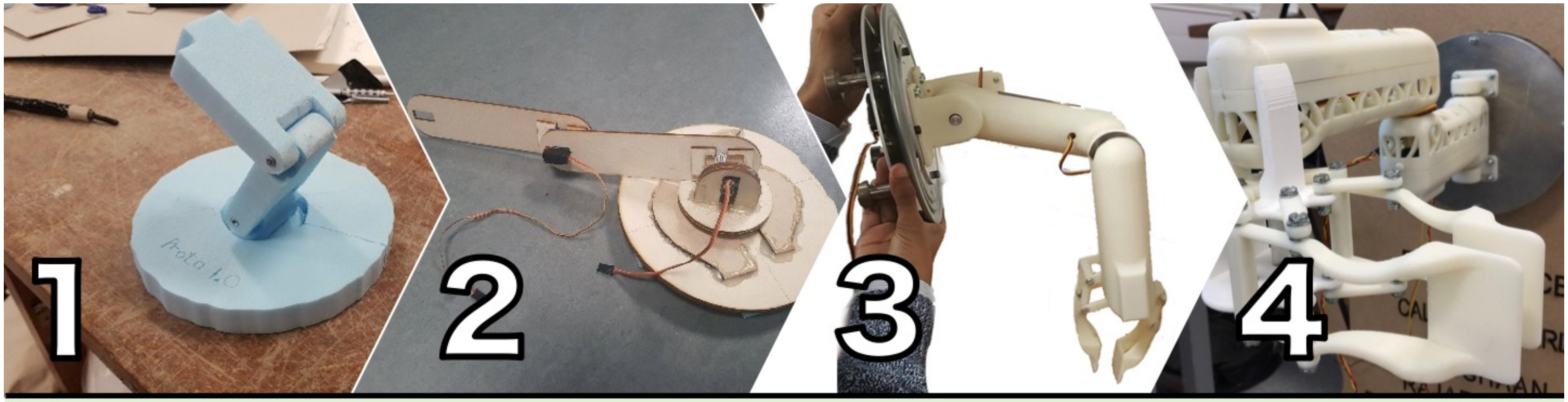


Figure 11: Casing Sketches

Final Ideation This final ideation stage was seen as an opportunity to refine the design of the previous iteration. The idea was to draw on the team's previous design successes, as such there was a much higher degree in similarity of design at this stage. This is indicative that the design had begun to converge into a final product, which in turn is indicative of the groups successful completion of initial goals set.

3.4 Prototyping

In total the team produced 4 physical prototypes within the time frame of the project, with the idea that the fourth prototype is a fully functional solution to the original problem, and the fifth would then be the space ready final product. Figure 12 summarizes the goals and limitations of each prototype stage 1:4. The purpose of each prototype was a response to their corresponding ideation stage as mentioned in Section 3.3.



	1	2	3	4
Goals	-Provide a very early visualization of degrees of freedom and basic ergonomics. -Test degrees of freedom needed for basic operation. -Investigate joint types and gain understanding of dimensions needed.	-Provide team with a platform to start testing code on.	-Be load carrying -Increase structural rigidity -House motors and wires -Integrate claw mechanism	-Reduce weight -Lean housing, sized to match motors exactly -Axially constrain modules to allow for horizontal mounting -House base motor within arm to create a more seamless, fluid, design that is also able to transmit torque more reliably
Limitations	-No control system -No way to test the code	-Motors used were too weak to support load.	-Base motor was mounted external to arm casing. -Base bearing used would not support horizontal mounting.	- No wrist joint for gripper, so always fixed orientation relative to arm casing.

Figure 12: Goals and limitations of each iterative prototype

4 Arm Design

4.1 Prototype 1

The first prototype iteration was a "looks-like" prototype of the minimum number of degrees of freedom nessecary for the required operation. Therefore, failure and motor selection calculations such as those discussed in section 4.3 were not relevant to this prototype. The arm was not constructed with the desired 0.5 meter reach specified in the pds. Blue foam was selected as the main material, as it is a quick material for shaping "looks-like" prototypes.

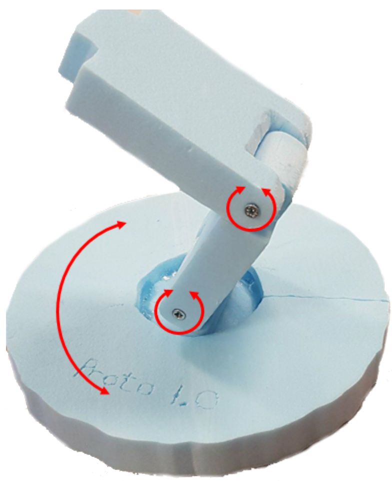


Figure 13: Photograph of Prototype 1

4.2 Prototype 2

Prototype 2 was the first prototype with motion capabilities. This was supplied by micro-servos mounted into the MDF structure. To act as a rapidly prototyped "works-like" design, the components were hot-glued together. Prototype 2 is shown in figure 14 .

4.2.1 Material Selection

Laser cut 4mm MDF was used, as it was the cheapest and quickest material and manufacturing solution available.

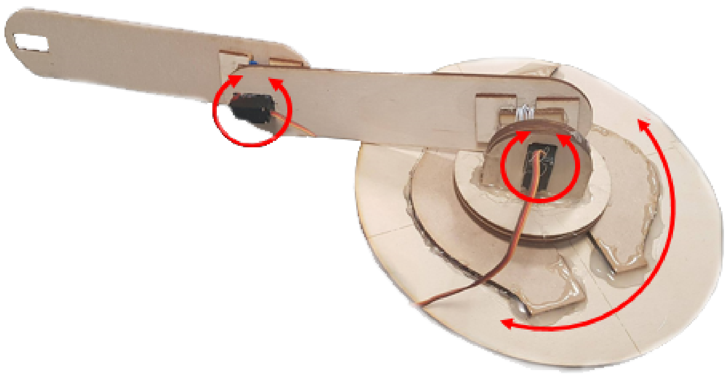


Figure 14: Photograph of Prototype 2.

4.2.2 Control and Wiring

It was decided to use an Arduino Uno as the primary micro-controllers for the project. This was because of its inexpensiveness relative to their processing power - perfect for rapid prototyping. This also allowed for interaction with other open-source software such as the Microsoft Kinect to physical inputs and outputs.
Small, low cost servomotors were wired directly into an Arduino Uno which was connected to a laptop via the serial port. The servos were small enough to be powered via the 5V output of the Arduino Uno. This is shown in Figure 15.

4.3 Prototype 3

4.3.1 Housing design

The housing forms the main body of the 2 arm segments as seen in 16. It is important that the design satisfies the requirements set out in the PDS; in summary,

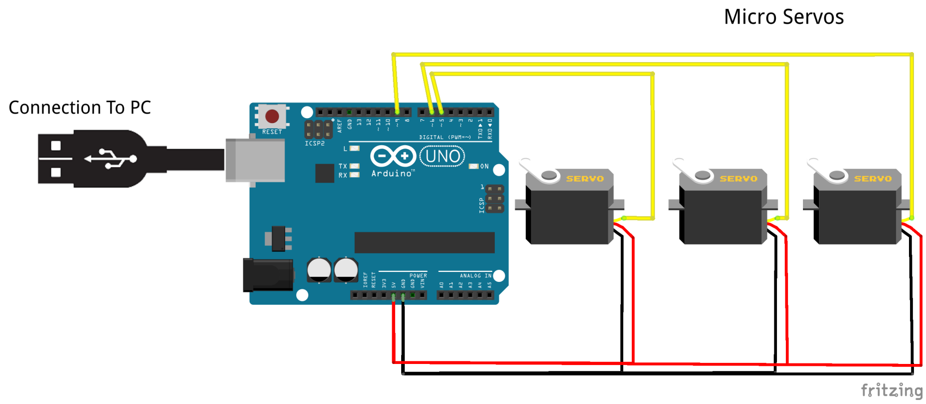


Figure 15: Schematic of the wiring for prototype 2.

the arm housing should be modular, compact in volume, and have a minimum reach of 0.5 meters.

To be able to maximise space and design efficiency, rapid prototyping was chosen as a method of manufacture for the casing design. This also enabled more complex geometric designs to be generated in order to minimise the weight of the casing. As mentioned in the literature review it was found that the USNA used selective laser sintering rapid prototyping to manufacture their casing on the RSat [3]. This justified the team's decision to follow the rapid prototyping route as opposed to milling. If a future prototype were to be made SLS would have been used by the team, and was only avoided due to budget constraints. The team instead opted for the cheaper Fused Deposition Modelling technique.

4.3.2 Motor selection

As stated in the PDS, the motors needed to have high torque, low angular speed, and their own control system to reduce overshoot and improve travel time to the desired position. Therefore, it was decided that the most appropriate type of motor for each degree of freedom would be high torque servo motors as seen in Figure 17.

In order to select appropriate servo motors for each degree of freedom, a rotational body calculation (Figure 18) was implemented to determine the required operational torque for the motor which has the highest demand (the shoulder joint).

Moments were taken in this system, giving general pendulum motion Equation 1.

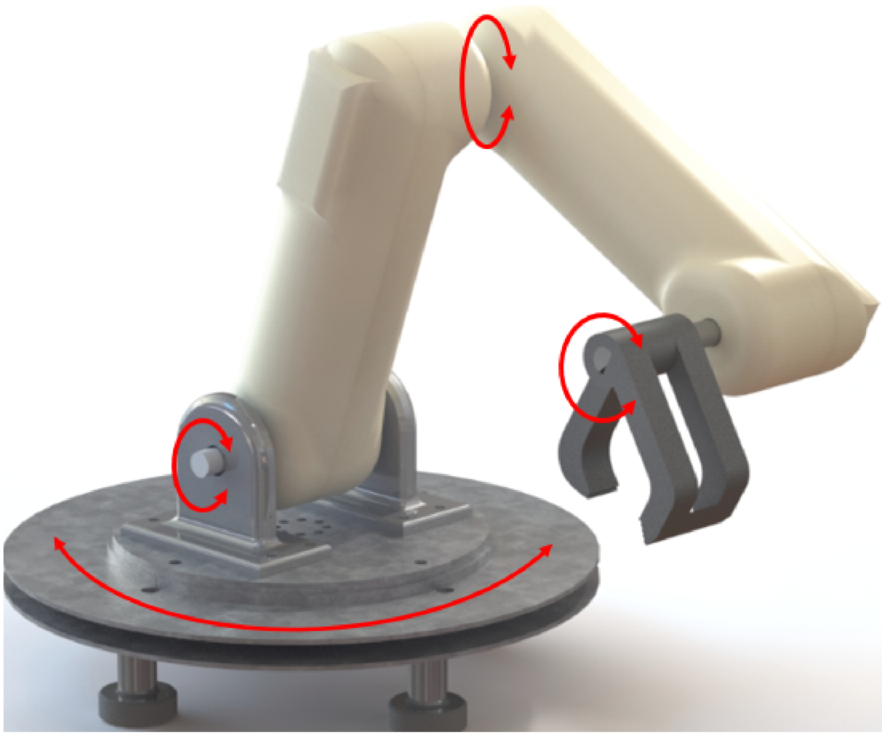


Figure 16: CAD Render of prototype 3

$$T - \sum(mg\frac{d}{2}cos(\theta)) = I_{sys}\frac{d^2\theta}{dt^2} \tag{1}$$

Expanding the summation term for the distributed arm mass and point masses acting on the arm gives equation 2:

$$\frac{d^2\theta}{dt^2} = \frac{T - gl(2m_{arm} + m_{servo} + 2m_{grip})}{l^2(\frac{2}{3}m_{arm} + m_{servo} + 4m_{grip})} \tag{2}$$

The arm will rotate in the direction torque is acting if it can accelerate due to torque overcoming inertial and mass moments (i.e $\frac{d^2\theta}{dt^2} > 0$). From here, an appropriate minimum torque was calculated to be 17kg.cm. By comparing this value with the motor specifications in Table 2, it is possible to deduce that the HS-8335sh would be suitable for the shoulder and elbow joints. For the base degree of freedom, there was no loading besides the friction of the base bearing, hence a low-torque servo motor (Hs-311) was selected.

The control is done via pulse width modulation through a control wire, the motor expects a pulse at a set time interval and the length of the pulse determines how far

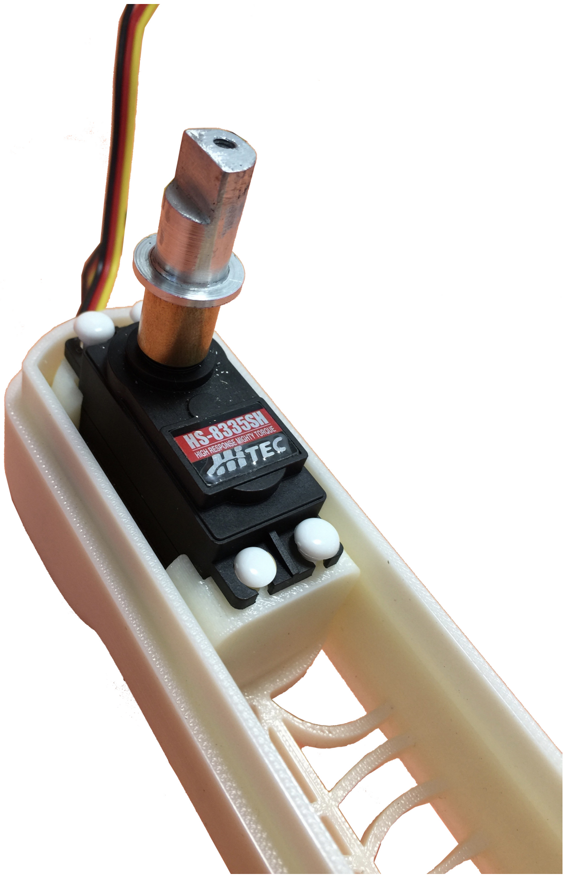


Figure 17: Servo motor in shoulder degree of freedom mounting bracket

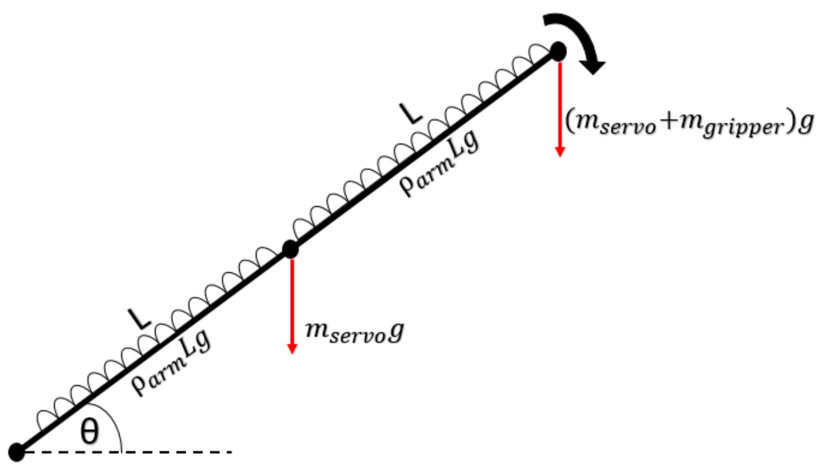


Figure 18: Rotational free body diagram for Arm

it turns. After moving, the motor holds the commanded position and resists some external forces pushing it away. The maximum force it can withstand is accounted for in the torque reading, servo motors also only maintain the commanded position for a

Table 2: Servo specifications for prototype 3

Servo model	Stall Torque/ Kg.cm	Weight/g	Operating speed/ s/60°	DOF used for
HS-8335sh	24	64	0.13	elbow, shoulder
HS-311	3.7	43	0.19	base, gripper

certain amount of time.

4.3.3 Bearing selection

Roller bearings were implemented to reduce and redistribute the radial load applied to the servo motors from the weight of the arm during operation. To determine the bearing life, a dynamic load rating calculation was applied in Equation 3.

$$Life = \left(\frac{c_{dyn-load}}{W}\right)^k, \tag{3}$$

where k=3 for roller ball bearings.Re-arranging,

$$c_{dyn-load} = e^{\frac{ln(Life)}{K} + ln(W)} \tag{4}$$

The life was determined to be 2.5 years constant usage, with a life safety factor of 2. This provided a value of $c_{dyn-load} = 361.86N$. This load rating is an order of magnitude below most commercial roller bearings of the dimensions which we required, hence the bearings will not fail due to fatigue.

Shaft-supporting bearings were constrained fully inside the casing of the arm. In order to bear the axial and radial bending load applied to the base, a slewing bearing was chosen as they are capable of supporting a combination of axial, radial and bending loads, and are hence most commonly used in ’lazy susans’.

4.3.4 Shaft selection

For the shoulder and elbow degrees of freedom there is both bending and torsional loading during operation. The shaft loads will impact the shaft material selection and minimum shaft diameter. To begin calculations, the shaft was initially assumed to be made of aluminium due to it’s low density and high yield strength.

The torsional load was assumed to be due to the static moment of the arm due to weight, giving Equation 5:

$$T = g(m_{arm}\frac{l}{2} + m_{arm}\frac{3l}{2} + m_{servo}l + 2m_{grip}) \tag{5}$$

From torsional stress theory [15] this can be used to give Equation 6:

$$\tau = \frac{T}{(\frac{\pi d^4}{32})} x \frac{d}{2} \tag{6}$$

The maximum stress was determined through bending moment calculations: $M_{max} = 147.15Nmm$ The stress in the radial direction, σ_y was determined in Equation 7:

$$\sigma_y = y\frac{M}{I} = \frac{d}{2}\frac{M_{max}}{0.25(\frac{d}{2})^4\pi} \tag{7}$$

To determine the maximum stresses, $\sigma_{1,2}$ in the shaft, Equation 8 gives:

$$\sigma_1, \sigma_2 = \frac{\sigma_y}{2} \pm \sqrt[2]{(\frac{\sigma_y}{2})^2 + \tau^2} = \frac{1}{\pi d^3}(2.354 \pm 58.907) \tag{8}$$

using Tresca failure criterion, Equation 9 concludes:

$$Y = 55Mpa = \sigma_1 x SafetyFactor \tag{9}$$

Given a safety factor of 3, this provides a minimum diameter of 10mm, which was ensured in design of the shoulder degree of freedom shaft and other shafts.

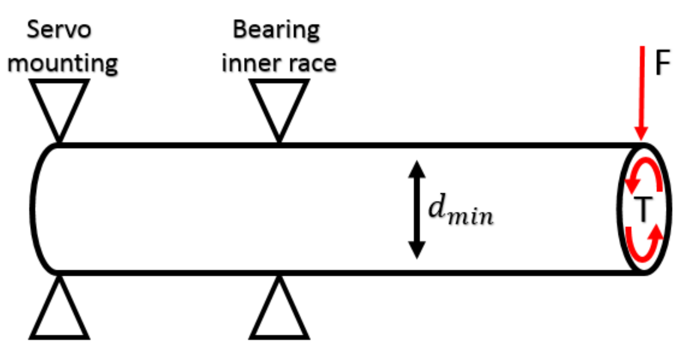


Figure 19: Simplified constraint and loading diagram of shoulder degree of freedom shaft

In regards to fatigue failure, it can be read off Figure 20 that with the stress amplitude determined through σ_1 and σ_2 and giving a safety factor of 3, the fatigue life is 10^8 cycles. A year of operation will provide $8.31x10^6$ cycles at the servo motors loaded operating speed; this fatigue life is significantly higher than the operating life in a year, and hence the arm shafts would show no sign of fatigue failure between yearly inspections. Furthermore, there should be no fatigue failure during the 10 year operating life specified in the PDS.

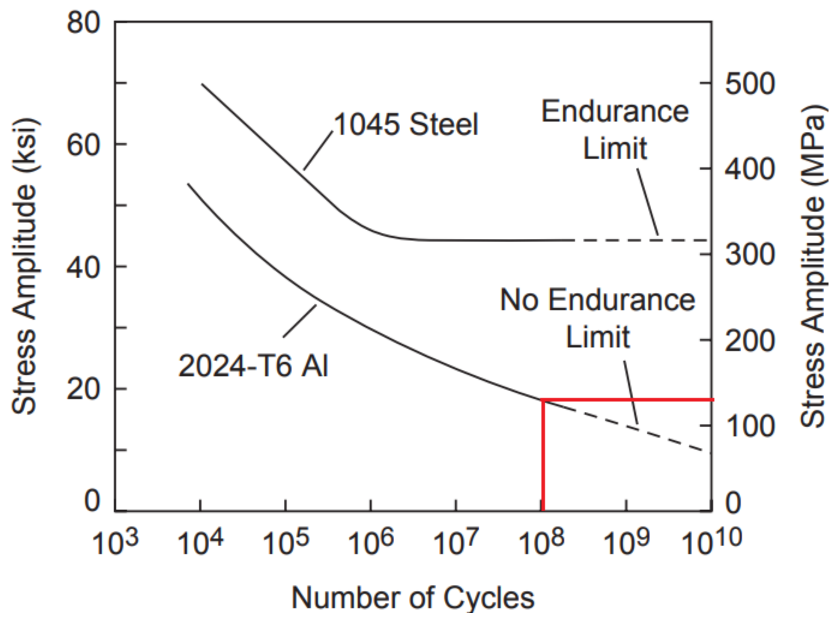


Figure 20: Fatigue curve for Aluminium [8]

4.4 Prototype 4

4.4.1 Casing design

One of the key design considerations of the project is to minimise the mass of the arm. The mass of the arm can be minimised by reducing print density and removing sections from the casing structure. Both of these methods would potentially decrease the strength under loading of the casing itself, so it must be ensured that the casing modifications will not cause failure close to operating parameters.

Triangular cutouts were chosen for minimising arm mass, as this maintains sufficient structural ridgidity.

In terms of material, it was determined that ABS 3D printed plastic was a material that provided appropriate ridgidity, density and capacity for complex shaping during manufacturing.

4.4.2 Casing finite element analysis

To ensure the cutouts did not compromise the structures resistance to failure under loading a Finite Element Analysis was carried out before the casing halves were 3d-printed (figure 21). The mesh was made of 3d tetrahedral brick elements.

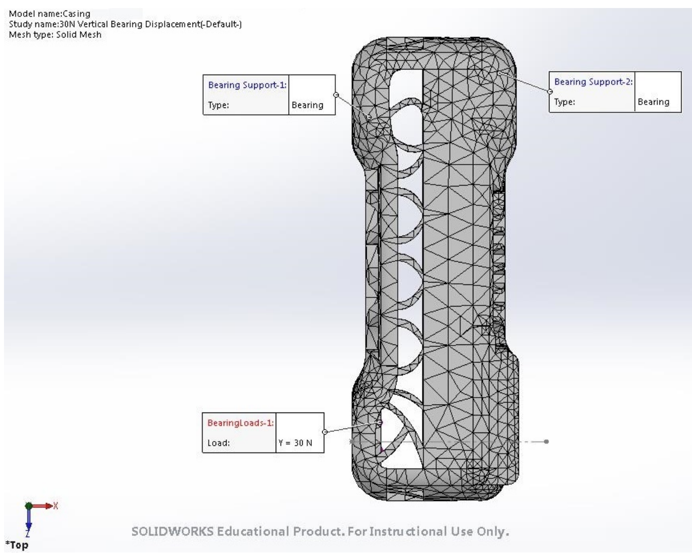


Figure 21: FE Mesh for arm section

From here, displacement, von mises stress and strain simulations were carried out, as seen in Figure 22.

The visible deflection in these simulations was exaggerated by a factor of 41 for visibility. It was found that the deflection was within permissible values, and the maximum von mises stress found gave a safety factor of between 7.9-9.1 relative to the yield strength of ABS plastic (approximately between 28.4-32.8 MPa, depending on layer printing orientation respective to the loading direction) [16].

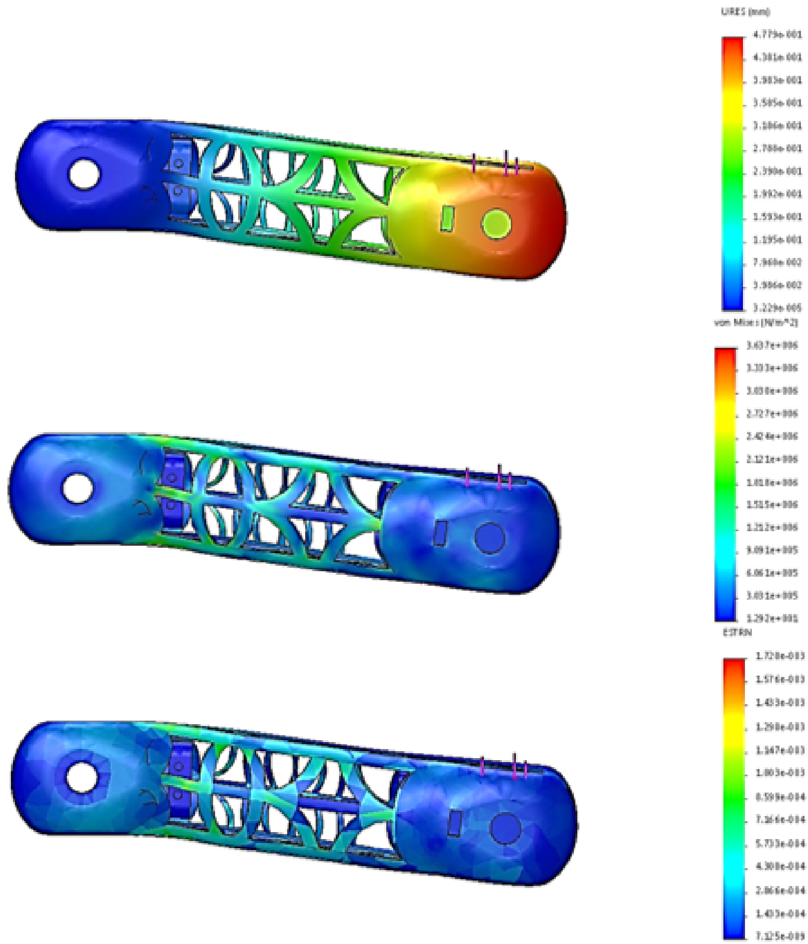


Figure 22: FE simulations for Displacement, Von-mises stress and Elastic strain for arm casing section

4.4.3 Base design

There were several key design restrictions realised in the testing and assembly of the Prototype 3 base:

1. The range of motion for the base degree of freedom was restricted to roughly 120 degrees.
2. To make modifications to the arm or its internal components, the entire base had to be disassembled, beginning with the feet.
3. The bearing used did not support axial load in all orientations (e.g. does not support when arm is upside-down).

To rectify these points, the following design modifications were made:

1. Single step spur gears with a ratio 2:1 (notated in red and blue in Figure 23) were implemented to double the rotational range of the base. This halved the precision of this degree of freedom, but the increased range was prioritised.

2. The assembly was designed in such a way that to modify the arm components, the entire base did not need to be disassembled.

3. A new bearing type that supported axial load in any orientation was used to ensure that the base degree of freedom functions in all orientations.

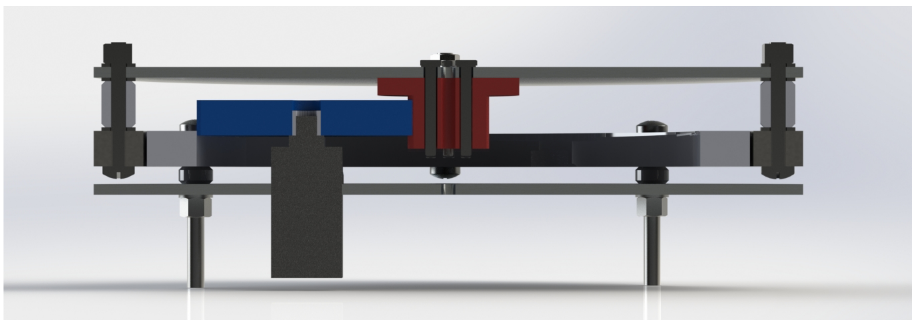


Figure 23: CAD Render of prototype 4 base plate cross-section

4.4.4 Shaft Constraints

To link each shaft to its respective servo motor, a servo-shaft connector (magenta in in Figures 24 and 25) was used. These have a female servo spline on one end, and a shaft bore with grub screw on the other. Each rotating shaft was milled down to a D-shape on one end to allow rotational constraint from the grub screw.
To ensure securement to the opposite casing half (green) or shoulder mounting bracket (blue), each respective shaft is threaded at the end, to allow a countersunk screw to secure it to the mounting bracket.

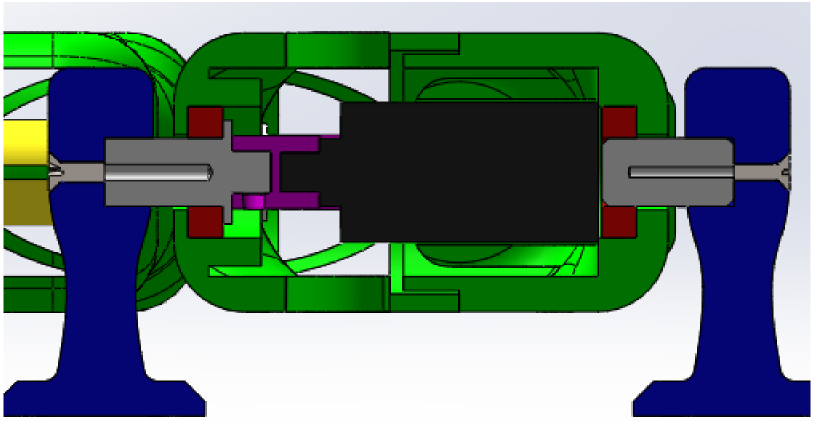


Figure 24: shoulder degree of freedom cross section

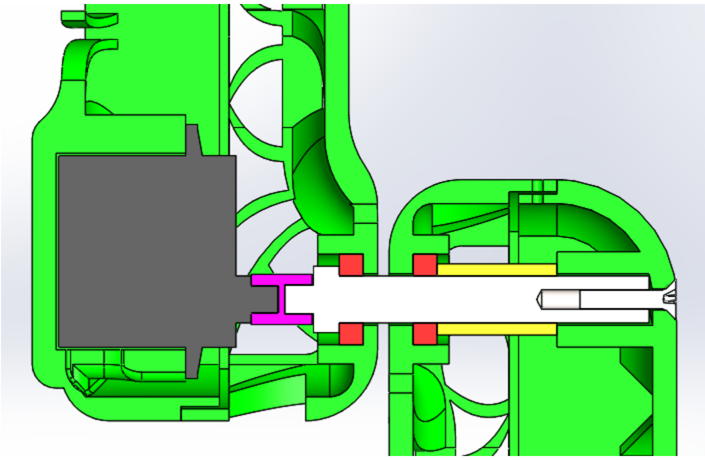


Figure 25: elbow degree of freedom cross section

4.4.5 Manufacture

The combined assembly of the arm required the manufacture of 21 unique parts. Figures 26 and 27 show labeled exploded views of this prototype and Table 3 justifies each manufacturing technique used. The three types of gripper connectors have been collated in the table for simplicity as all used the same manufacture technique.

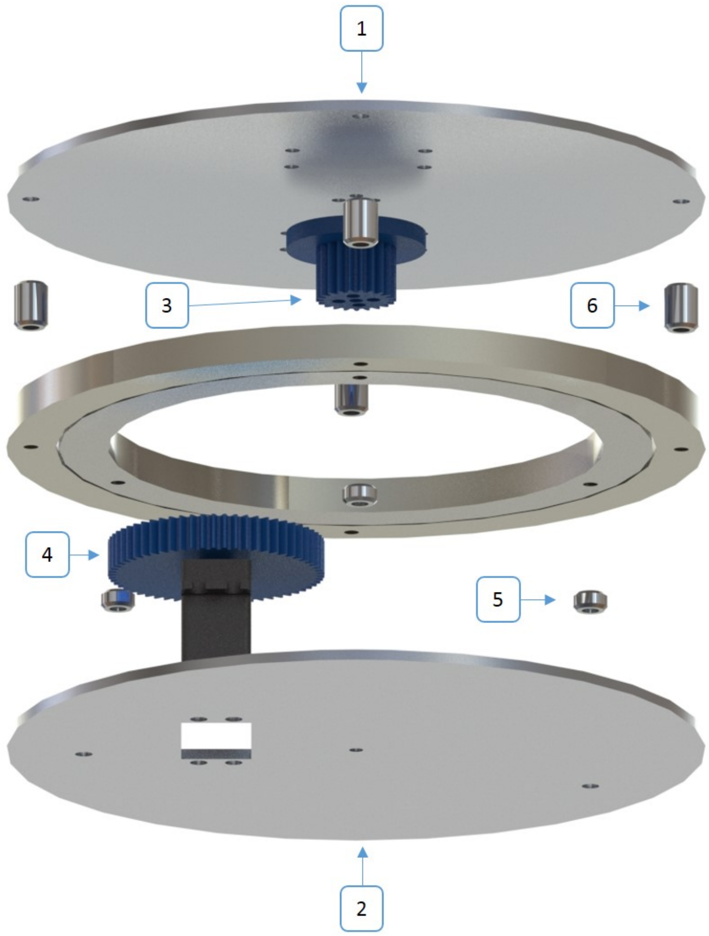


Figure 26: Exploded view of manufactured components in the Base Assembly

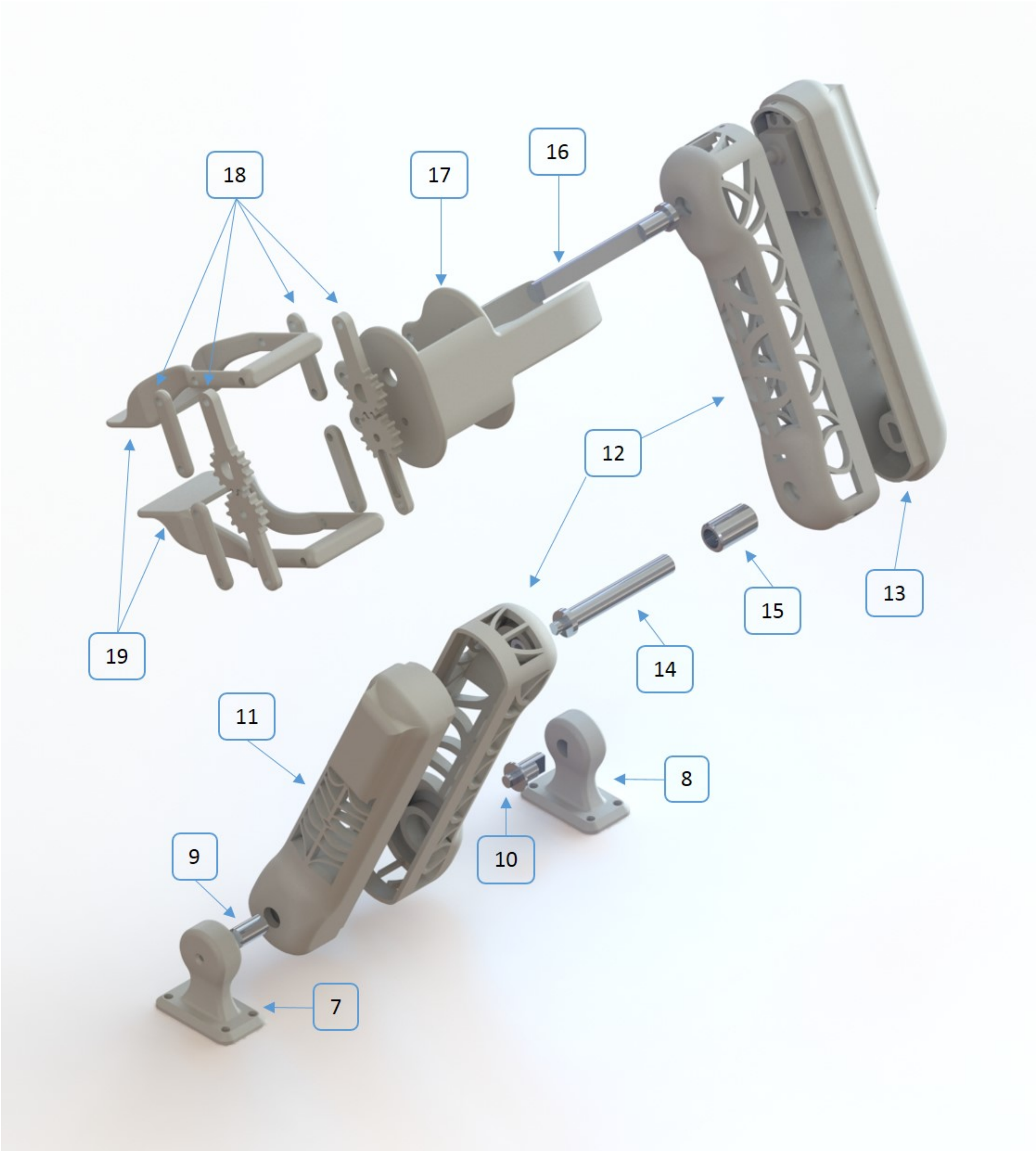


Figure 27: Exploded view of manufactured components in the Arm Assembly

No	Component	Manufacturing Technique	Justification
1 2	Base Plate Servo Plate	Laser Cut Aluminium	Multiple precisely located holes and circular plate shape needed. Aluminium has low mass and high flexural ridgidity to support the shoulder degree of freedom of the arm.
3	Base Gear	Additive Manufacture PLA	Precise technical specifications needed as a result of printing the servo gear, PLA used over ABS due to better strength.
4	Servo Gear	Additive Manufacture PLA	Precise geometry of the servo spline was printed to allow the gear to fit onto the motor directly.
5 6	Lower Spacers Upper Spacers	Lathe Aluminium	High durability and ease of manufacture, precise length allows proper gear meshing and no interaction between rotary and stationary parts.
7 8	Base Hub Free Base Hub Constrained	Additive Manufacture ABS	Speed of manufacture, no dynamic contact points so high durability not a concern. The Constrained hub also needed a female D slot which would be impractical to make using a mill.
9	Plain Shaft	Lathe Aluminium	High strength needed as supports entire weight of arm assembly so couldn't use plastic, lathe allows ease of precise manufacture.
10	Shoulder Shaft	Lathe and Mill Aluminium	High failure resistance needed as it must resist torque to rotate the entire arm assembly. Precise geometry needed for transition fit with base hub.
11 12 13	Casing Half 1 Casing Half 2 Casing Half 3	Additive Manufacture ABS	Lightweight, allows for intricate design and reduces the number of components needed to achieve same constraints.
14	Elbow Shaft	Lathe and Mill Aluminium	Required a D profile at the end of the shaft so used a mill, aluminium chosen to reduce weight whilst still remaining durable.
15	Elbow Spacer	Lathe Aluminium	Lathe used due to speed of manufacture and precision needed for the length measurement. Aluminium used for increased durability over plastic.
16	Gripper Shaft	Lathe and Mill Aluminium	Same reasoning as Elbow Shaft
17	Gripper Plate	Additive Manufacture PLA	Higher Strength needed than ABS to rotationally constrain gripper
18 19	Gripper connectors Gripper Arm	Additive Manufacture ABS	Using Additive Manufacture allowed for design intricacies, ABS used as lightweight and durable enough for purpose.

Table 3: Manufacturing and Material justification

4.4.6 Assembly

Two key advantages of the fourth prototype over the third are it's ease of assembly/disassembly, and it's ability to be horizontally mounted.
The ease of assembly/disassembly was achieved through the addition of removable snap rivets to secure the arm casing halves together.
In order to allow the motor to be mounted horizontally, the two arm segments

needed to be axially constrained in relation to each other. this was achieved through the addition of a screw to the end of the elbow shaft as shown in Figure 25.

The motors were secured in their housings with a transition fit and four M3 screws to secure them in place; this is shown in Figure 28.

Figures 22 and 23 show how the base and arm are respectively assembled.

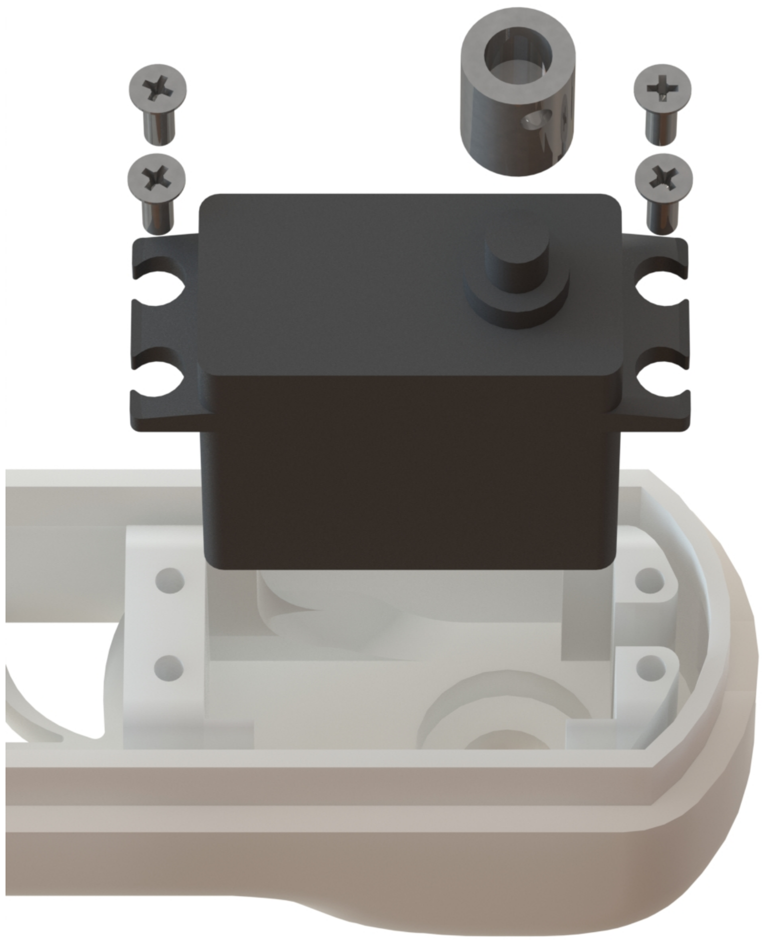


Figure 28: Exploded view illustrating how motors are housed within casing

5 Functional Head Design

Early designs of the functional head were dependent on the intended use for the robotic manipulator. As some of the key applications for the manipulator were to assist astronauts with external ISS repairs and possibly to repair old satellites (if attached to a cubesat style satellite), it was thought that a functional head capable of installing and removing bolts and screws would be suitable. Initially a range of designs were generated that included complex bolt guns, and ideas involving magnets to remove and keep screws in place. Further research revealed that the automation of screwdriver capabilities was already largely realised, (such as the KUKA KR-3 AGILIUS [17]) and therefore there was no need to pursue this area within the scope of the project. A screwdriver as a functional head also greatly limited the use of the manipulator, and so a gripper design was chosen for maximum versatility.

5.1 Gripper Requirements

Research conducted by the United Stated Naval Academy during the creation of the RSat revealed that typical grappling locations the manipulator would be likely to encounter were no more than 25mm in size [3]. Therefore it was decided the reach envelope for the gripper was to be 35mm to account for potential grappling locations outside of their research.

5.2 Gripper Design

A design capable of parallel open and closing motion was conceived to ensure the best grip on what the robot was holding. This is shown in Figures 30 and 31. ABS was chosen as the material, manufactured via FDM for the same reasons as the casing. The first iteration of the gripper is shown in Figure 30, and was mounted onto Prototype 3. The components were fixed together using M4 screws, washers and nylock nuts. Initial testing showed that the fastenings were far too tight, preventing the components of the gripper from moving. It also showed that the gripper required further mounting onto the arm, as rather than opening and closing the gripper, the motor was causing the shaft to rotate the gripper.

To mitigate the rotation issue, the second prototype's gripper base was edited. This included the creation of two large supports protruding from the base. For the issue of limited motion, the nylocks were greatly loosened making movement much easier. Prototype 2 is shown in Figure 31.

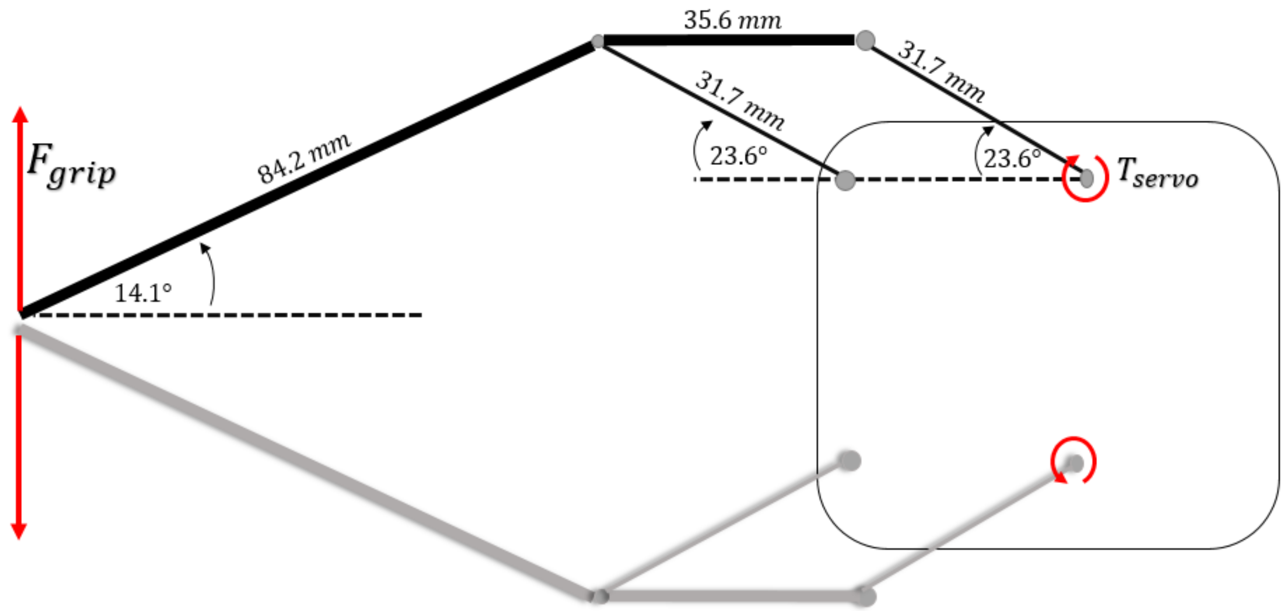


Figure 29: Rigid body force analysis for gripper mechanism

A force analysis was carried out to determine the gripping force. By taking horizontal forces, vertical forces and moments around each rigid body, this gave Equation 10:

$$T_{servo} = F_{grip} x 0.0317 x ((\frac{84.2}{35.6} x (cos(14.1)cos(23.6) + \frac{cos(14.1)sin(23.6)}{tan(14.1)}) + \frac{sin(23.6)}{tan(14.1)}) \tag{10}$$

$$F_{grip} = \frac{T_{servo}}{0.23306} = 9.59 Newtons \tag{11}$$

Therefore, in theory the gripper can carry roughly 1kg when in standard earth gravity. In space, this will not be a restriction, and reluctance from inertia and friction will become the key loading parameters. To reduce slipping, rubber pads were added to the inside of the gripper.

Figure 30: Initial Prototype of the gripper

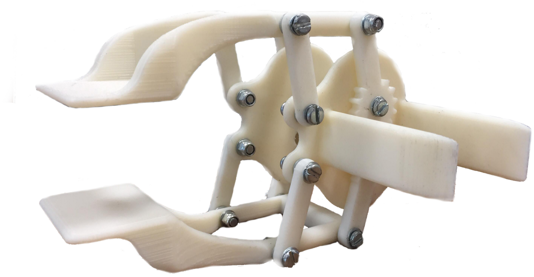


Figure 31: Second Prototype of the gripper

This gripper base failed during testing, at the base of one of the supports. The lessons learned were that the supports were too weak, and that the motion of the manipulator was too forceful. For the next prototype the supports required reinforcement, but also the motor shaft to be placed already in its start position to avoid sudden snap-movement.

6 Control System Design

A major criterion for this project involved intuitive and user friendly control of the robot arm. Therefore how the user was able to interact with the robot arm greatly affected the corresponding control system. The detection of user movements were confined to that of how an arm would naturally move - since this allowed the user to control the robotic arm in the most natural way possible. As such detecting only the shoulder, elbow and wrist movements was enough to model the arm motion of the user.

6.1 User Interface

It was decided early in the project that vision based recognition involving the Xbox Kinect was to be used to control the robot. The vision recognition capabilities of the Kinect allowed for rapid skeletal mapping of major joints, easily capable of recording spine, shoulder and elbow joint angles to ± 1 degree (see Figure 32 and [18]). This provides the correct balance of accuracy and ease of use for control of a robotic arm in space [19].

Figure 32: Kinect being used to render skeletons and angles

Other sensors such as rotary encoders, potentiometers and inertial measurement units (IMUs) were considered but not used due to there being negligible differences in accuracy and computational efficiency. Using the other sensors would have required many being mounted physically onto different parts of the user's arm - it was noted how this would have made the system limit user's freedom of movement. Multi-body analysis would then have been performed so that the individual joint movements could be accurately measured - this has a similar level of computational cost as the vision based recognition algorithms needed to be performed when using the Kinect. Figure 32, is a summary of how the kinect program obtains movement data from the user (in the form of joint angles) before it is sent to the robot. It should be noted that once the angle data was obtained, an iteration of the program involved filtering in an attempt to get more accurate angle data (highlight in yellow). A crude low pass filter was used where a moving average of the incoming data was taken (shown in Figure 33).

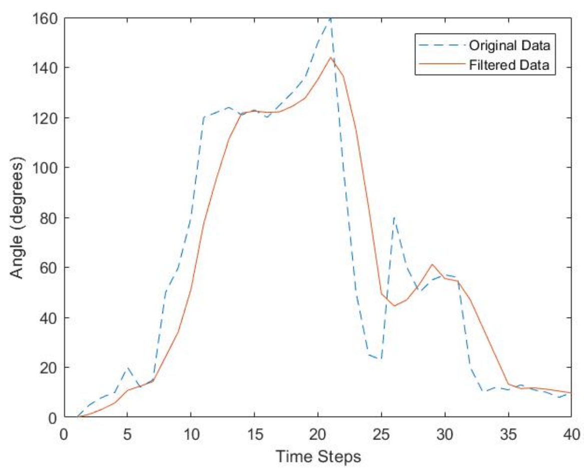


Figure 33: Moving average filter used on sample angle data

When this version was tested with the robot, it was found that although the angle data was more consistent, the sampling rate was far lower due to the delay needed in filtering the data. This lower sample rate lead to an overall decrease in the smoothness of the robot's motion, therefore in the final iteration of the program it was decided to reject the crude low pass filter in exchange for a higher sample rate.

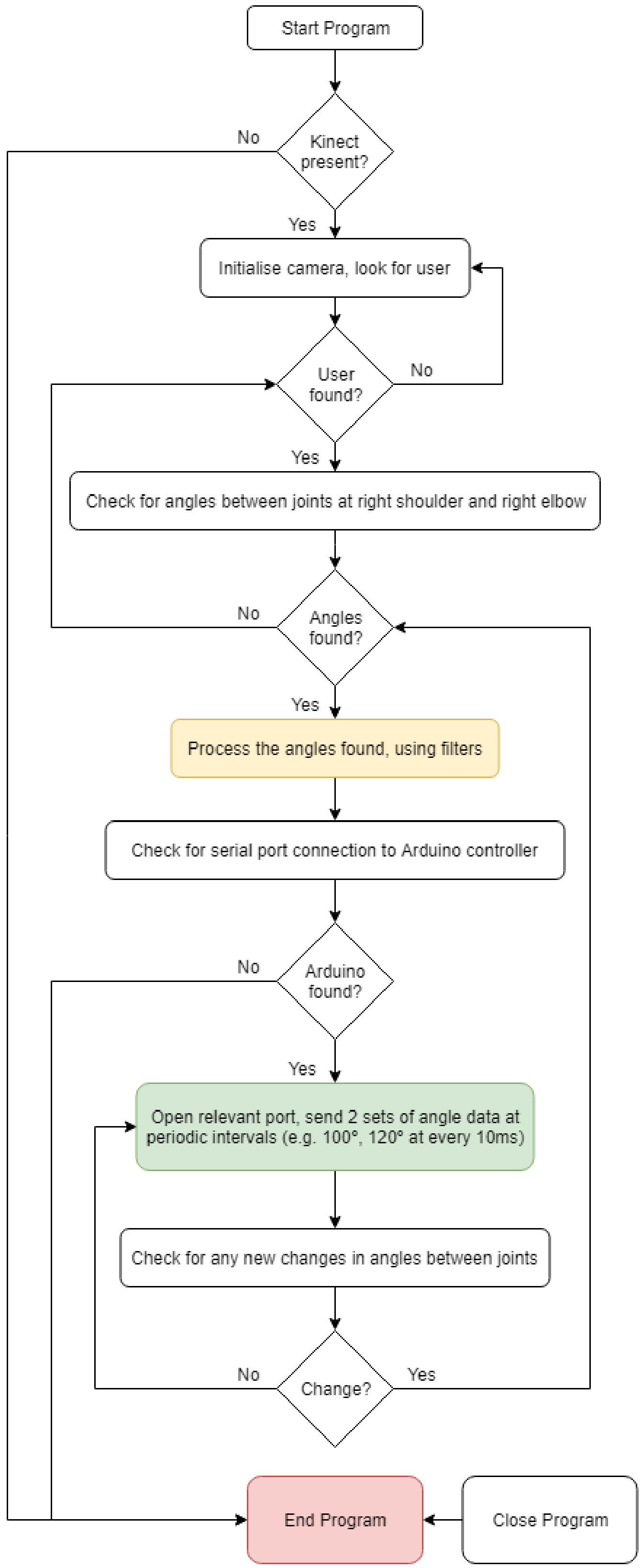


Figure 34: A flow diagram of Kinect program

6.2 Motor Control System

Servo motors were used for their high torque and inbuilt control which involved closed-loop feedback that reduces steady state errors and overshoot (see Figure 35). Therefore there was no need for building a dedicated controller for the motor movements; this would also add extra complexity and weight to the design.

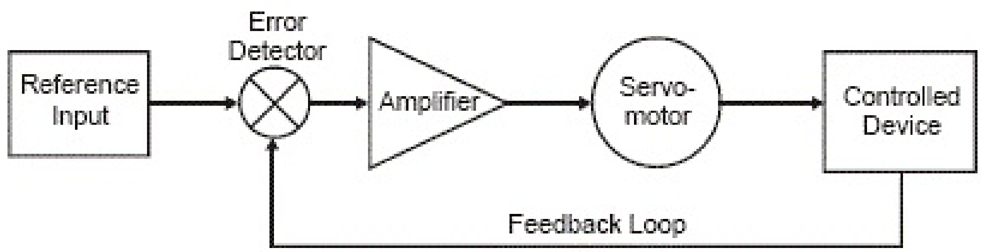


Figure 35: Typical servo system block diagram [9]

Even with use of this control system, it was realized that making the servo respond immediately to angle changes was a major cause of jerky motion. This was because the servo motor would try to instantly move to a received position even if the change in angle was small - this also leads to high current draw and additional stress on the drive-train (gears etc) [20].

To account for this problem, the motion between changes in angle was spread over an adjustable time period. It should be noted that the greater this time period was the smoother the motion was, but this would additionally cause the system to lag behind the input angles. Therefore it was important to keep this time period as low as possible while maintaining smooth motion. In the final system this time was set to be 100ms, this allowed for reasonable smooth motion without comprising on delay time - being under the average human reaction time.

At first the motion was spread linearly over the change in angle - steps of angles following the gradient of the overall angle change (see Figure 36 left). This was then improved by making the motion follow a cosine mapping - meaning that the motion would initially be slow, then rapid accelerate, and then return to being slow just before reaching the desired position (see Figure 36 right).

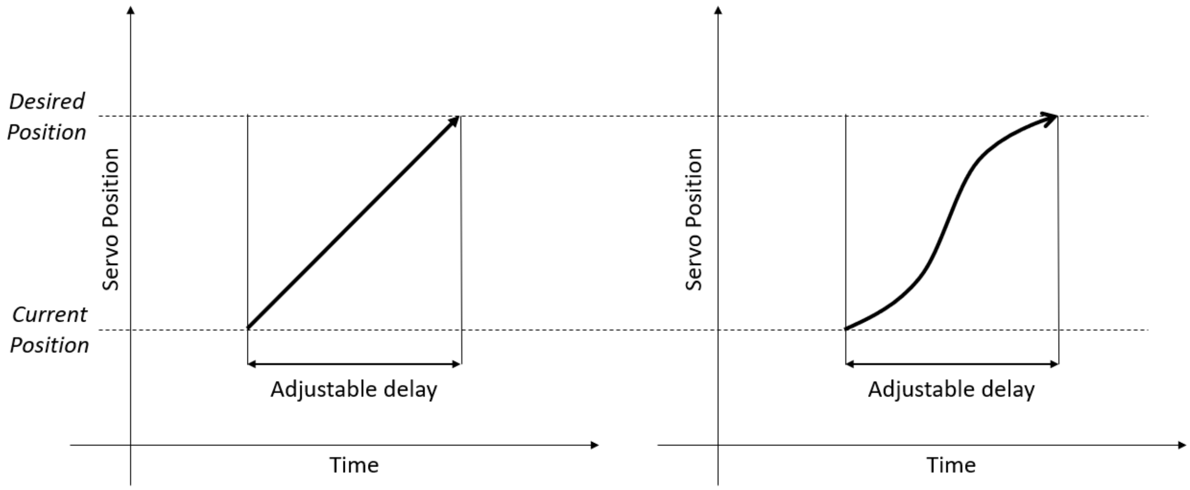


Figure 36: Linear (left) and cosine (right) adjustment of servo position over given time period

6.3 Wireless interfacing

Another criterion for the system was that control of the robotic had to be wireless, with the size of data transfer being low enough that it can be used over ground to space distances. It was noted that NASA is capable of data transfer speeds of up to 300 megabits per second (Mbps) with the Space Network (SN) [21]. This data transfer rate was taken as upper limit but the system was designed to have data transfer rates as low as possible.

The major method of data transfer with the micro-controllers (Arduino Uno and Mega) used for the project was serial port communication. Wireless modules which operate through using radio transceivers were used as the main method of serial communication. The final module used (the NRF24L01 transceiver module) had baud rates from 0.25 to 2 Mbps, which is much lower that the NASA data transfer limit. Even though the NRF24L01 module is only capable of wireless data transfer up to 100m, it serves as a good proof of concept showing that if the SN was used the robot can be used in ground to space applications.

Since the system was to be controlled from large distances, the user would have also needed some kind of feedback system so that may react to how the robot moved when controlled. A wireless first-person view (FPV) camera (commonly used in long range RC airplanes/drones) shown in Figure 37 was used. This camera gave a 110 degree viewing angle and was mounted onto the claw of the gripper, allowing for the user to view the surrounding area of the robot and navigate the robot accordingly. The transmitter/receiver combo allowed for ranges of up to 600m which was well within required limits. It should also be noted that this data transfer occurred in a different pipeline, such that there was no interference with the angle data transfer. Therefore each transfer was independent of each other, guaranteeing that one should work if the other fails.

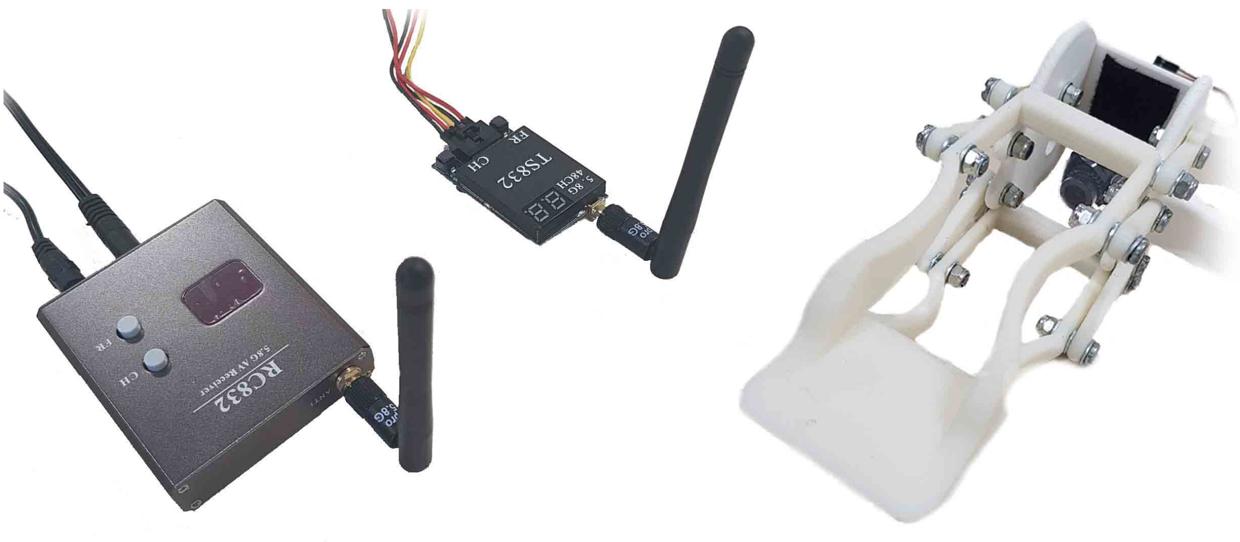


Figure 37: FPV setup components: including the receiver, transmitter and camera inside claw of gripper

6.4 Final Design

The final design involved combining the discussed components as shown in Figure 38. The Kinect would receive data from its RGB color VGA video camera and depth sensor, then send it to an computer to be processed. From this data, the computer generated user skeletons and then found joint angles (specifically the shoulder and elbow joints). This angle data was then sent to the transmitter which involved an Arduino Mega micro-controller where the data was made into packages and sent through an wireless NRF24L01 module to the receiver (shown in Figure 39 left). The receiver involved another NRF24L01 module which obtained the data and an Arduino Uno micro-controller which unpacked the data into a set of 4 angles (shown in Figure 39 right). These angles were then sent to the servo motors within the robot, each of the 4 angles refer to a different DOF: the base rotation, the shoulder rotation, the elbow rotation and gripper actuation.

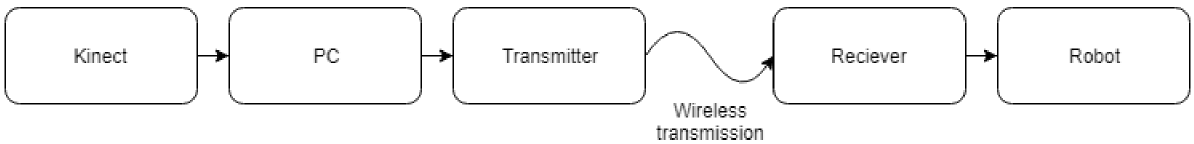


Figure 38: Block diagram of overall system

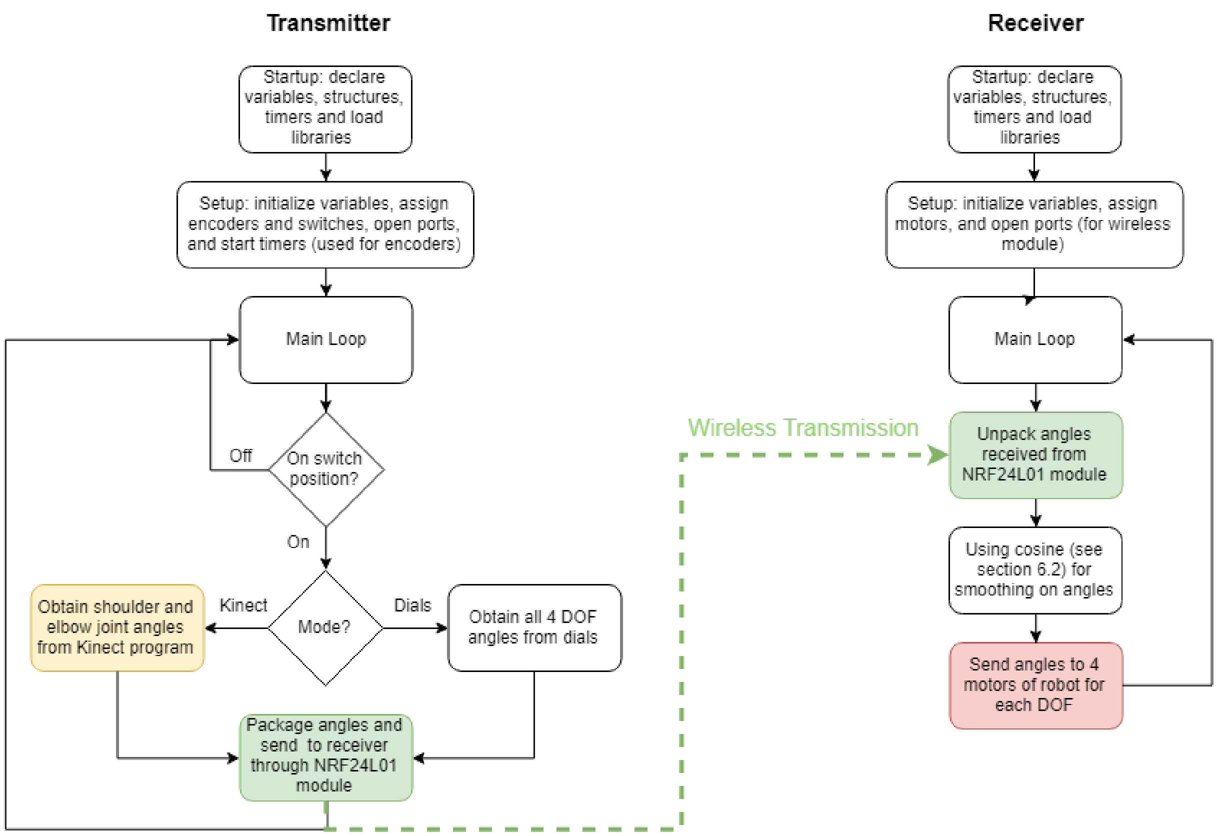


Figure 39: Flow diagram of transmitter (left) and receiver (right) programs

Shown in Figure 40 is the final electrical design that was used for the transmitter block of the system. It is worth noting that the Arduino Mega was used here as a microcontroller instead of an Uno because it allowed for extra ports (required for the encoders). The greater computation power also allowed for faster processing of the angle data from the encoders, as well as quick packaging and transmission of angle data. The inclusion of the encoders allowed for achievement of one of the stretch goals; a control box was created to allow for mode switching between Kinect control and dial control (shown in Figure 41). There was also hardwired On/Off switch that would physically stop sending signals to robot, this acted as the overall On/Off for the system.

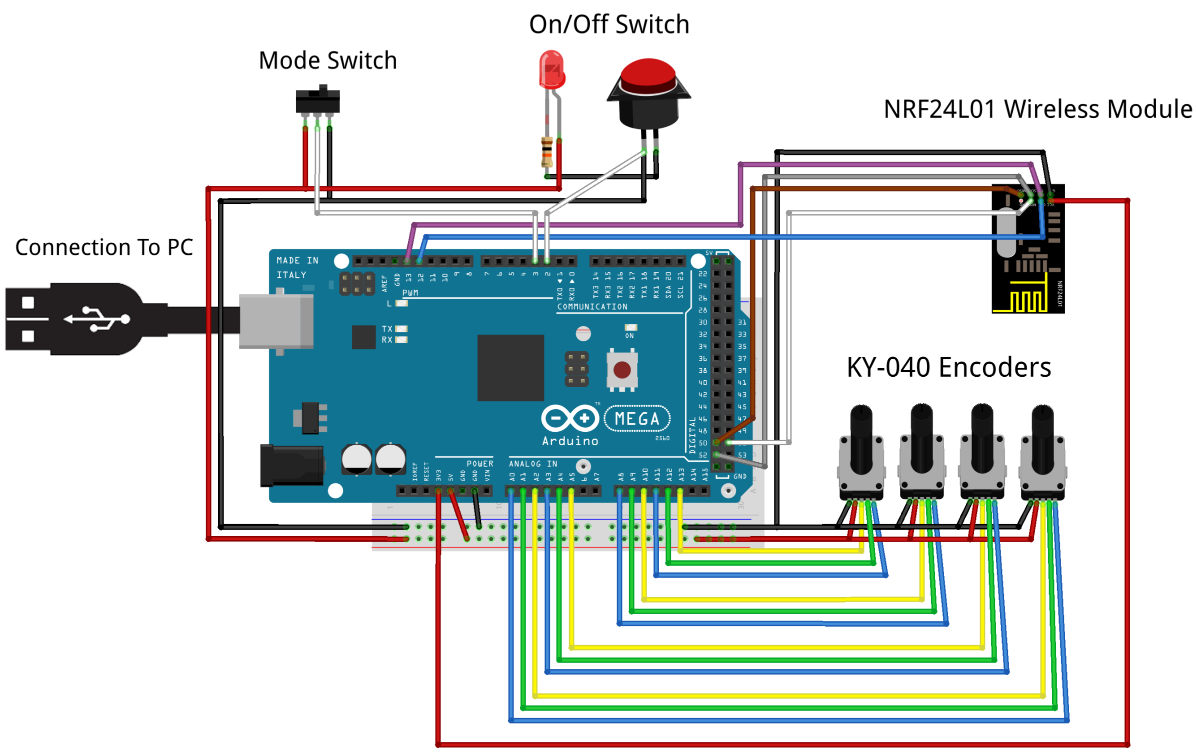


Figure 40: Wiring diagram of transmitter unit

Figure 41: Final assembly of transmitter control box

Shown in Figure 42 is the final electrical design that was used for the receiver block of the system. Here an Arduino Uno was used as fewer ports were needed, and and so the transmitter could be fitted in a smaller form factor casing (shown in Figure 43) providing an overall lower weight for robotic arm unit. It was decided to use an 7.4V 6600mAh Li-Po battery to power the unit - which powered the Arduino Uno and the motors. This allowed for the robotic arm unit to be tested for up to an hour at full load, this was enough time to perform any relevant testing required. Due to the high current and voltage the battery could potentially deliver to the system, safety measures further discussed in section 7.1 were implemented. The HS-8335SH servo motors are part of the robotic arm, which allow for the robot’s 4 DOF discussed in section 4.3.

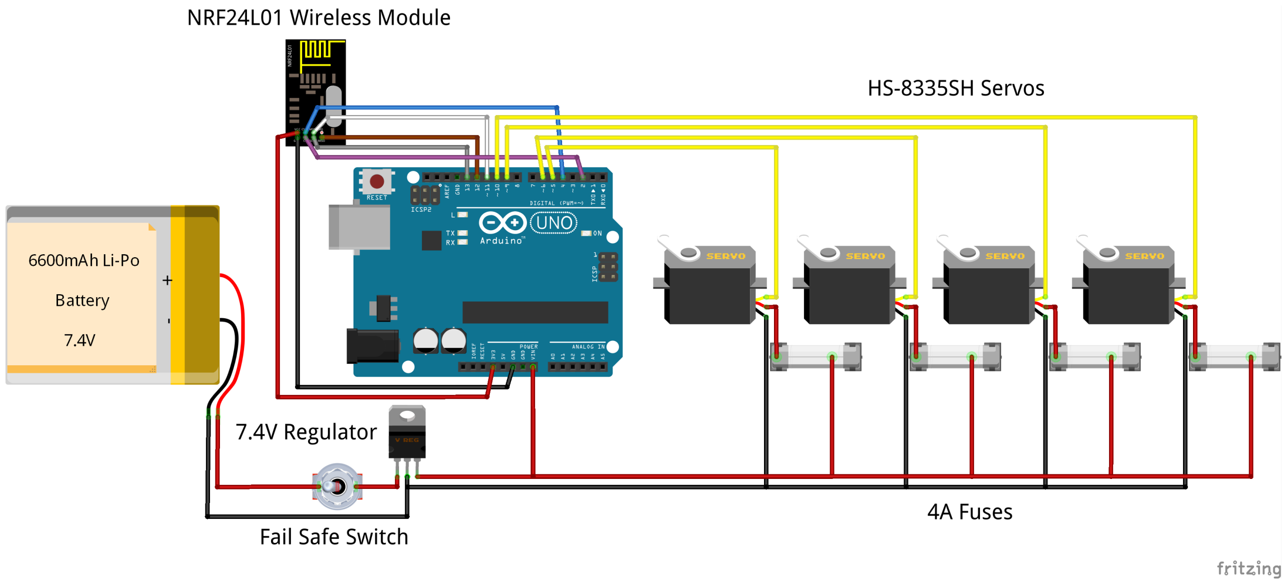


Figure 42: Wiring diagram of receiver

Figure 43: Final assembly of reciever control box

7 Safety

As with many electromechanical engineering projects, there are many hazards that must be accounted for to negate damage to person and property. To this end, a risk assessment was filled out for the project. The primary objective for engineering projects should always be to ensure the highest standards of safety, and so extra measures were taken by the team.

7.1 Electrical Safety

Although the arm did not have a high voltage requirement, the current was high enough to cause respiratory issues if shocked. Therefore, all wires were properly insulated; key electrical components were stored in insulating boxes, and kill switches were added to both the arm power system and the data link sender.
During testing (see section 8.1.1) the overall system current draw was measured during different loads - the max current of any motor was determined to be 3.8A. Therefore for the final revision of this product, the system would be fitted with 4A fuses to prevent any current overdraw. It should be noted for the purposes of this project the circuit was fitted with 5A fuses to prevent accidental blowing during the presentation/testing.
The HS-8335SH motors used were only able to be supplied a maximum of 7.4v, as such it was important a 7.4V voltage regulator was used to ensure that that this voltage was never exceed. It was noted that when fully charged the battery would discharge at 8V, therefore solely powering the system with the battery would not have been feasible.

7.2 Mechanical safety

To ensure that no components fall apart and cause damage during operation, the final assembly was fully constrained. To prevent collision from violent movement, the arm has 2 kill switches as mentioned in electrical safety.

8 Testing

8.1 Arm testing

The progression of arm prototyping followed a simple progression as mentioned in Section 3.2:

1. Develop a prototype
2. Test a prototype
3. If the prototype does not meet test criterion, iterate to another prototype

To this end, prototypes were iterated upon until a final prototype arm was tested and satisfied all test stages:

Stage 1: Unloaded motion of arm

Stage 2: Loaded motion of arm

Stage 3: Unloaded motion of arm with control interface

Stage 4: Loaded motion of arm with control interface

Please refer to Section 8.1.1 as to how loaded motion testing was conducted. Testing with the control interface was verified by frame by frame analysis determining the accuracy of robot motion, shown in section 8.2.1.

Table 4: Pass/Fail of testing gates for each arm prototype

	Prototype 1	Prototype 2	Prototype 3	Prototype 4
Unloaded	Fail	Pass	Pass	Pass
Loaded	Fail	Fail	Pass	Pass
Unloaded with control	Fail	Pass	Pass	Pass
Loaded with control	Fail	Fail	Fail	Pass

As shown in Table 4, Prototype 4 satisfied all test gates, and hence prototyping iteration was stopped.

8.1.1 Load testing

Load testing was carried out to determine the carrying capabilities of the robotic arm and how much additional strain this added to the electrical systems. The test was conducted by attaching weights to furthest point of the robotic arm as shown in Figure 44 - this strained the system the most as it created the greatest moment on the robotic arm. It should be noted that the gripper was not used in this scenario as it was not designed to carry the additional loads. While the loads were being added, the current draw of the system was measured, these results were then plotted on a scatter graph as shown in Figure 45.

From the graph it was discovered that the current draw increases almost linearly as the system is loaded but then it starts to fluctuate at higher loads. This was understandable as the motors generally undergo a linear increase in current load until hitting their stall current - when current draw increases beyond stall current the motor risks being damaged (see section 7.1). The fluctuations in current draw were expected due to high loading creating a lot of stress on the servo motor drive-train [20]. From these results it was concluded that the robot was able to reliably resist a maximum force of 5N or approximately 500g on Earth.

Figure 44: Image detailing how load testing was carried out

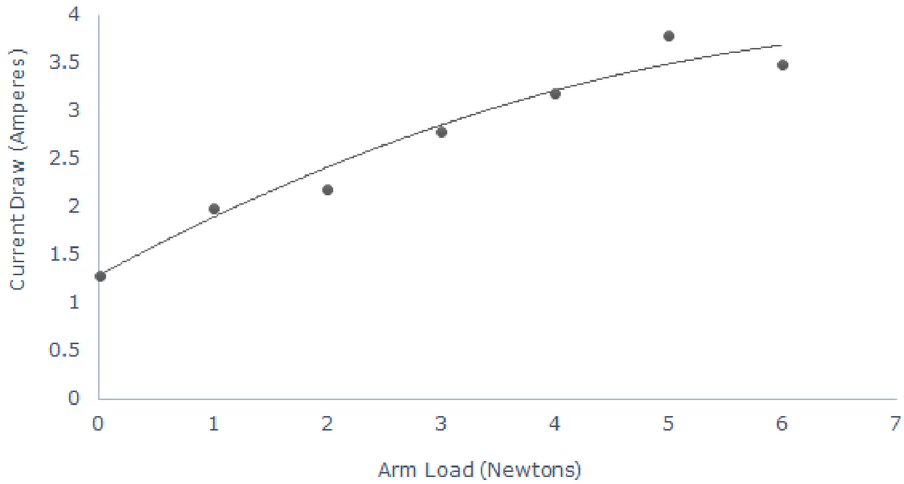


Figure 45: Graph detailing current draw increase against load increments

8.2 Interface testing

8.2.1 Positional Accuracy testing

Frame by Frame analysis of the robot’s motion was performed against the users motion to determine the overall positional accuracy and smoothness of the manipulator. Video at 30 frames per second (fps) was captured of the user performing basic actions, the user and robot joint angles were then measured from each frame as shown in 46. There were a total of 3 motions captured, each lasting approximately 3 seconds resulting in a total of 257 frames to be analyzed. Tests were performed under standard conditions: the robot was unloaded, and the transmitter/receiver distance was 1m. This prevented additional positional errors or delays being caused from these aspects (refer to Sections 8.1.1 and 8.2.2).

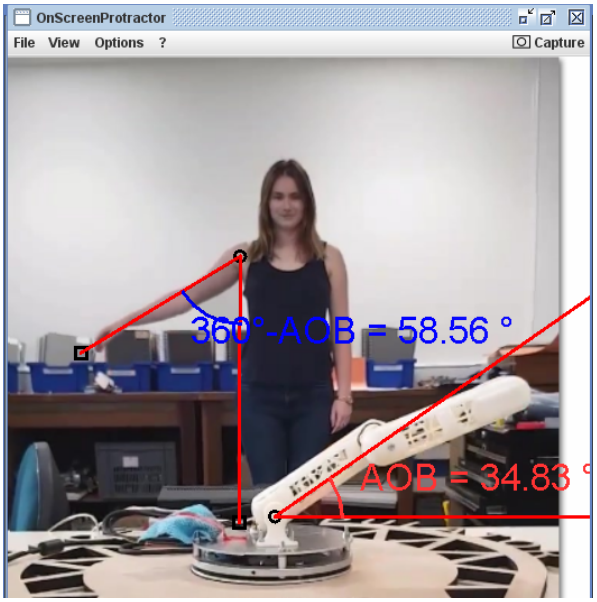


Figure 46: Image detailing use of an on screen protractor to measure the user's and robot's shoulder joint angles.

Shoulder Movement Test

The first motion tested was pure shoulder movement shown in Figure 47. The user raised their shoulder while having their elbow locked in place thereby leading to a approximately linear increase in elbow joint angle as represented in the scatter plot in Figure 47. The corresponding robot shoulder joint angle also increased in approximately a linear pattern thereby confirming that the robot control interface was mapping the user motion.

The smooth motion of the robot can be judged by the linearity of the robot's joint angle increase. It can be seen that there are points (such as at time = 1.1s, 1.3s, 1.5s, etc.) where the joint angle rapidly increases, thereby making the graph less linear and resulting in jerky motion. This phenomenon arises primarily due to the robot's low sampling rate of angle positions as previously mentioned in Section 6.1. Improvements for this problem are further discussed in Section 9.4.2.

It is worth noticing the flat-line of the robot joint angle at the beginning of the motion. This was likely due to a calibration error of the motor mounting hub leading to the robot arm being misaligned causing the robot was to push into the ground at the start of its motion. This problem can be fixed by use of a mounting guide mechanism to mount the hub accurately instead of doing it by hand.

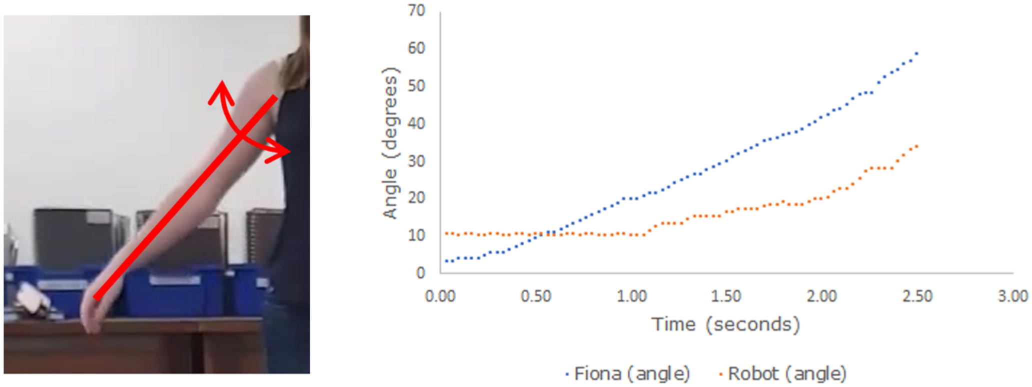


Figure 47: Scatter of joint angles during pure shoulder movement of user and robot against time

Figure 48 shows the error, represented as the difference in shoulder joint angle between the user and robot arm as the test was performed. This scatter graph allows for further validation of the positional accuracy of the robotic arm. The maximum error was calculated as 25.67 degrees and the average error as 10.32 degrees.

As mentioned earlier part of this error was due to misalignment of the motor hub mounting, but there was also an inherent error due to user calibration existing in the Kinect program. The program was unable to measure the angle from shoulder to the side of a user, instead it measured the angle from the shoulder to the collar bone as seen earlier in Figure 32, then it subtracted a constant to obtain the joint angle value. This constant was user specific and needed to be calibrated, and when not correctly done it would lead to a joint angle error. This error can be reduced in future iterations of the Kinect program by use of more accurate algorithms to determine the side of a user.

Noticeably Figure 48 shows that error increases with time. The potential source of this is the momentum caused from the previous movement which could build up and cause the arm to ’swing’ slightly out of the desired position, building up as the arm moves further. Solutions to this would involve a critical look into the programming of how the arm moves between points, discussed in Section 9.4.2.

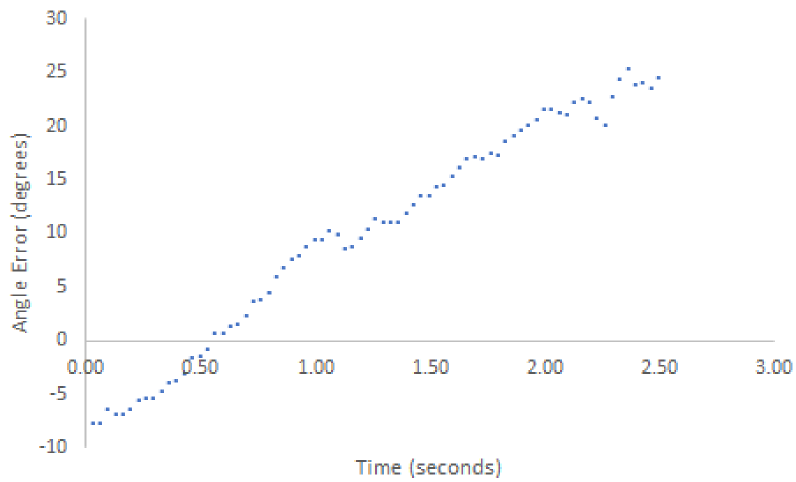


Figure 48: Scatter of shoulder joint angle error

Elbow Movement Test

The second motion tested was pure elbow movement by the user shown in Figure 49. The user lowered their elbow only, resulting in an approximately linear decrease in the joint angles of both the user and the manipulator. Figure 50 shows the error of elbow joint angles. The maximum error was calculated as 56.15 degrees and the average error as 24.27 degrees. The elbow had similar issues as to that of the shoulder joint suffering from mount hub mounting miss alignment.

It is worth noting that there were much greater errors with the elbow joint angles when compared to the shoulder joint angles. This was due to the D-shaft that was used to angularly constrain the elbow having exceeded its tolerances during manufacture. This meant the elbow joint of the robot traveled some distances without being angularly constrained to the motor, leading to more jerky motion and positional inaccuracies. Use of a better angular constraints such as keys or splines will prevent this in future iterations of the arm.

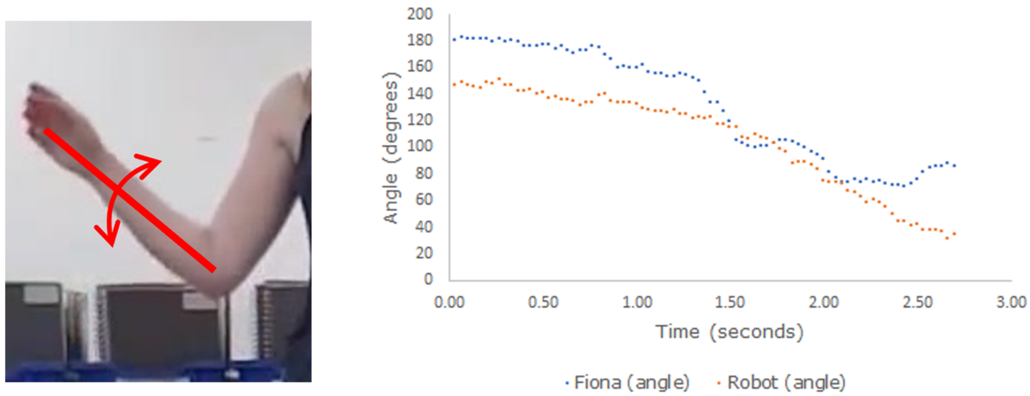


Figure 49: Scatter of joint angles during pure elbow movement of user and robot against time

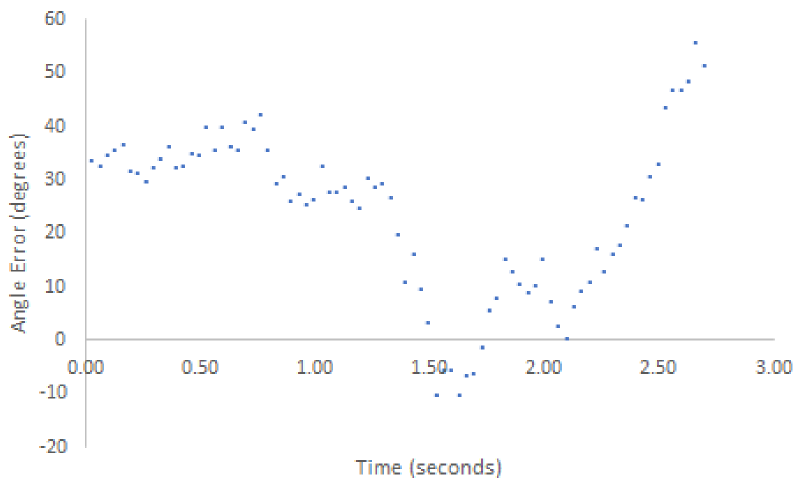


Figure 50: Scatter of elbow joint angle error

Combined shoulder and elbow test

The final test (shown in Figure 51) involved the user moving both their elbow and shoulder simultaneously, thereby testing the dual motion positional accuracy of the robotic arm. As expected, the same joint angle errors as discussed earlier arose with this test. Nevertheless, this test served as a good overall positional accuracy test for the system, showing that the system was able to still track user motion but with a large margin of error.

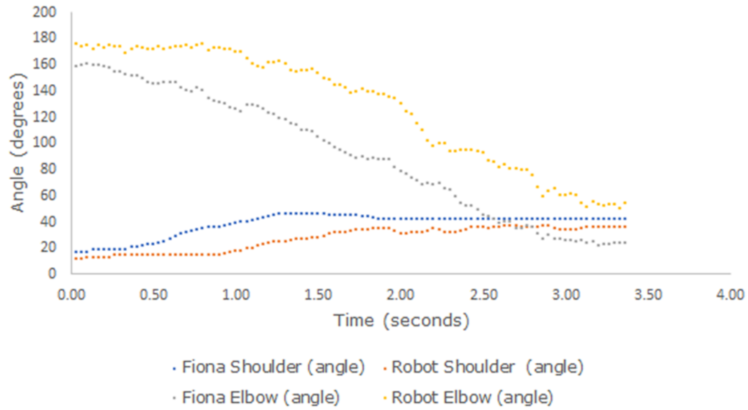


Figure 51: Scatter of multiple joint angles during dual limb motion of user and robot against time

It is worth noting that since the test procedure involved reading angles from images by eye, the precision of testing procedure itself was limited at best to ± 1 degree. Since the joint angle errors are much larger in magnitude that this precision it is unlikely that this had much affect. To improve this experiment, angles should be directly measured from the user and the robot using tools such as directly fitted rotary encoders.

8.2.2 Wireless testing

The range capabilities of the system were tested quantitatively and the results shown in Table 5. The test involved increasing the transmission distance between the control box and the arm's receiver modules. The same signal would be sent to the arm and the time taken to complete the task was recorded. The results obtained are average values from a total of three tests.The system successfully managed to respond until 14m, beyond the required specification of 10m. The radio wave wireless modules used in the system were rated to be capable of up to 100m of communication - the tested system likely was not able to reach this range due to the number of surrounding interferences (the tests were carried out indoors where the radio waves likely reflected off of many surfaces). The system responded very poorly to obstructions, with the test failing if there was any solid objects in the way. This issue will be further discussed in Section 9.4.2.

Table 5: Table of wireless testing at differing distances

Distance (meters)	Response Time (s)
1	0.1<
2	0.1<
5	0.1<
10	0.5
14	0.8
15+	Failure

9 Discussion

9.1 Final Attained Objectives

To determine how effectively each component of the PDS was met, a testing score from 0 to 10 was implemented for each section. By multiplying each of these by the priority (1- beyond scope, 3- design critical), a design percentage was determined. Overall, a PDS Completion score of 84.6 % was calculated, as shown in Table 52.Showing an outstanding project outcome, and therefore the finished product met the PDS goals.

The completion of project stretch goals described in Section 1.2 were also evaluated:

1. Secondary control system was made (Figure 41)
2. An additional 3rd degree of freedom was added, and given the potential for further prototype iteration, a wrist DOF would be added.
3. The final arm prototype was tested in sideways orientation, and all but the base DOF operated normally in this orientation.

	Objective	Criteria	Evaluation	Priority	Success index
Arm	**Performance**				
	High precision	±2cm positional accuracy	All DOF give a positional accuracy greater than specified	3	10
	Multiple DOF	Has minimum 2 DOF	3 DOF in final prototype	3	10
	Speed	60cm/s unloaded 6cm/s loaded	All DOF can operate at speeds specified	2	10
	Small Reaction Time	Reaction speed of 0.25s	Reaction speed of roughly 0.5s	2	2
	Quick and easy assembly	Assemble in no more than a day using no more than 2 astronauts	Arm subassemblies assembleable within 1 hour for 2 trained Engineers	1	10
	Power draw	<1000W Operational, <500W Keep Alive	Maximum operating power is 35W, significantly below requirements	1	10
	Operating Life	10 years or 100 missions	See shaft calculations section; fatigue life significantly higher than operating life	2	10
	Dimensions				
	Take-off Volume	Packable for minimal take-off volume	Overall volume of disassembled arm can fit within a 0.5x0.5x0.5 meter cube	1	10
	Reach	Minimum reach of 0.5m	Reach of arm is 0.6m	2	10
	Scalable Design	Modular design	Arm can be partially disassembled into modular components	2	10
	Safety				
	Spatial Awareness	Breaking distance of 10cm from when obstacle is detected.	Breaking distance is less than 10cm, but no spatial detection system is integrated into the arm	2	3
	No Short Circuits	All wires coated and not touching	Wires sufficiently contained and bound inside casing	3	10
	Minimal maintenance	Require maintenance once a year	See shaft calculations section; fatigue life significantly higher than period between inspections	2	10
	Resources				
	Budget	< £500	Target met, see budget section	3	5
	Manufacturability	Able to be manufactured in house	Manufactured completely with manufacturing techniques available	3	10
Control Interface	**Performance**				
	Minimal Lag	Response delay of 0.25s	Current response delay around 0.5 seconds	2	4
	High Precision	±2cm positional accuracy	Target not met, current positional accuracy approximately ±4cm	3	2
	Quick and Easy set up (plug and play)	Can be set up in room in an hour	Target met, setup within 45 minutes on multiple tests	2	10
	Dimensions				
	Portable	Can be transported without excessive protection required	Target met	2	10
	Small operating space	Only requires a 5x5m empty space for operation	Tested in 5x5m space, operates effectively	3	10
	Safety				
	Operational Instructions	Easy to use instructions must be provided	Intuitive design for usage, however instructions currently not provided	2	8
Data Link	**Performance**				
	Low Bandwidth (information)	Less than 250 Mbit/s	Target met, maximum data transfer is 2Mbits/s	3	10
	Minimal Interference	System guarded using relevant materials	Wires and electrical components contained in insulating boxes and appropriate wire management	2	10
	Suitable Range	Minimum operation distance of 10m	Can operate wirelessly beyond 10m range	2	10
	Resources				
	Budget	<£100	Target met, see budget section	2	10
				SCORE	84.55%

Figure 52: Table of PDS targets and their level of attainment

9.2 Budget

The total expenditure of the project was £984.24, so was within the allocated budget of £1000. Figure 53 shows a breakdown of expenditure for each prototype. Prototype's 1 and 2 did not cost anything as they were made of materials that were free of charge in house. It also shows a trend that the prototypes gain in price, with the majority of the budget spent on Prototype 4. This backs up a prediction that as the prototypes increase in complexity and get ever closer to being space ready, the cost per prototype will increase exponentially.

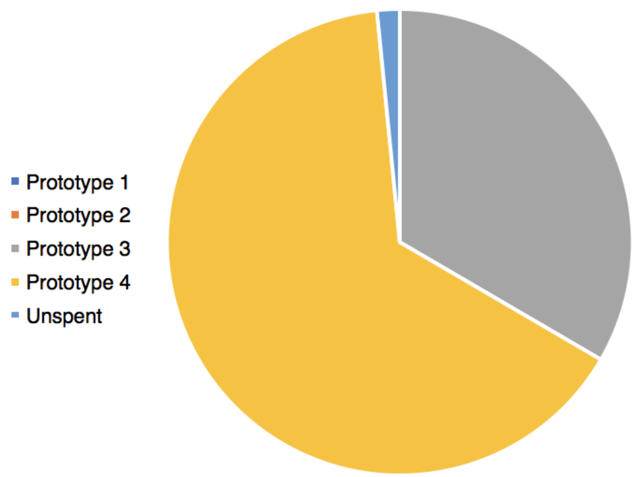


Figure 53: Total Expenditure by Prototype

Figure 54 shows the breakdown of the budget as laid out in the PDS. The blue bars represent the actual spend for that aspect of the project while the orange represents the predicted spend as stated in the PDS. The control interface and data link sections of the project were within the estimated requirement. The arm incurred more costs than expected, however these were absorbed by the much lower than expected costs of the control interface aspect.

Overall the allocated budget was adequate enough to produce all prototypes to a satisfactory standard, though more would be required for future iterations of this project.

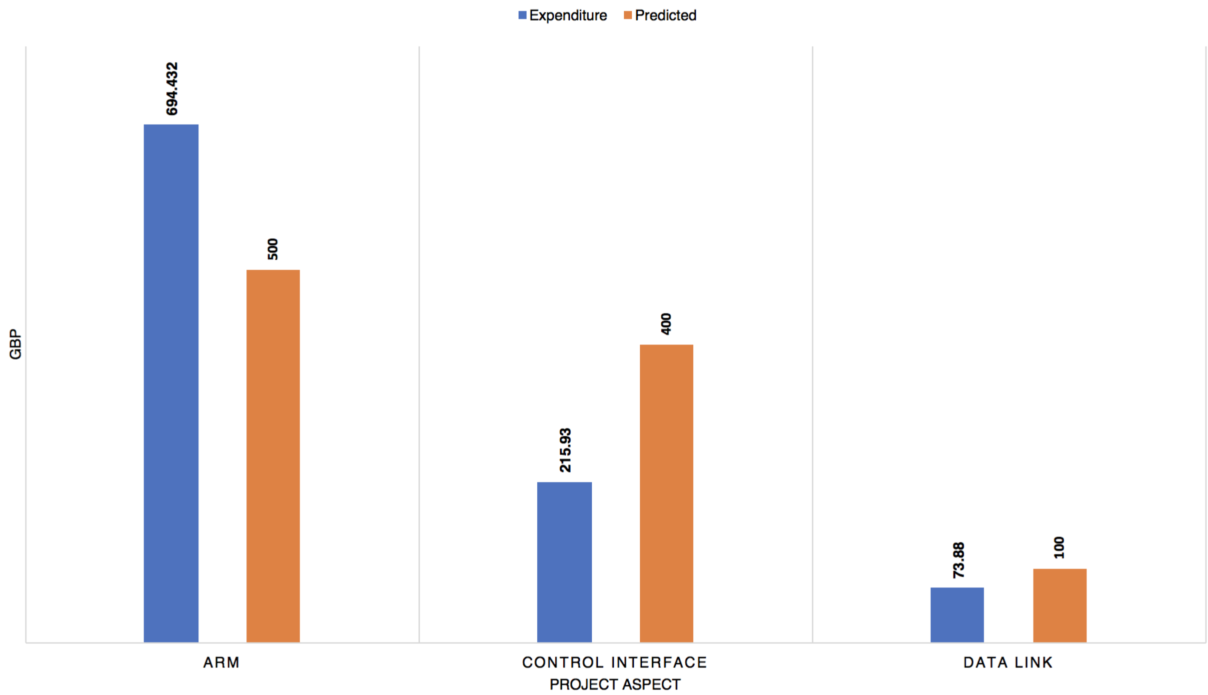


Figure 54: Project Expenditure compared to PDS Requirements

9.3 Risks and Challenge Management

To limit technical, cost and scheduling risk during the project, risk-analysis has been carried out, as shown in Figure 55. To negate timing issues where component delivery was delayed, insured and tracked delivery was selected for all vital components. Furthermore, reputable companies (ie. IBIS verified sellers such as RS components) were used frequently, so that if delivery goes wrong they are easily contactable. This strategy worked extremely well, as no components arrived later than desired.

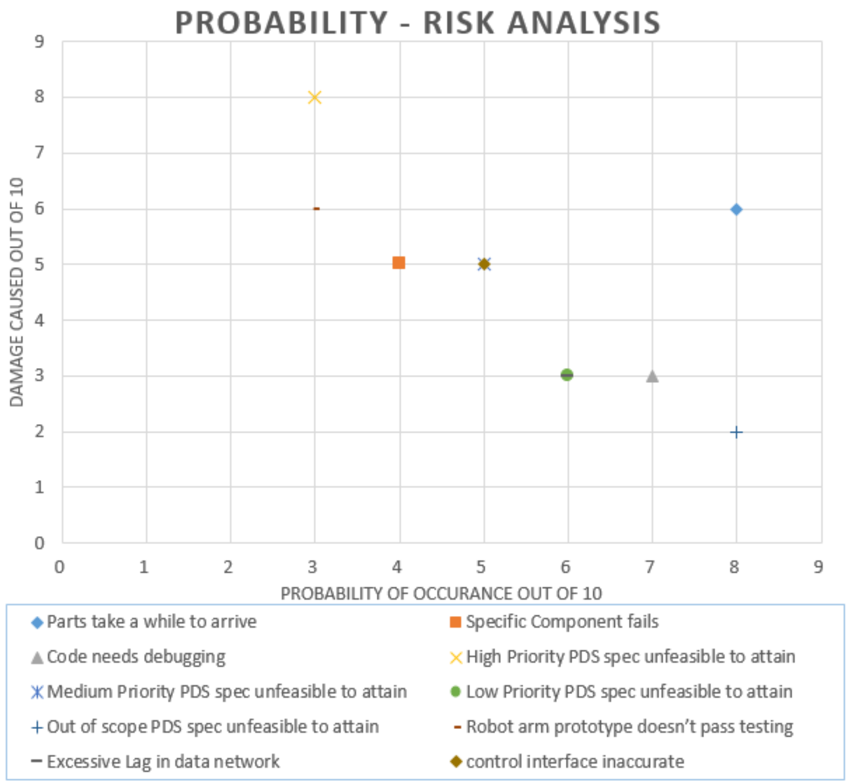


Figure 55: Risk analysis diagram

9.4 Potential Development

To say the sky was the limit for this DMT Project may be a bit cliché, especially as it is a Space related project, nevertheless there really was no limit to the scope of potential improvements. As such the team was constantly finding additional features that could be added. This is also reflected by the relatively large quantity of prototypes produced by the team. This section will explore what the team would have produced if they were to continue the project.

9.4.1 Arm Development

Wiring

Wiring is an inherent issue when dealing with bodies that can move relative to each other, as with conventional wiring it must be ensured that there is enough slack for the robot to move between extremes without putting strain on the wires. The most elegant solution to this problem is to use circular contact points at the joints as motion is limited to 180 degrees.

Gripper

The current arm assembly for Prototype 4 does not include a wrist degree of freedom. The same high torque motor to control the opening and closing of the gripper is used in the shoulder and base joints which is unnecessary. For the next prototype this motor would be used as a wrist joint and a secondary smaller motor (potentially with a cabling system) to open and close the gripper. This would allow the team to fully replicate the degrees of freedom of the human arm.

Material

Additive manufacturing was used due to our fast turnaround times and pace of the project. From Section 8 it is possible to see that the material choice was suitable in regards to tensile loads experienced for the use cases. As the ultimate goal is mounting to a satellite, a more durable material would be needed. Machining the casing halves from a solid block of material, or using Selective Laser Sintering would have eliminated potential issues inherent with 3D printed parts such as layer separation.

Motor Couplings

The coupling used between the servo motors and their respective shafts utilized the use of a grub screw into a D’d shaft to constrain the shaft axially. This becomes an issue as over extended periods of time the grub screws are worked loose and so begin to constrain the shafts less and less. This would not be acceptable for a space ready prototype as regular maintenance is undesirable for a product in an extreme environment. The alternative would be to use couplings that screw into the end face of the shaft at multiple points.

Servo Motors

In order to lift greater weight hydraulics or pneumatics could be used. When side mounting the robotic arm to better replicate the range of motion of a human arm, the base motor would sometimes overheat trying to rotate the assembly. The advantage of a hydraulic system would be that it would be able to deliver much greater forces. However, since this robot is intended for space more power may not necessarily be required, as the robot will not have to overcome the effects of gravity.

Cooling

When under load for extended periods of time the servo motors used have a tendency to heat up. This is an issue as with increased heat there is increased resistance and so a greater current draw for achieving the same task. This current draw will keep increasing and eventually reach the stall current of the motor which would cause operational failure. To combat this additional vents could be added to the rear of the motor housing to improve air flow around the motor.

9.4.2 Interface Development

Multi-Dimensional Vision Recognition

The vision recognition technology used involving the Kinect is only able of detecting motion in a 2D plane, therefore it is unable to detect the motion of specific user motions due to the viewing angle. Use of multiple camera systems would allow for 3D mapping of the user's motions thereby being able to more accurately predict the motion intended for the robotic arm by the user.

Collision Detection

Currently the robot has no form of collision detection as such it is incapable of preventing potential damage to itself and any other objects nearby (such as the space station or other satellites). Installing a range of proximity sensors over the robotic arm will allow for detection of nearby objects. This could potentially be used in tandem with the multi-dimensional vision recognition system to allow the user to simply hold their hand at a specified position and robotic arm calculates the most effective way to reach that point in 3D space without collision - utilizing path finding algorithms. This is where the modularity of the team's robotic arm would be advantageous, as the greater the number of degrees of freedom available, the more complex the path finding routes could potentially be.

Data Transfer

The data transfer rate is limited by the relatively inexpensive wireless modules used - this is what primarily determines the sample rate and response delay. With use of NASA systems such as the SN, the system would be able to transfer data at a higher sample rate and with less delay thereby making the robotic arm have smoother motion and faster response. The SN system is also able to generate signals of a much greater amplitude (due to the much large antenna's and satellites being used), as such these signals are less likely to be absorbed by objects therefore resolving the wireless issue due to obstructions mentioned in section 8.2.2.

10 Conclusion

The goal set at the beginning of the project was to create a manipulator remotely operable through human gestures. This was achieved in full (satisfying all critical PDS objectives), on schedule for the 32-week deadline, and under budget by £15.

A Microsoft Kinect sensor system was implemented to control a prototype-iterated robotic arm with 3 degrees of freedom. This was then implemented wirelessly (i.e. with a communication gap). The arm used high-torque servo motors to actuate each degree of freedom, controlled using an arduino coded control interface to regulate motion.

The Microsoft Kinect camera system determined angles in the users right shoulder and elbow. Rotary encoders were used for the base and gripper degrees of freedom. These inputs were then filtered at a set sample rate and then mapped to each respective degree of freedom on the arm prototype.

It was determined that 84.6% of PDS criterion were met. The most significant areas for further development to this regard are the increase in control interface positional accuracy and response delay, and the integration of a spatial awareness system into the arm to improve the braking distance.

From the potential development section it can be seen that there are many areas of the project that could be developed further by an abundantly-resourced company such as NASA, or the ESA. However, the project has been concluded at a point where it is possible for handover to one of these companies for the further refinement of the design for its intended purpose.

11 Individual Conclusions

11.1 Fiona Boyce

I really enjoyed having the chance to propose a DMT project; so decided to focus the applications towards space, something that has fascinated me for a very long time. I'd therefore like to thank Ravi for helping me to pursue it. Researching the project during the literature review was particularly enjoyable as I was able to increase my knowledge of technology at the forefront of the space sector. Finding a team that shares my passion for the subject was excellent, and one with such a brilliant skill set even better.

As team lead, I felt I had a good grasp of all aspects of the project and what was necessary to achieve the various project goals. My role included the design and implementation of the robotic arm at a systems level. Planning the different project stages, ensuring everyone kept to the program and making various technical decisions. My development roles included the firmware for the receiver end of the control system and the design and manufacture of the gripper. In addition to this, I performed the interface testing and data analysis with Thushaan.

The end result was fantastic, with so many requirements and stretch goals met. The organisation of the project went well, we were on time with all submissions. Something that could have been improved was generating the gripper designs earlier and producing more prototypes to achieve a higher end result. One disadvantage of such a complex project is that it can become a challenge keeping the development of the multiple subsystems processing. For my next project, I will create a more detailed plan of all areas of the project earlier and discuss it with my supervisor, to ensure no areas of the project are forgotten.

I've learned a lot more about programming during this project, and also about different hardware considerations in electrical design. I also spent more time in the workshop than I had done in previous years. As a result of this I believe my capability at manufacturing has greatly increased, as has my confidence in the workshop; something I am looking forward to bringing to my final year project next year.

11.2 Caleb Goddard

Space has always been a passion of mine so the opportunity to work on a DMT project related to the field is one that I have been very appreciative of. The group's overall enthusiasm for the sector has really been evident in the hard work and dedication from all members, and the fruit of this shows in the final product as most product design specification sections were met.

One key to the group's success was the diversity in skills each individual brought to the table. As the project was self-proposed the group were familiar with each other prior to the project start and the full range of skills needed to complete the task were addressed in total by each group member. The group was able to have members specialise in tasks that they naturally excel at, which allowed the group to be as productive as possible.

My main role in the team was to design and develop the arm casing for all the prototypes. Due to the fact that 4 unique prototypes were able to be manufactured I believe my work was integral to helping the group achieve their goal. This also meant that throughout the project I was constantly tweaking and advancing the arm design, and the end product is truly a result of a long iterative design process.

One of the challenges I faced was coordinating with the other individuals in the group to ensure that the base, arm, and gripper all worked together. This coordination was achieved through consistent communication. This is one area in which I grew in throughout the project, as I learned how to communicate effectively, and realised the importance of spending time with other members to ensure they have a full understanding of what needed to be achieved.

Another challenge I faced was finding the balance between form and function for the casing design. My original vision for the arm was to produce a unique, aesthetic design with a clear design language throughout everything the team produced. However, this was never to be at the sacrifice of form and structural integrity, and every single aspect of the design had to have purpose. I believe we have fairly comprehensively addressed the design features throughout this report. The need for the cutouts stemmed from the need to reduce the weight of the casing to fit the motor requirements. These cutouts became a clear defining feature of the project and the language continued into our exhibition stand and poster. As such this challenge was fully addressed.

11.3 Harry Mitchell

As a student who as been a participant in multiple group projects, I have never worked with a more effective and diversely skilled group than in this project. The scope and application of the project drove all of us since the beginning of the project, since the Space sector is an area that some of us are interested in as a future career. Overall, this project was successful, as we began with an initial problem (manipulating debris/satellite components in space), and prototyped quickly and frequently, concluding with a well-developed proof of concept design. This design met the PDS with a 84.6% rating, which can be considered as a success.

Since I have more experience manufacturing from past projects, my practical role was focused towards arm and control box design and manufacture. Furthermore, I was responsible for the component selection and gripping force calculations, which involved failure and ridgid body analysis. Overall these roles were engaging, as it allowed for a balance of practical and theoretical work. I have been a member integral to the operation of the team. This project also gave me the opportunity to strengthen my skills in mechatronics and programming.

The most valuable lesson from this project I have learned is working with a team of multiple engineering disciplinary strengths; much as I am stronger on the mechanical side of tasks, some of my teammates are highly capable in mechatronics and computing. Therefore, I now understand the importance of communication between these discipline groups, to avoid overlap or gaps in the project; for example, we ensured that the servo motors could be integrated not only mechanically into the casing, but also into the electronics and control interface.

I would Like to thank Dr. Ravi Vaidyanathan for his guidance and engagement in our project. As a self-proposed project, to agree to support our vision requires faith in our ability as a team and individual Engineers, which we are immensely grateful for.

11.4 Thushaan Rajaratnam

I began this DMT envisioning trying to create a human-machine interface that would allow for users to seamless interact with robotic devices. The final stage that was reached by the team not only goes to show how much potential there is in such a venture but shows how successful the project was to come close achieving such a monumental task.

The project for the most part was organized well, with communication being like that of a flat team structure. The benefit of such communication was that it was very easy for any member to discuss any component of the project. Sometimes crucial information would not be delivered to the relevant team member if the specific topic was not raised by the team. At other times there might have been too much information being delivered. In hindsight, the group would have been able save more time if discussion around any component of the project was done periodically by each member in an organized manner.

I believe from the beginning the team's skill-sets were very suited for the task in hand, with having many members specializing in the different areas required for such a project. As such the team was able to simultaneous succeed in multiple aspects of the project by allowing each member to focus on implementing their component for the system. It is worth noting with such a specialized structure how crucial open communication was in making our team work.

My personal contribution was predominantly in the software and electrical aspects of the project. I undertook the the Kinect programming, multiple aspects of the micro-controller programming and general design of the electrical systems used for the robot. Whilst my team were successfully implementing the mechanical design required for robot arm, I undertook and completed the task of making the system function as intended.

My major weakness during the project was not allowing more time for communication with team members. In future projects I intend making better use my time with my teammates - this will allow me to not only understand their components better but to also better explain my components to them.

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