The University Of Adelaide
School of Mechanical Engineering

Honours Project 2017

Final Report

For

Project #2366: The Robotic Exoskeleton for Assisted Upper-Body Motion

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Executive Summary

This document is the final report for honours project 2366, and shall discuss the work done for the design and build of the Robotic Exoskeleton For Assisted Upper-body Motion known as the REFAUM system. This project aimed to design and build a full prototype of an upper body exoskeleton which could be used to aid wearers in rehabilitation, or teach movements by running users through motions using the correct timing and techniques. At the conclusion of this project all of the primary aims and goals have been achieved within the given time frame and budget. The REFAUM system is capable of replicating the motion of a human arm, allowing it to guide users through five degrees of freedom extending from the shoulder to the wrist. A systems engineering approach was used in this project, to break the REFAUM system down into three main subsystems: electrical, mechanical, and control. Each of these systems have been completed, and integrated to obtain an upper body exoskeleton consisting of one powered and one unpowered arm.

At the initial stages of the project a literature review was conducted, looking into existing exoskeleton projects along with the torque and size requirements the suit would have to adhere too. Several studies were found giving a full understanding of how much torque each joint was likely to require, what the expected ranges of motions were for each degree-of-freedom, and what the normal range of human limb sizes are to make sure the prototype could fit a wide range of users.

The electrical system primarily consists of three different component types: sensor, actuator, and controller components. The sensor components are required to provide information relating to the position of the exoskeletons joints. Linear potentiometers were selected for this purpose, they output a different voltage depending on their position which can be converted to the actual position of the exoskeletons joints using an equation determined from various tests. The Actuator components are required to provide physical power the mechanical system. They consist of three differently sized gear reduced DC motors and their respective controllers and are able to provide the required torque values found in the literature review. The controller components act as a bridge between the electrical and mechanical system allowing them to interact with one another. They consist of a Raspberry Pi 3 Model B, A PWM generator and two ADC chips. The ADC chips read the voltage from the linear potentiometers, the Raspberry Pi then figures out what speed and direction to run the motor controllers at using the PWM generator. In addition to the selection and integration of these component types a control box was also designed and constructed to safely house the electrical system in.

The mechanical system deals with the physical build of the REFAUM system. It was designed to be strong, cheap, lightweight, and modular, whilst providing the ability to complete motion in all five degrees of freedom, and include safety stops to avoid over extending joints. Water-jet cutting and 3D printing were used extensively throughout the build, with most of the parts being made from aluminium, plywood, and ABS plastic as these materials are relatively light, strong and cheap. The final design had some issues dealing with comfort and weight, however has achieved the main goals it set out to accomplish which resulted in the completion of both of the exoskeleton arms. Modularity was built into the design allowing each joint to be adjustable, and easy to disassemble in order to facilitate future improvements.

The control system consists of a Matlab GUI and two Simulink control models. The GUI allows users to move between the REFAUM's different functions: record, execute, and mirror image. In record mode the position of the exoskeleton joints are read, allowing users to record and save a custom move-sets. The execution mode allows the user to select preview and run previously saved move-sets using the GUI or the physical system. The mirror function uses one powered and one unpowered arm, and starts a program where the powered arm will mimic the motion of the unpowered one. The control model uses PID controllers on each joint to determine appropriate PWM signals to be sent to the motors. A model based control system has also been implemented to improve this model creating an effective multi-input multi-output controller.

The project has successfully completed what was aimed for this year, however there are many extensions that could allow this project to be carried forward into the future. These include improvements to the power and capabilities of the electrical system, the weight and comfort of the mechanical system, and the overall functionality and portability of the control system.

Disclaimer

The ideas and designs discussed throughout this report are the intellectual property of the 2017 REFAUM team and The University of Adelaide, unless otherwise stated by appropriate references. All content was produced by REFAUM team members to the best of their abilities and should not be distributed or copied without their authorisation. By signing below, you agree to the above statement.

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Glossary

- **REFAUM:** Robotic Exoskeleton For Assisted Upper-body Motion
- **D.O.F:** Degrees of freedom
- **RPM:** Revolutions per minute
- **CAD:** Computer aided design
- **GUI:** Graphical user interface
- **SMART:** Specific, measurable, achievable, realistic, and time based
- **SOP:** Safe operating procedures
- **PID:** Proportional-integral-derivative
- **SISO:** Single input single output
- **MIMO:** Multiple input multiple output
- **DC:** Direct current
- **ADC:** Analogue to digital converter
- **PWM:** Pulse width modulation
- **RAM:** Random access memory
- **GPIO:** General purpose input/output
- **PCB:** Printed circuit board
- **D-H:** Denavit-Hartenberg
- **FPS:** Frames per second

1 Introduction

This project aims to design and build a Robotic Exoskeleton for Assisted Upper-Body Motion which shall be referred to throughout this report as "REFAUM". This document is the final report for the REFAUM project and contains information relating to the motivation/background behind the project, the goals it set out to achieve, the research behind the designs, information relating to the projects management and finally detailed descriptions of each of exoskeletons primary systems: Electrical, mechanical and control.

1.1 Background

Assistive human exoskeletons have been conceptualised in some form or another as far back and the 1890s, with the first powered exoskeleton prototypes occurring in the 1960's (Ali 2014). Initially focused on defence applications, their uses have expanded over the past few decades and now include civilian industries such as rehabilitation. The bulk of the research put into rehabilitative exoskeletons has revolved around the lower sections of the body, to assist people in wheelchairs suffering from leg muscle weakness or dystrophy. Upper body exoskeletons for use in rehabilitation have been in development since the 1990's, with the first commercially available upper-limb exoskeleton being released in 2011 (Jarrassé 2014), however they are expensive and mostly non-portable.

At the university of Adelaide assistive exoskeletons have been developed over several years in students' honours projects. In 2016 some of these projects included assistive exoskeletons for use with hand and lower body movement. This project plans to extend upon the knowledge and technology developed by these projects to create an upper-body exoskeleton which aims to provide assistive motion to the shoulder, elbow and wrist.

1.2 Motivation

Every year millions of people around the world suffer from various issues that can impair the muscles in their upper limbs. According to a study by Cannan et al. (2012) on average someone around the world will have a stroke every five minutes. Most of these people will be left with some form of disability, the majority of which can cause upper limb muscular issues on one side of the body (Cannan & Hu 2012). Therefore, in order to prevent long lasting damage repetitive rehabilitative motions are essential. This is an area where assisted upper body exoskeletons could have huge beneficial effects towards patients. A wearable device capable of running users through rehabilitative motions has the potential to reduce the cost and need for physical therapy sessions. Allowing the patients to recover at their own pace and in their own time.

Research has proven that assistive exoskeletons have the power to greatly assist the recovery of patients suffering from muscular issues (Cannan & Hu 2012). Although many exist, they are mostly large and/or very expensive. This project aims to provide a smaller cheaper prototype of an upper body exoskeleton in comparison to what is already available on the market. The REFAUM system will be able to control user's arms running them through predefined repetitive move-sets similar to that of the moves provided by physical therapists.

In addition to rehabilitation the REFAUM system could also be utilised for recreational activities. Move-sets could be created to teach people movements using the proper techniques and timings. The repetitive nature of the system would reinforce the muscle memory of the user overtime until they were able to perform the movement by themselves without the suit. Potential benefits for using the exoskeleton in this way include raising awareness for the technology so more funding could be invested towards it. This extra funding could be reinvested into more useful applications such as the rehabilitation industry mentioned earlier or even for areas that don't exist yet the possibilities are endless.

1.3 Aims

This project aimed to design and build the electrical, mechanical and control systems required to fully construct an upper body exoskeleton. The exoskeleton in question, known as the REFAUM system, had two primary objectives: Firstly, the system was required to be used for rehabilitation purposes. To achieve this the exoskeleton had to be able to provide assistance to the user in the form of repetitive rehabilitative motions. These motions would assist with the restoration of muscular strength and reduce the side effects associated with hemiparesis. Secondly, the system was to provide functionality for recreational activities such as Tai Chi. This involved the use of more complicated move-sets aimed towards teaching the user the specific techniques and timings of a move or routine. In terms of mobility the REFAUM system was required to control the user's arm from the shoulder to the wrist. Being able to replicate the workspace of the average human, which was defined to consist of five degrees-of-freedom per arm. Both arms of the exoskeleton were to be designed and built but only the right one was required to be powered by actuators. Each of the exoskeletons limbs had to be modular and adjustable to make future integration would be possible and a wide range of users would be able to wear the suit.

1.4 Goals

To make sure the project was completed in time goals were assigned as milestones to be completed throughout the year. The project's success is based off how many of these goals were completed during the year and to what extent. Table 1 below lays out the basic descriptions for all of the goals allocated for the 2017 REFAUM project. More detailed versions of these goals are located in the appendices section A and are represented in the "SMART" format. Several of these goals depend on one another for completion and generally relate to one of the exoskeletons three major systems: Electrical, mechanical and control. The goals are displayed in the order that they were roughly achieved throughout the year, although some of them were completed in parallel.

Reference	**Goal Name**	**Brief Goal Description**
G1	Research Into Human Kinematics & Dynamics	Determine the full extent to which the average human adult can move their shoulder, elbow and wrist in terms of kinematic and dynamic movement.
G2	Mechanical System Design	Design a mechanical system to replicate human upper body motion as close as possible, be comfortable to wear for long durations of time and fit a wide variety of users.
G3	Modular Actuator Subsystem Design	Design a modular actuator subsystem to provide the necessary torque to each of the mechanical system's joints in order to assist the users movement.
G4	Sensor Subsystem Design	Design a sensor subsystem to measure the position, velocity and acceleration of the exoskeletons joints during operation.
G5	Build The Exoskeleton	Use the initial designs from the mechanical, modular actuator and sensor subsystems to come up with a final detailed design that is able to be manufactured by the workshop in a reasonable amount of time.
G6	Electronic System Design	Design an electronic system capable of safely housing, connecting and powering all logic and actuator circuits.

G7	Trajectory Generation Subsystem Design	Design a trajectory generation system capable of both animating and refining the data recorded from move-sets.
G8	Simulink Controller Design	Design a model based control system, using Simulink, that is capable of providing closed loop feedback control for the exoskeleton.
G9	Interface Design - GUI	Design and implement a GUI capable of giving the user a simple way to interact with the exoskeleton to record and execute move sets.
E1	Integration with Lower Body Exoskeleton	Determine a way to physically attach this years upper and lower body exoskeletons for demonstration purposes at the end of the year during Ingenuity.

Table 1: List of project goals (Note: G = Primary Goal, E = Extension Goal)

2 Management

This section of the report focuses on the managerial issues associated with the project. A status update has been provided to give some insight into the work completed by the 2017 REFAUM team in addition to the current status of the projects goals. An explanation is given towards how the project was broken down into manageable subsystems and allocated appropriate time slots and resources. The project and safety risks are discussed in more detail, including the preventative measures taken to avoided them. Finally, the different aspects of the budget will be explored to see what happened to the $800 that was provided by the university at the start of the year.

2.1 Status Update

Since the publication of the preliminary report some slight updates have been made to the project goals. More specifically the old extension goal ”Interface Design - GUI” and goal 9 ”Integration with Lower Body Exoskeleton” have switched places. The reason behind this being that the GUI was deemed more important to the operation of this years project when compared to the integration with the lower body exoskeleton which would have been useful for future projects. The work completed by the 2017 REFAUM team has resulted in the finalised version of the electrical, mechanical and control systems required to create an exoskeleton prototype capable of providing assistive motion.

The electrical system has been fully designed, constructed, tested and implemented on the final exoskeleton marking the completion of project goals 3, 4 and 6. Sensors were selected capable of detecting the angular position of each of the exoskeletons ten degrees-of-freedom. Actuators powerful enough to lift the user's limbs as well as the weight of the actual exoskeleton were purchased and modularly attached to the five degrees-of-freedom located on the exoskeletons right arm. A controller, along with the necessary additional components, were selected to allow the electrical system to effectively communicate with the control system. Finally a control box was deigned and built to safely house the electrical system on the back of the mechanical system. Overall the electrical system satisfies all of its requirements and specifications, although due to budget restrictions extra actuators/motor controllers could not be purchased for the left arm of the exoskeleton.

The mechanical system has been fully constructed after the designs were completed in the preliminary report marking the completion of goals 2 and 5. It attaches to the user through the use of several velcro straps, two wrist braces and a stab proof vest. The suit itself is able to provide the user with movement equivalent to five degrees-of-freedom per arm which allows for some interesting move-sets. Every limb of the exoskeleton is adjustable to some degree to account for a wide range of users. Safety stops are present on each of the exoskeletons joints to stop them moving in ways that they are not supposed to. In terms of its performance the mechanical system works relatively well. The arm alignment is a bit off and it weights a bit too much to be comfortable but it does a good job at showing what the system is capable of which is what prototypes are all about.

The control system was developed using MATLAB and Simulink and gives the user access to the exoskeletons different functionalities through the use of a GUI. The exoskeleton functionalities developed in the 2017 REFAUM project include:

- Record Move-Set: Allows the user to record and save move-sets to memory by moving the left arm of the exoskeleton.
- Execute Move-Set: Executes the currently loaded move-set on the right arm of the exoskeleton.
- Mirror Image Mode: Enters a mode where the right arm of the exoskeleton replicates the motion of the left arm.

- Animate Move-Set: Displays the currently loaded move-set through the GUI using the robotics toolbox for MATLAB.

Overall the control system does what it is required to do but not in the most efficient manner. Problems arose with the Raspberry Pi Simulink blocks and as result could not be used in the final design of the system. Therefore a less optimal method was adopted which involved the use of level 2 S-functions to control the Raspberry Pi which meant that the Simulink control models had to be run on the host computer rather than Pi itself.

2.2 Systems Engineering Breakdown

In order to reduce the complexity of this project systems engineering techniques were used to iteratively break the project down into manageable subsystems. In particular the project was broken down into four primary systems:

- **Hardware:** Focused on the design and build of the exoskeleton's mechanical and electrical components
- **Control:** Focused on the design, testing and implementation of the exoskeleton's software components
- **Management:** Focused on the project management techniques/processes required to complete the project on time and to an acceptable level of quality
- **Deliverables:** Any and all of the assessable items required by the honours project course

Each of these primary systems were broken down into several subsystems as seen in figure 1 below.

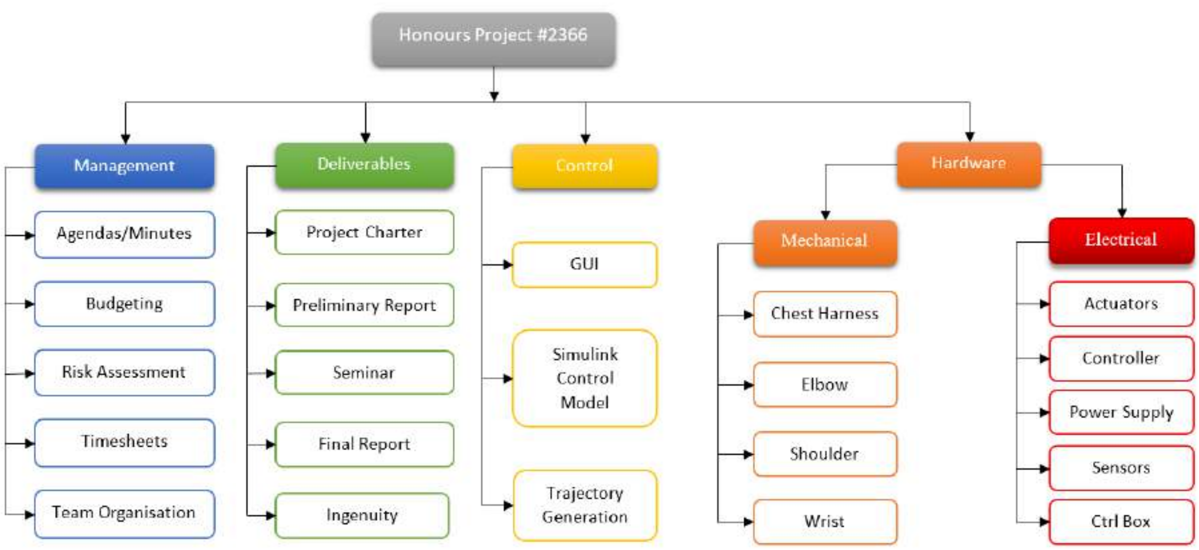

Figure 1: Systems Engineering Breakdown Flowchart

Additionally systems engineering techniques were utilised to assign specific roles to each of the REFAUM team members, these roles included:

- Project/Electronic System Manager - Adam

- Mechanical System Manager - Theodore
- Control System Manager - Riley
- Ergonomics Design Manager - Edmund

This made the allocation of work much simpler, as tasks could be directly assigned to the team member best suited to complete them. From there the team member in charge could either complete the work themselves or allocate resources in such a way that made sure the task was completed. This is essentially how tasks were allocated throughout the work breakdown structure in appendix C of this report. It should be noted that several tasks throughout the work breakdown structure were assigned multiple team members to complete them. This decision was made to increase the chance of successful integration between subsystems, resulting in a higher quality end result.

2.3 Project Timeline

The project timeline consists of two major entities, the Gantt chart and the work break down structure. These project management tools can be found in the appendices section B and C respectively. The Gantt chart is able to provide a visual representation of the major tasks that were completed throughout the year whereas the work breakdown structure is able to breakdown these major tasks into a more detailed list. Since the publication of the preliminary report several changes were made towards the later sections of the project timeline. The most significant of these changes include:

- Construction times for the mechanical and electrical systems were significantly increased due to delays with the workshop. As a result of this REFAUM team members had to take matters into their own hands, constructing all but the pins of the mechanical system by themselves, to make sure that the control system could be tested in time.
- Work on the GUI was started earlier than expected as it turned out that it had an important role to play in the early stages of the electrical and control systems development. Additionally it didn't take long to get an operation GUI running as MATLAB provided several tools to speed up the development process.
- The trajectory generation system was simplified down into two primary tasks. The first of which involved the design of a function that ensured move-sets didn't exceed any of the actuators maximum speed limits. The second task involved creating animations for the move-sets using the robotics toolbox for MATLAB. These animations were seen as a low priority task, only required for demonstration purposes at ingenuity, and were therefore pushed back to the later stages of the project.
- Development on the control system took longer than expected due to complications with the Simulink blocks associated with the Raspberry Pi. Because of this alternative control methods had to be researched and implemented to ensure that the control system worked as intended.

2.4 Risk Assessment

There are two major risk types associated with this project. Project risks and safety risks, each of which can be found in the appendices section D.1 and D.2 respectively.

Project risks have more of a focus towards organisational and management issues and were used to make sure that the project stayed on track and the project goals were accomplished. Since the publication of the preliminary report a major project risk was discovered that wasn't considered during the initial stages of the project. The risk in question, R011, involved the workshop and the possibility that they could be severely delayed due to other projects and priorities. In the Gantt chart two months were allocated for the construction of the mechanical system. This value turned out to be too short as the workshop wasn't ready to start working on the REFAUM project until week 8 of semester 2. Because it was no longer possible to mitigate this risk a compromise had to be made. That compromise involved making the REFAUM team members responsible for the construction of both the mechanical and electrical systems of the exoskeleton. This resulted in other delays throughout the project and was the leading factor towards why the extension goal wasn't considered this year.

In addition to the project risks, considerations also had to be made towards the safety risks involved with the project. These safety risks primarily related to the construction/testing of the exoskeletons mechanical and electrical systems. Two different forms of risk assessment, relating to safety measures, were conducted: A hazard management - risk assessment (long form) and a hazard management - safe operating procedure form. Both of these forms can be found in the appendices section D.2.1 and D.2.2 respectively. The hazard management - risk assessment form was used to consider the different types of safety risks involved with building and testing the electrical and mechanical systems of the exoskeleton. Some of the identified risks include:

- Potential to get small electric shocks from the electrical system
- Possible back strain when wearing the exoskeleton for too long due to its weight
- Injuries from motors trying to bend limbs the wrong way
- Possibility of getting pinched or stuck in moving/rotating parts of the exoskeleton

Once these safety risks were identified the appropriate mitigation strategies were put in place to make sure they either couldn't happen or at the very least were unlikely to happen. On the other hand the hazard management - safe operating procedure form focused on explaining the exact steps that should be taken to operate the REFAUM system properly and was required for Ingenuity demonstrations. This year the safe operating procedure form only covered the steps to operate the REFAUM system without a user, as more thorough safety testing techniques are required before a user can get involved.

2.5 Budget

The projects budget consists of three different cost types; Direct, in-kind and salary costs. Direct Costs involve expenditures made from the initial $800 donated by the University of Adelaide and include purchases relating to the mechanical and electrical components required to build the exoskeleton. The in-kind project costs relate to all of the items used throughout the duration of the project that were provided for free either by the University of Adelaide or REFAUM team members. Finally, the salary costs which include the theoretical wages of the REFAUM team members as well as the mechanical engineering workshop staff that assisted with the construction of the exoskeleton. A summary of the final budget can be found in table 2 below, for more detailed information relating to the individual expenditures made please refer to the appendices section E.

Source	**Income/Expenditure**
University of Adelaide Contribution	+$800.00
Direct Costs	-$771.52
In-Kind Costs*	-$720.00
Salary Costs*	-$110,700.00
Remaining Funds:	$28.48

Table 2: REFAUM - Final Budget as of October 27th, 2017

Note: * Doesn't count towards the final cost of the project

Overall the initial budget of $800 was able to fund the mechanical and electrical systems to the point where one powered and one unpowered exoskeleton arm could be constructed. Future projects should focus their budget towards powering the second arm in addition to reducing the weight of the overall system.

3 Literature Review

A literature review was carried out to draw from existing knowledge in order to determine the overall specifications and requirements of the project. The review itself is broken down into two sections. Section one focuses on finding the range of motion and human size information required to base the mechanical design off of, as well as finding the torque requirements required for the selection of the actuators in the electrical system. On the other hand, section two focuses on investigating previous exoskeleton projects to gain some knowledge in the area and find out how to better approach the different aspects of design. Hopefully this will help with future integration between projects.

3.1 Human Kinematics & Dynamics

The specifications and requirements for the different systems of the REFAUM project were determined from research into several different forms of literature. The primary focus of this research revolved around finding out how many degrees-of-freedom were required to best replicate the human upper body workspace as well as the force required to do so. Additionally, human sizes were researched to assist with the design for adjustability in the mechanical system.

3.1.1 Degrees of Freedom

The REFAUM is to extend from the user's shoulder down to their wrist. Therefore, the movement of the human shoulder, elbow and wrist joints must be investigated in more detail. The shoulder is one of the most complex joints in the human body, allowing for both rotational and translational motion in almost every direction (Tondu 2007). For the purposes of this project only the rotational motions of the shoulder will be considered, and thus the joint is simplified to a ball and socket joint allowing three degrees of freedom; Pitch, yaw and roll (Sing 2016). The elbow can be modelled as a simple hinge joint, and thus will only require one degree of freedom: Pitch (Sing 2016). Similar to the simplified model of the shoulder the wrist contains three degrees-of-freedom: Pitch, yaw and roll (Sing 2016). As this project only cares about designing and building an upper body exoskeleton only the wrist roll will be considered as it effects the orientation of the user's forearm. Adding up the movements of all the joints results in a five degree-of-freedom kinematic model of the human arm. To achieve a sufficient level of upper body motion the REFAUM system must be able to replicate this model's movement. Naming conventions for each of the degrees-of-freedom can be seen in the appendices section F of the report.

With reference to figure 2 the axis for each DOF will be represented throughout the report as:

- Axis 1: Shoulder Pitch, y-axis: + Flexion, - Extension
- Axis 2: Shoulder Yaw, x-axis: + Abduction, - Adduction
- Axis 3: Shoulder Roll, z-axis: + Internal Rotation, - External Rotation
- Axis 4: Elbow Pitch, y-axis: + Elbow Flexion , - Elbow Extension
- Axis 5: Wrist Roll, z-axis: + Pronation, - Supination

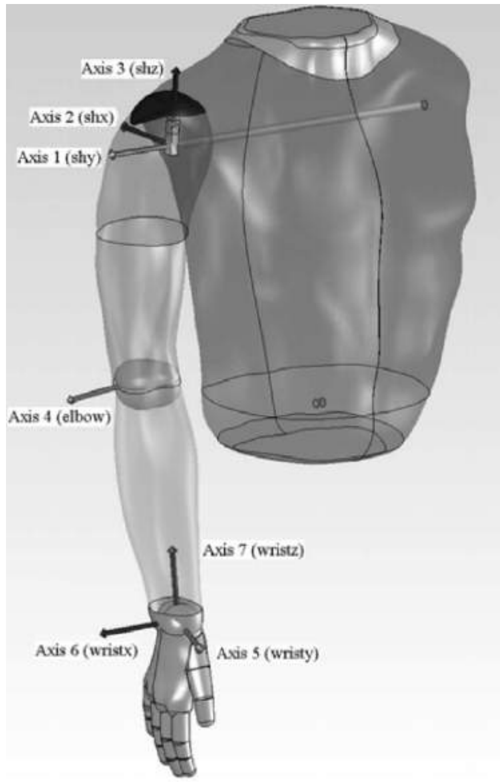

Figure 2: D.O.F Axis Locations (Perry et al. 2007, p.409)

3.1.2 Range of Motion

In order to select appropriate sensors for the exoskeleton and to determine where mechanical safety stops should be implemented, a firm understanding of how the human body moves was needed, or more specifically the ranges it can move in. A research paper titled "Upper-Limb Powered Exoskeleton Design", written by Perry et al. (2007, pp.408-410), contained a study relating to the angular motions and torque experienced by the average human during every day activities. In this study the subject performed nineteen different daily activities, ranging from eating/drinking all the way to hygiene related activities. The results were recorded and are shown below in figure 3:

After analysing these results, the key angles were determined regarding the minimum and maximum angles experienced in daily activities for each DOF. These values along with the full range capabilities of the joints have been tabulated in table 3.

Joint	**Daily Range (deg)**	**Full Range (deg)**
Shoulder Yaw: x-axis	-20 to 140	-20 to 150
Shoulder Pitch: y-axis	-20 to 80	-20 to 180
Shoulder Roll: z-axis	-60 to 80	-60 to 80
Elbow Pitch: y-axis	0 to 150	0 to 150
Wrist Roll: z-axis	-80 to 80	-80 to 80

Table 3: Range Summary

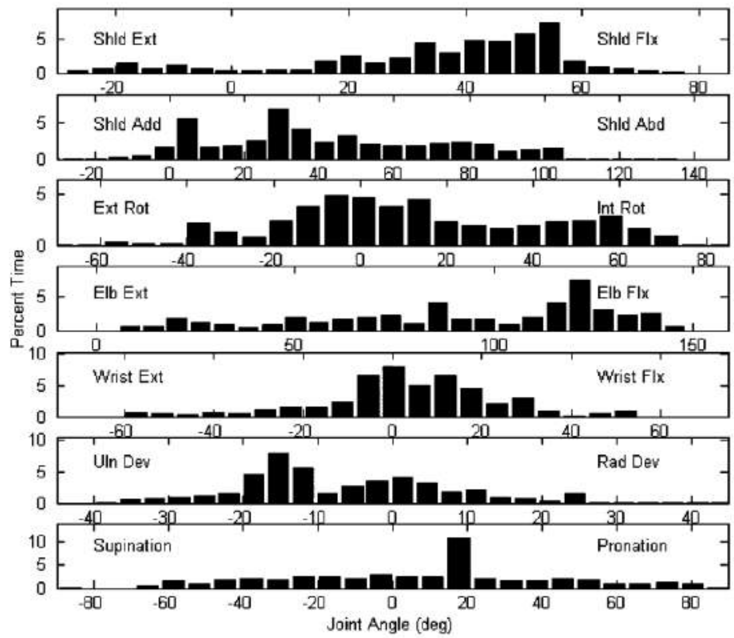

Figure 3: Joint Angles Chart (Perry et al. 2007, p.409)

For this project the REFAUM system will focus on attempting the replicate the minimum and maximum ranges discussed in the daily range section above. Some joints may extend capabilities slightly to the full range, however for safety reasons these values will not be exceeded.

3.1.3 Required Torque

When selecting the actuators for the exoskeleton's electrical system considerations had to be made towards the torque they had to output. This was accomplished using the additional data collected from the "Upper-Limb Powered Exoskeleton Design" research paper in relation to the torques required to perform the daily activities carried out in their experiment, seen in figure 4. The maximum torques for each degree-of-freedom used in the REFAUM project were extracted from this data and collated onto table 4. Required torques for the electrical system's actuators, or motors, were then selected to be around twice the values found form the experiment. This would hopefully allow the actuators to lift not only the users limbs but also the weight of the actual exoskeleton.

Joint	Max Daily Torque (Nm)	Required Motor Torques(Nm)
Shoulder Yaw: x-axis	10	20
Shoulder Pitch: y-axis	10	20
Shoulder Roll: z-axis	3.5	7
Elbow Pitch: y-axis	3.5	7
Wrist Roll: z-axis	0.04	0.1

Table 4: Torque Summary

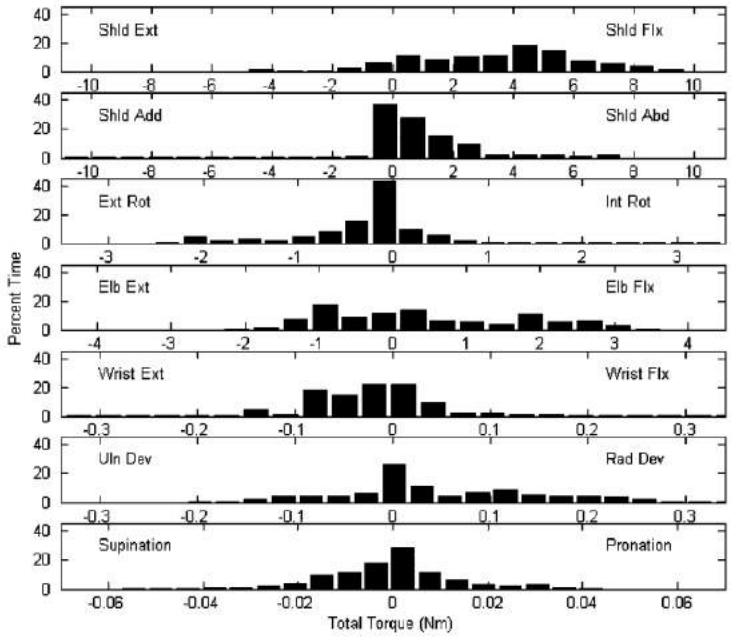

Figure 4: Torque Chart (Perry et al. 2007, p.409)

3.1.4 Anthropometric Data

In order to fulfil the modular design requirement of G2, human sizes had to be taken into account. For this purpose, research was conducted into anthropometric data to allow the modular limbs of the mechanical system to fit as much of the population as possible. More specificity a NASA Anthropometry and Biomechanics study was investigated to determine the required centroid positions of the exoskeletons adjustable limb segments. The data relating to this study can be found in the appendices section G.

3.2 Existing Exoskeleton Projects

Throughout the process of the literature review several projects were found that dealt with both upper and lower body exoskeletons. These were read through extensively to find aspects that could help with the design process of the REFAUM system. The two main things that were found include: Upper body exoskeleton papers which were read to help with design ideas and quantify the REFAUM project's goals, and previous exoskeleton projects conducted at the University of Adelaide which helped with some of the control aspects of the suit.

A 2012 report out of the University of Essex "Upper Body Rehabilitation: A Survey" by James Cannan and Huosheng Hu provided an excellent summary of rehabilitative upper body exoskeletons. This paper suggested that repetitive mechanical actions were an ideal way to assist in upper limb rehabilitation, and listed several examples of exoskeletons being used in this way including providing assisted motion, and mirrored motion between arms. Other examples of exoskeletons were also found which were used to increase a user's strength or provide slight motion assistance. In assessing these for design ideas none were found to completely encompass the aims for this project; that is an exoskeleton capable of five degrees of assisted motion that is also wearable, portable and affordable. The designs that were found generally fell into one of two categories: Those such as the "ARMin Eobotic Exoskeleton" (Cannan & Hu 2012) depicted in figure 5 which provide five degrees of fully assisted freedom, however are quite large and are not able to be worn, and projects such as the "Titan Arm" (Barat 2013) shown in figure 6 which are fully portably and wearable, however only provide assistance to a limited number of degrees-of-freedom. The designs for both of these exoskeletons were examined to help further the development of the mechanical system.

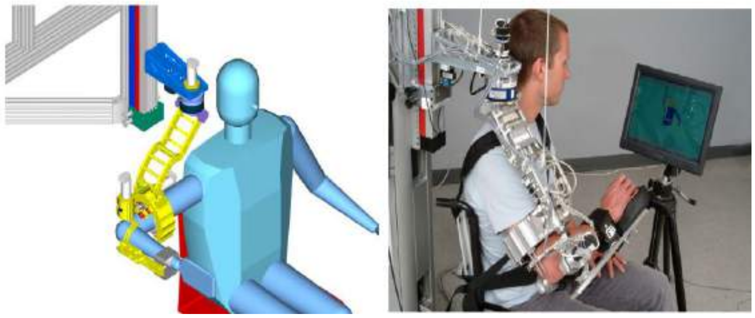

Figure 5: ARMin Eobotic Exoskeleton (Cannan & Hu 2012)

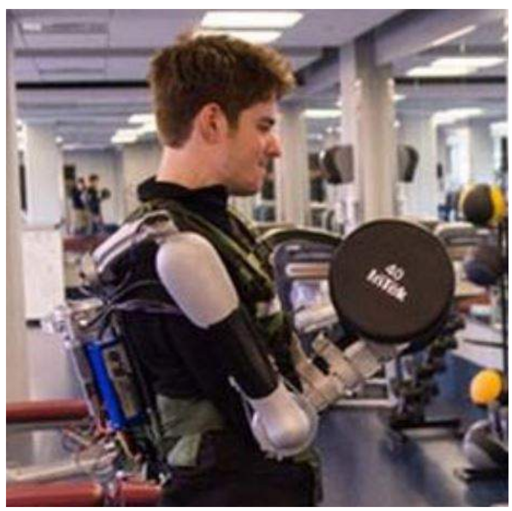

Figure 6: Titan Arm (Barat 2013)

In 2016 the honours project #2045: "Lower Body Exoskeleton - Ready For Production" was conducted. The project aimed to continue the development of a lower body exoskeleton that had been previously designed for child rehabilitation (Gabrielli et al. 2016, pp.1-5). This involved modifying previously constructed mechanical systems as well as designing an entirely new control system. The literature review on this project focused on the control and electronics systems designed within this project, more specifically how the creators went about selecting the hardware components and the control methodologies used throughout it.

In section 8 of the report Gabrielli et al. (2016, p.65) describe the different hardware components required to measure angular position, velocity, motor current as well as control the overall system. Rotational potentiometers were coupled with the actuator shafts to measure the angular position of each of the exoskeletons joints. Rotational encoders or hall effect sensors were used to measure the angular velocity of each of the exoskeletons joints. Hardware associated with the motor drivers were able to provide information on the amount of current drawn from each motor. Two Arduino Due micro-controllers were used to control all of the hardware components. One was known as the main controller and executed the Simulink control program associated with the exoskeleton. The other was known as the auxiliary controller and took care of the C code responsible for controlling the spasm detection program. Together these controllers are able to accept incoming information from the trajectory generation system to control the walking pattern of the exoskeleton. In hindsight Gabrielli et al. (2016, p.89) would have preferred to use a more powerful micro-controller to control the system rather than using two separated Arduino Dues.

Several different control methodologies were investigated including PID, State space and neural networks (Gabrielli et al. 2016, p.66). Ultimately PID control was selected, primarily due to that fact that it didn't require much computing power allowing it to be utilised by the Arduino Due micro-controllers. While PID control does lack robustness, due to its simplistic design, it does have some redeeming qualities as it is relatively easy to tune and construct (Gabrielli et al. 2016, pp.69). In the future work section of the report Gabrielli et al. (2016, p.89) express their desires to use state space control over the previously implemented PID control. This would allow them to utilise coupled dynamic equations to potentially obtain more accurate and personalised results.

3.3 Summary

Overall the literature review provided an excellent starting point for the designs of all three primary REFAUM systems. The torques and angular limits allow for specifications to be decided upon for motors and help to dictate some of the requirements for the mechanical design. The anthropometric data is used throughout the mechanical design to ensure that the system is able to fit a wide variety of users. The review conducted into upper body exoskeletons has provided a starting point for designing the mechanical system. Finally, lessons learned from the previous lower body exoskeleton honours project have helped guide the selection of the components used in the electrical system.

4 Electrical System

The exoskeleton's electrical system acts as a bridge between the mechanical and control systems. It relays information about the current orientation of the exoskeletons joints to the control system through the use of sensors. The control system compares this orientation to a reference position designated by the currently loaded move-set, and sends the appropriate control signals back to the electrical system. The electrical system uses these control signals to power the actuators connected to the mechanical system in turn moving the exoskeletons limbs.

This section of the report will delve deeper into the individual components the electrical system consists of. In particular:

- **The Sensor Components:** Used to measure the angular position of the exoskeletons joints
- **The Actuator Components:** Used to control the angular speed and direction of the exoskeletons joints
- **The Controller Components:** Used to integrate all of the electrical components and provide communication with the control system
- **The Control Box:** Used to safely house all of the electrical components on the back of the mechanical system

4.1 Sensor Components

The sensor components primarily consist of the ten individual linear potentiometers used to measure the angular position of each of the exoskeletons joints. Each potentiometer is mechanically coupled to one of these joints, either directly or indirectly through the use of gears. Depending on its position each potentiometer outputs a different voltage to the controller which can be converted to an angular position through the use of equation 1:

$$Angular\_Position = 83.414 \times Voltage + 11.697 \tag{1}$$

This equation was determined from a test involving a linear potentiometer mounted on a protractor. The potentiometer was turned in 45 degree increments and the corresponding voltage was recorded, the results are shown in figure 7. Inspection of this graph proves that the linear potentiometers are indeed linear, at least for the most part. The line of best fit does vary for some points on the graph and as result an error or around +-3% can be expected on average. The linear potentiometers also have a dead zone, of around 11 degrees, as indicated by the fact that the y-intercept doesn't coincide with the origin. Because of this the potentiometers were offset when attached to the exoskeletons joints to ensure that the dead zone would never be reached.

In terms of the linear potentiometers overall performance they do extremely well for their cost. They provide a turning radius or around 260 degrees, once you take into account the dead zone, which is enough to handle the maximum angular movement produced by one of the exoskeletons joints (200 degrees for the shoulder pitch). Additionally, an accuracy or around +-3% is satisfactory for this project as the exoskeleton is a prototype and the budget was limited.

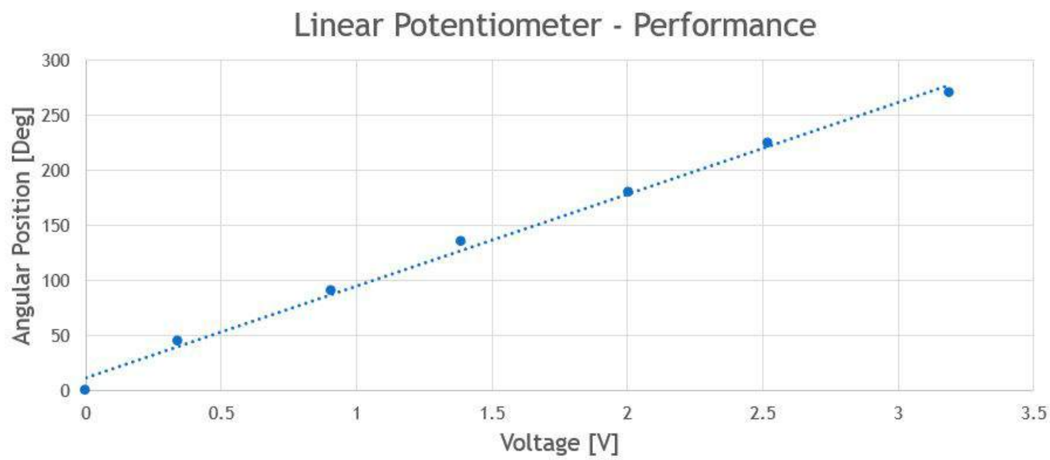

Figure 7: Results from linear potentiometer test

4.2 Actuator Components

The actuator components consist of the DC motors and motor controllers used to power the exoskeletons joints. Ideally servo motors would have been utilised as they would have worked as the actuator and sensor components of the electrical system. However they could not be used due to the projects limited budget and therefore DC motors were selected as an alternative solution.

4.2.1 DC Motors

In the literature review the maximum torque required to move each of the exoskeletons joints was discovered. Each of these maximum torque values were doubled when looking for the specific DC motors to power each of the exoskeletons joints. This was done to make sure that the DC motors selected could lift the user's limbs as well as the weight of the exoskeleton itself. Overall three different 12V DC motors had to be selected due to the differing torque requirements:

- **Large Motor:** Speed = 7RPM, Torque = 32Nm, Stall Current = 5.89A
- **Medium Motor:** Speed = 15RPM, Torque = 6Nm, Stall Current = 1.6A
- **Small Motor:** Speed = 30RPM, Torque = 0.4Nm, Stall Current = 0.466A

Each of the motors have a gear box attached to them in order trade off speed for torque, which is a more desired trait for this project. In addition to reducing the maximum speed of each motor, which is good for safety, this also means that weaker motors can be used to provide the required torque therefore saving money.

4.2.2 Motor Controllers

DC motors might be able to output a good torque for their price but they come with a drawback. They are either on or off, clockwise or counter clockwise, there is no default way to control them. Therefore, motor controllers are required to give the control system the ability to change the speed and direction of the motors. Overall due to the differing max current requirements of the three motors two separate motor controllers were selected:

- L298n Dual H-Bridge DC Motor Controller: Capable of controlling a single medium sized motor or two small sized ones
- Cytron 13A, 5-25V Single DC Motor Controller: Capable of powering a single large motor

Both of these motor controllers control the motors speed through the use of an H-Bridge and direction through the use of a PWM signal. Further analysis was conducted into the performance of each of the motor controllers through a series of tests involving a single DC motor/controller coupled with a potentiometer. Different PWM values were sent to the motor controllers and the corresponding power output was recorded (Motor Power = Output Voltage/Input Voltage).

The results, as seen in figures 8 & 9, indicate that although the motor controllers work in the same way they have very different performance characteristics. The small motor controller behaves in a logarithmic manner whilst the large motor controller behaves in a linear one. This means that the small motor controller is more sensitive to the initial PWM signals and therefore the control system will have to make sure it accounts for this. More importantly to notice is that both motors won't start until a certain value of the PWM signal is reached (around 9% for the small motor controller and around 6% for the large motor controller). Additionally, the large motor controller is more efficient than the small motor controller, 97% Vs. 85%. Therefore, motors being controlled with the small motor controllers won't be able to reach their maximum power output, a drawback due to the cheap components used.

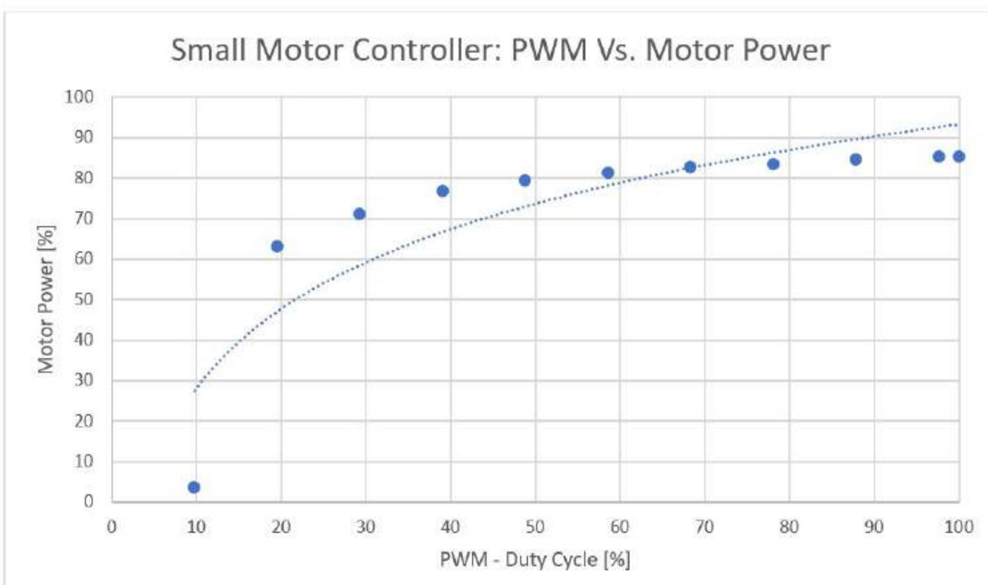

Figure 8: Small motor controller performance

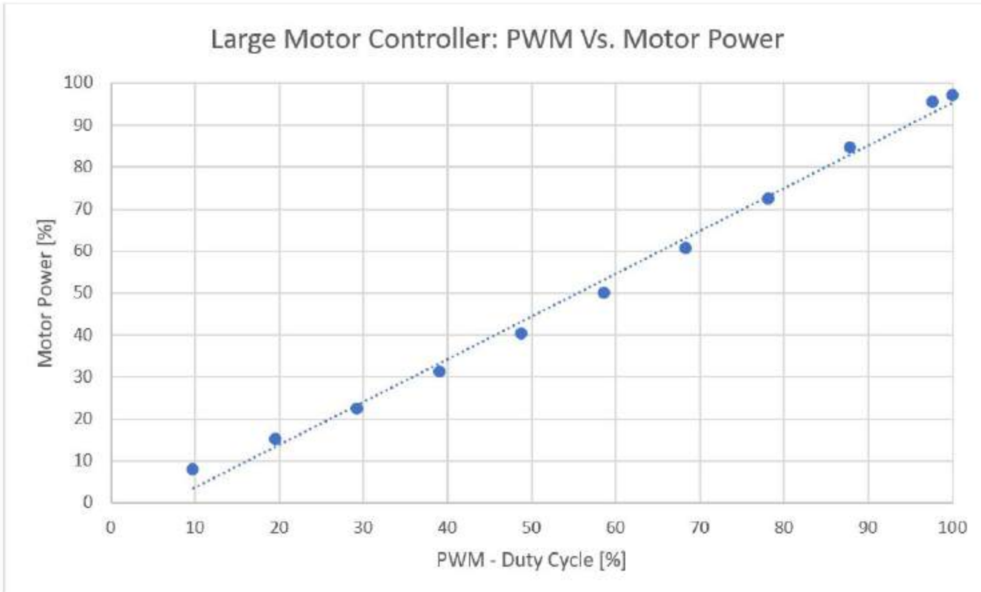

Figure 9: Large motor controller performance

4.3 Controller Components

The controller components consist of the primary controller, ADC and PWM generator required to fully integrate the sensor and actuator components of the electrical system. In addition to providing a means of communication between the electrical and control systems.

4.3.1 Primary Controller

A Raspberry Pi 3 Model B was selected as the primary controller for the electrical system. Research from the literature review, in the preliminary report, indicated that the Raspberry Pi is an upgrade in every way form the controller used in previous years projects, the Arduino Due. The Raspberry Pi boasts:

- A 64bit, Quad core CPU with a clock speed of 1.2GHz and 1GB of internal RAM: Easily capable of running all of the MATLAB code and Simulink programs required from the control system.
- An SD card slot: To store the operating system on as well as additional move-set data if required in the future.
- WI-FI, LAN and Bluetooth connectivity: To allow the Raspberry Pi to easily communicate with the host computer.
- 40 GPIO pins: 17 of which can be programmed for additional purposes such as controlling the direction pins of the motor controllers.
- SPI and I2C buses: That allow additional components to be connected to the Raspberry Pi using a small number of pins.
- DSI Display port: Which could be used in future projects to replace the host computer and GUI with a touch screen display mounted on the right wrist.

In particular the SPI and I2C buses were extremely useful, as additional components such as the ADC and PWM generator were required to enable the Raspberry Pi to communicate with the sensor and actuator components of the electrical system.

4.3.2 ADC

The Raspberry Pi only deals with digital inputs and outputs. Therefore, in order for the Raspberry Pi to read the analogue signals from the linear potentiometers an analogue to digital converter or ADC is required. There are a total of ten analogue signals that need to be converted, five for each arm, and because of this two MCP3008 ADC chips were used. Each of these chips has the capability of converting 8 separate analogue signals through the SPI bus on the Raspberry Pi.

- ADC_1: CE1 - The first ADC chip runs through the second chip select pin of the Raspberry Pi's SPI bus and reads the input from the right arm of the exoskeleton.
- ADC_2: CE0 - The second ADC chip runs through the first chip select pin of the Raspberry Pi's SPI bus and reads the input from the left arm of the exoskeleton.

4.3.3 PWM Generator

The Raspberry Pi is capable of generating the PWM signals required for the motor controllers although they are what is known as software PWM signals. Each software PWM signal would take up some of the Raspberry Pi's processing power in addition to one of the GPIO pins. Because most of the GPIO pins are used to control the direction of the motor controllers and software PWM signals are generally less reliable then hardware PWM signals a PWM generator was used as an alternate solution. In particular the Adafruit PCA9685 PWM Driver was selected, a PWM generator capable of supplying sixteen individual PWM signals over one of the Raspberry Pi's I2C buses. The libraries for the chip were originally written in python for Arduino products so they had to be rewritten in MATLAB code in order to ensure compatibility with the Raspberry Pi. The rewritten functions can be found in the appendices section H and include:

- i2cpwm_init.m: Sets up the initial I2C connection between the PWM generator and the Raspberry Pi.
- i2cpwm_freq.m: Sets the frequency at which the PWM Generator operates at.
- i2cpwm_set.m: Sets the specific PWM duty cycle for each of the 16 channels. Used to control the speed of each of the motors.

4.4 Final Design

The schematic diagram for the electrical system can be seen below in figure 10. It contains all of the sensor, actuator and controller components that make up the electrical system and shows how they interact with one another. This year the electrical system only powers the right arm of the exoskeleton due to budget restrictions.

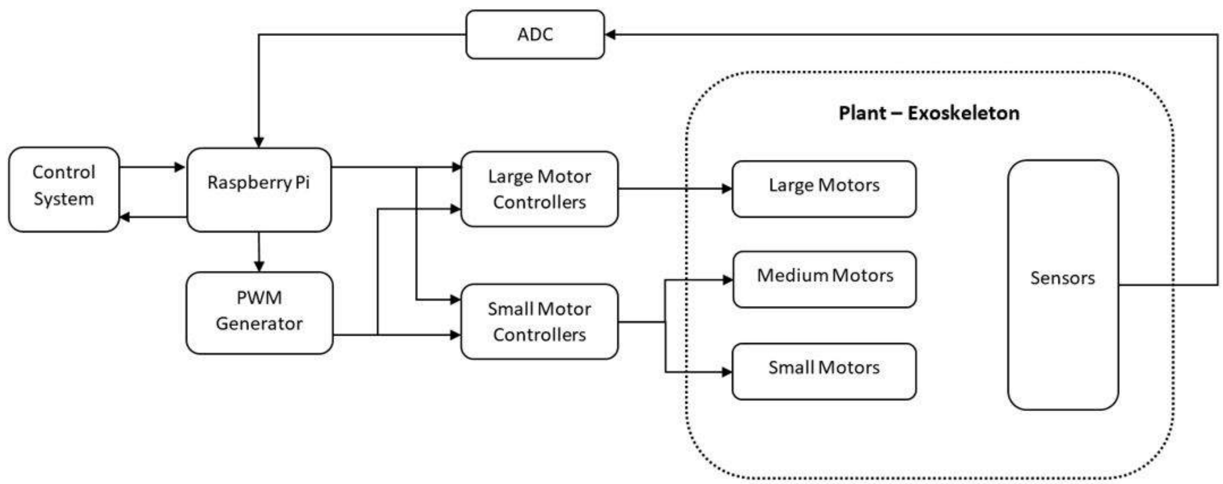

Figure 10: Schematic Diagram of the Electrical System

The electrical system has two different circuits it has to consider when it comes to power management. The 12V actuator circuit, which consists of the DC motors and their respective controllers, and the 5V logic circuit, which consists of the Raspberry Pi, ADC and PWM generator. This year an external 13.8V, 20A switch mode power supply was used as a temporary solution for the prototype build. Ideally the suit will run off of battery power in the future to allow the exoskeleton to be fully mobile.

In order to control the power to the exoskeleton a 25A DC toggle switch was included. Once the 13.8V DC power rail reaches the electrical system it is split up, using several terminal blocks, to allow the power to be routed to all of the actuator components. The 13.8V rail also indirectly powers the logic circuit through the use of a DC buck converter which reduces the 13.8V down to a suitable level of 5V. Under normal operating conditions the electrical system is expected to draw around 7-9A and under maximum load (i.e. all motors are stalled) 15-17A. This means that the temporary power supply can easily provide power to one of the exoskeletons limbs and maybe even both of them, under normal operating conditions.

4.5 Control Box

The control box, shown in figure 11, was designed and built to ensure that the electrical system could be safely mounted on the back of the mechanical system. It is made out of acrylic and takes the form of a U shape to ensure that the large bolt on the back of the mechanical section doesn't interfere with it. Some of the boxes features include:

- I/O shields that provide easy access to the potentiometers and DC jacks that power the motors.
- Easy access to the Raspberry Pi's USB and Ethernet ports.
- Fans on all sides of the box. The right and left fans bring air into the box cooling down the heat sinks of the motor controllers whilst the top and bottom fans extract the air through the bottom of the box.
- All of the sensor, actuator and control components are mounted on a modular floor that can be removed for easy maintenance.
- The user has access to the on/off toggle switch on the left side of the box. The side of the exoskeleton that will be free to move as no motors are attached to it.

Figure 11: The Electrical System's Control Box

For more information relating to the construction and internal configuration/wiring of the control box please refer to the appendices section M.1 & J of this report.

4.6 Summary

Overall the electrical system does what is required of it and ticks off most of the boxes for project goals 3, 4 and 6. It can relay the information about the position of the exoskeletons joints to the control system and apply the appropriate force back to the limbs of the mechanical system. Due to budget restrictions the additional motors/controllers required to power the left arm were not included in the 2017 electrical system but they were considered. This means that future projects should only have to buy the missing pieces to power the left arm. The only complication with this might be the power supply which might have to be reworked to provide power for both of the arms. Although only one arm was able to be powered this year the electrical system is still fully capable and able to display the intended functions of the 2017 REFAUM project making it a successful prototype system.

5 Mechanical System

The mechanical system covers the physical build of the exoskeleton. The main focus of this system is the ergonomics, dealing with how the REFAUM system will attach to the user, and the modularity, which deals with the designs ability to be adjusted and assembled easily. The design had to be able to achieve all required degrees of freedom, with the ability to connect and detach motors and potentiometers to each joint. This section will lay out the development of this design, in the design embodiment, and discuss what was actually produced, in the final design section.

5.1 Design Embodiment

This section uses systems engineering techniques to break down the REFAUM's mechanical system into smaller subsystems. The process of developing each of these subsystems will be laid out, including the evaluations made leading up to the final design. Each subsystem has slightly differing design criteria, however most were evaluated based on price, weight, safety, and simplicity. It was decided that each degree-of-freedom, along with the chest mount, could be considered as a separate subsystem. Thus, the individual subsystems of the mechanical system include: The wrist, elbow, upper arm, shoulder, back, and chest mount. More detailed information relating to the individual assembly of these subsystems can be found in the appendices section M.2.

5.1.1 Materials

The materials used for the REFAUM system had to be strong, lightweight, and affordable. For this reason plywood was selected for many of the larger parts, aluminium for connections between joints, and ABS for the more intricate 3D printed components. Two different bearing types were also selected to reduce the friction between moving parts and thus improve the suits capabilities. These were 20mm roller bearings and 20mm thrust bearings. The roller bearings go around shafts or pins to reduce friction between the pin and the hole it is passing through. Whilst the thrust bearings sit between two moving surfaces to reduce the friction between them.

5.1.2 Wrist

For the wrist it was decided that for the purposes of this project, only one degree of freedom would be necessary, thus the wrist mechanism only needed to provide assistance with the roll of the wrist/forearm. As the wrist mechanism is the furthest from the shoulder actuators it has the biggest leaver arm, and hence weight is a very large consideration. Research form the literature review indicated that several other projects achieved this motion by having the user hold the end of the device which would control the motion of the user's wrist. In this project it was decided that the approach should allow hands to be free. To achieve this a gear mechanism was designed to control the rotation of a brace around the users wrist with a very small motor providing power to it, this can be seen in figure 12. 3D printed plastic was used for the brace as it is light and able to be manufactured easily given the complexity of the brace's design. The gears were then water-jet cut from aluminium to allow them to have a high amount of strength given their size. A small system of plastic gears was then used to reduce the speed to be read by the potentiometer.

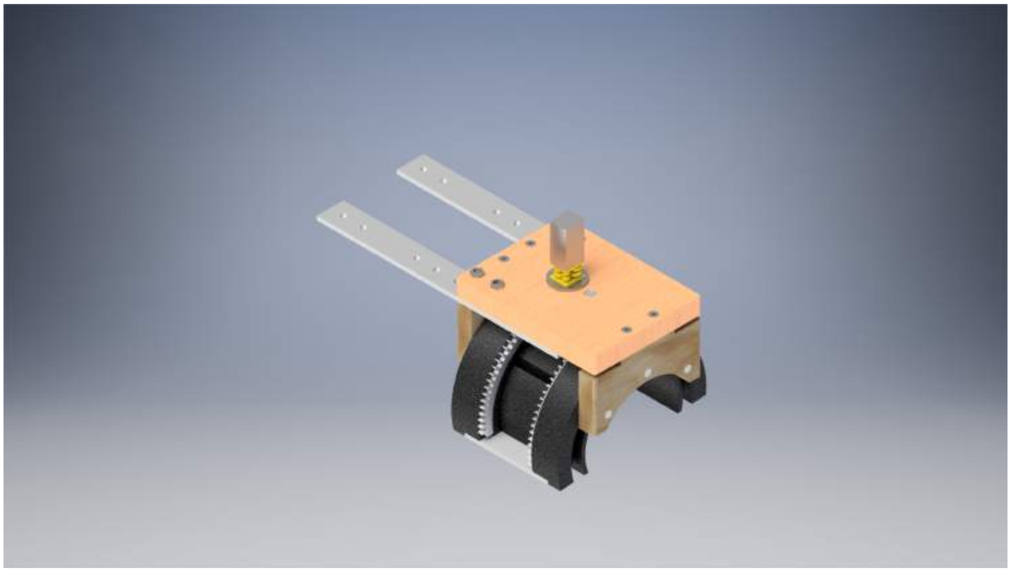

Figure 12: Wrist sub assembly

5.1.3 Elbow

The elbow subsystem consists of only one degree of freedom which could be achieved through the use of a single pin. As the elbow is the central subsystem on the arm it is very crucial for modularity, which is where most of the design effort was focussed. The centre of the elbow consists of two wooden pieces connected by a large pin, with both roller and thrust bearings between them, the motor inserts into this pin and is bolted to the plywood beneath it. Extending from the plywood pieces are lengths of flat aluminium bars, these bars have holes drilled into them to allow for adjustment of the user's forearm and humerus sizes. The overall design is shown in figure 13 below. For safety reasons a mechanical stop was included to make sure the user's elbow can't rotate out of its acceptable limits. To achieve this a slot was made around the main pin, which a small safety bolt could fit into to, stopping the rotation of the joint.

The pin shown in figure 14 was one of the more complex parts to be designed. To ensure modularity and future adjustments it was important that the subsystem was bale to hold itself together without the use of a motor. The top of the pin is larger than the hole to stop it from falling through, the main body is then a 20mm tube. The hole through the middle allows the motors pin to slot in, this is then locked in place by a grub screw. The lower half of the pin has a flattened section to allow it to slot into and rotate a metal locking piece. The whole thing is then clamped together with a large nut screwed onto the end. This same set up is used again later in this section.

The potentiometer was connected to the pin with a 3D printed connecting piece in the shaft. It was then held in place by another piece extending from the safety bolt.

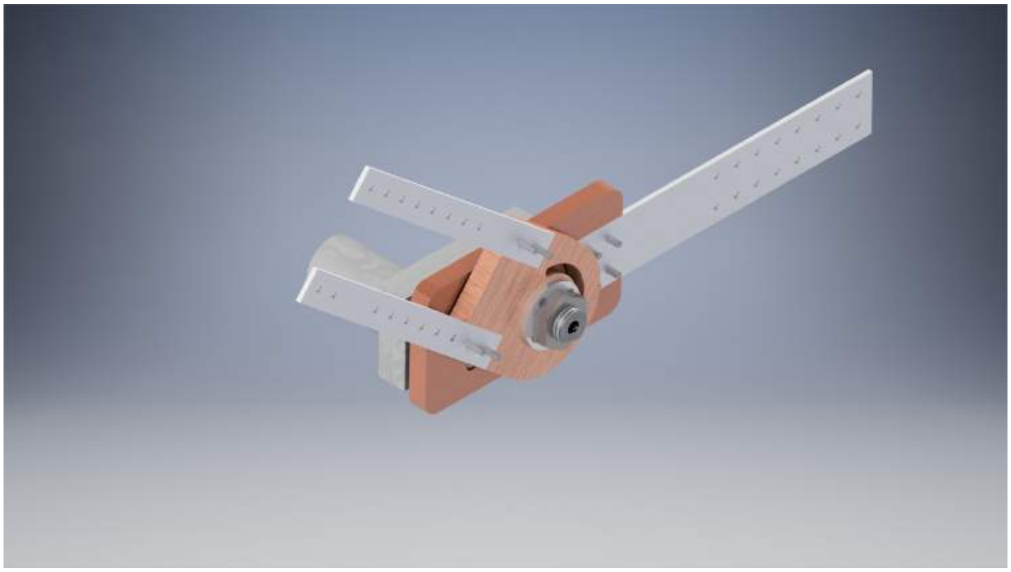

Figure 13: Elbow sub assembly

Figure 14: Elbow pin

5.1.4 Upper Arm

The shoulder joint was broken down into three separate parts in order to achieve the three degrees-of-freedom it required. The upper arm subsystem deals with the roll degree-of-freedom of the shoulder also known as internal and external rotation. The rotational motion for the upper arm was achieved in a similar fashion to what was done with the wrist subsystem, except scaled up. Again a large 3D printed part is used to go around the arm and is rotated by aluminium gears. The main difference is that the upper arm 3D printed part requires a slot to connect to the aluminium rods of the elbow subsystem in order to transfer the rotation through the rest of the exoskeletons arm. This is displayed in figure 15.

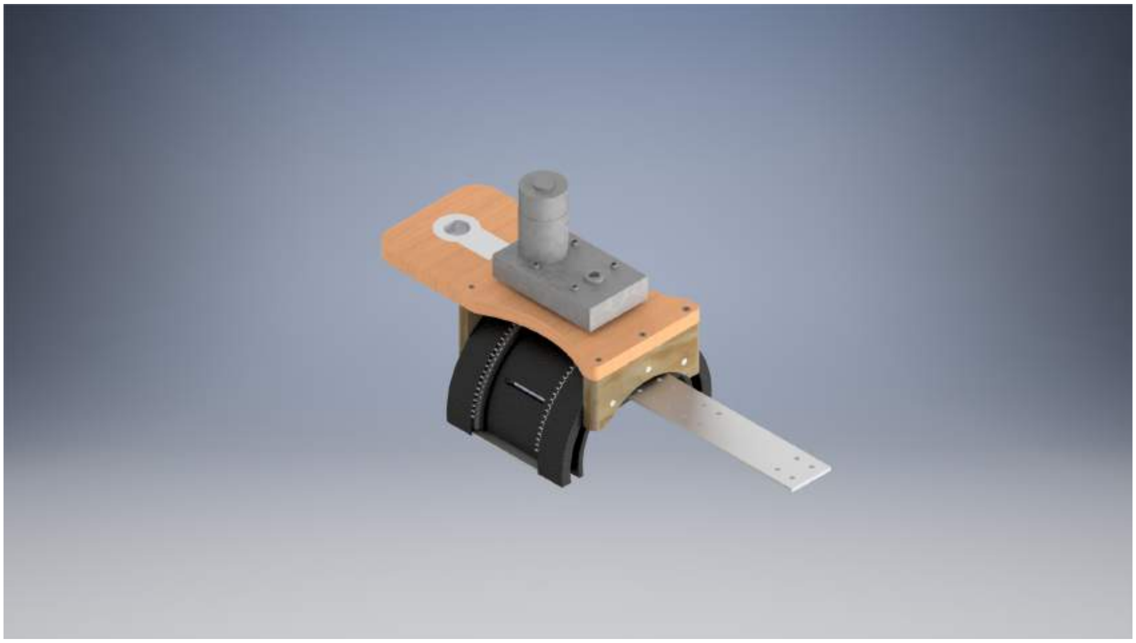

Figure 15: Upper arm sub assembly

5.1.5 Shoulder

The subsystem referred to as the shoulder is in fact just the system that deals with the shoulder's pitch. The motion is achieved through the use of a single large motor connected from a thick piece of plywood to the upper arm subsystem through a similar pin set up as used in the elbow. The motor is mounted such that the pin is in line with the shoulder joint, pointing to it from the side of the body. The shoulder subsystem can be seen in figure 16, and shaped in an L like configuration to connect to the back of the exoskeleton. The aluminium brackets connecting the two parts allow for adjustment by changing where they connect. The safety stops for this system were simplified and work by simply having the rest of the arm collide with the shoulder subsystem when outside of the allowed range. The potentiometer connects to the pin in the same way it does on the elbow subsystem. A 3D printed mount holds the potentiometer in the pin and additional 3D printed supports attach the potentiometer to the plywood.

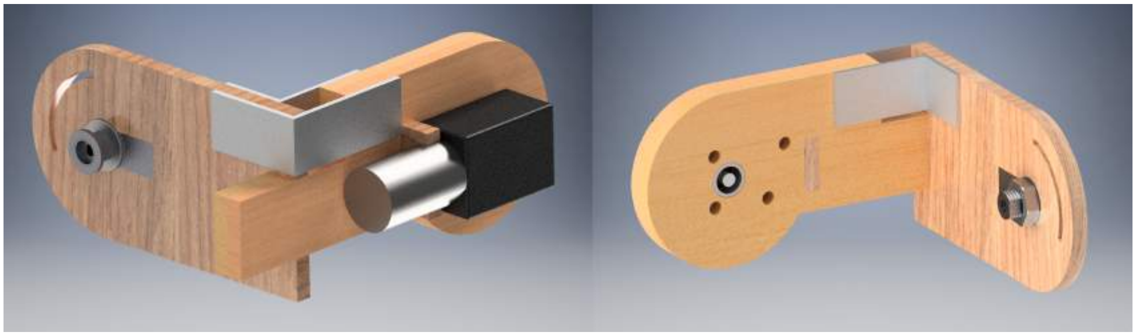

Figure 16: Shoulder sub assembly

5.1.6 Back

The back subsystem deals with the shoulder yaw and is where the final motor is mounted, it can be seen below in figure 17 . This subsystem was designed to be strong as it has to lift the weight of the entire exoskeleton arm. The subsystem works in a similar manner to that of the shoulders pitch subsystem, except it has been rotated by 90 degrees. The safety stop used is the same as in the elbow subsystem, a slot is cut around the pin and a bolt is inserted to restrict motion. The potentiometer is again mounted through the end of the pin and held in place by 3D printed supports.

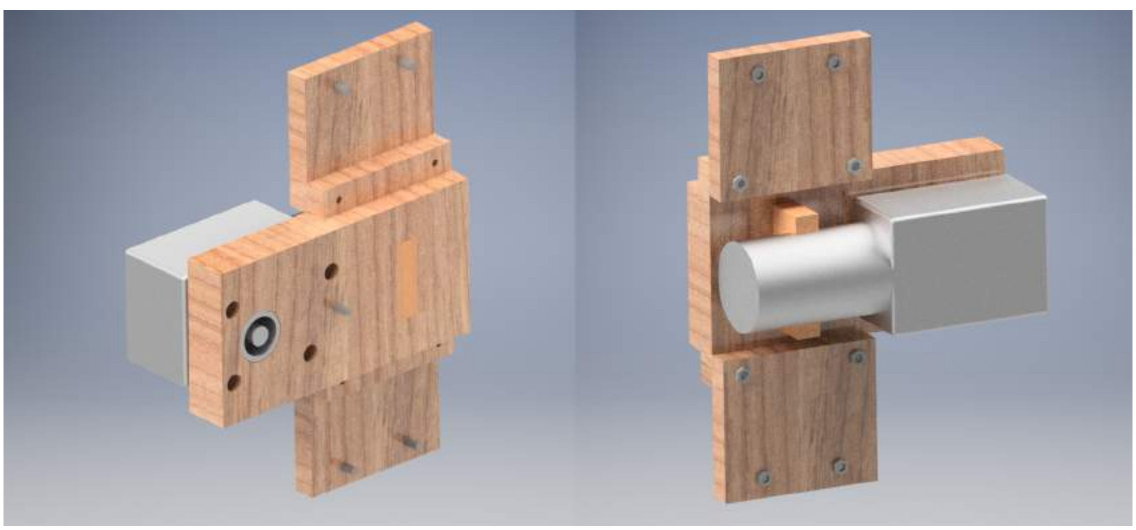

Figure 17: Back motor holder assembly

Figure 18 shows the rest of the back sub system. A large T piece made out of plywood allows the winged motor holder to slot in and be adjusted for differing shoulder widths. Down the bottom of the T piece is a nut mounted in the wood, a large bolt is able to go through this to adjust the distance from the body.

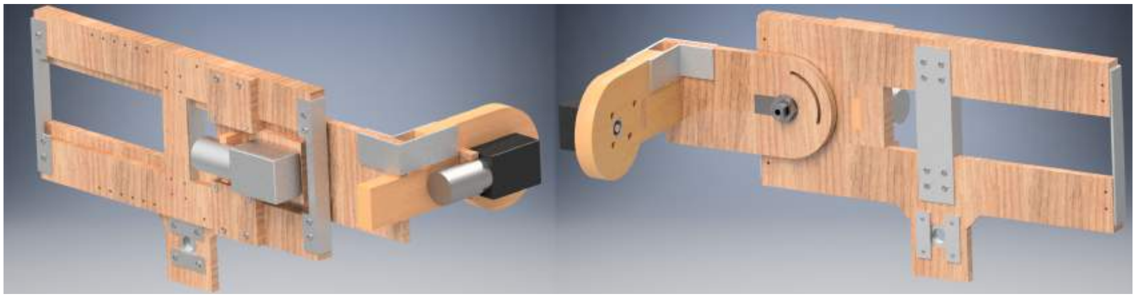

Figure 18: Whole back and shoulder part assembly for only one side (front and back)

5.1.7 Chest Mount

The chest mount subsystem deals with how the exoskeleton mounts onto the user. Strength, comfort and cost were the main considerations taken into account for this subsystem. The initial idea involved the use of an orthopaedic lumbar chest harness imported from China. Research indicated that the harness was to expensive for the projects budget as well as being too small to fit western sized users. Further research was conducted into military vests and chest rigs and the final solution for the chest mount was obtained, a stab proof vest made for air soft applications. Both options can be seen in figure 19. The stab proof plates were replaced with plywood to which the back system was attached to using hinges. This vest itself was made out of nylon and was therefore durable enough to hold the entire weight of the exoskeleton. In terms of comfort the vest does a pretty good job when you consider its cost and how much the actual exoskeleton weights.

Figure 19: Chest Mount Options (Ebay 2017), (Ali Express 2017)

5.1.8 Overall mechanical system

Throughout the entire design, modularity, weight, and cost have been the major considerations for each of the mechanical subsystems. Modularity was made the main focus during the integration between subsystems, to ensure that each of the joints could move smoothly with respect to one another and fit different sized users. Figure 20 shows the overall integration of the sub systems for the exoskeletons right arm. Additionally, all of the subsystems parts were designed symmetrically in accordance with the principles of design for manufacturability and assembly.

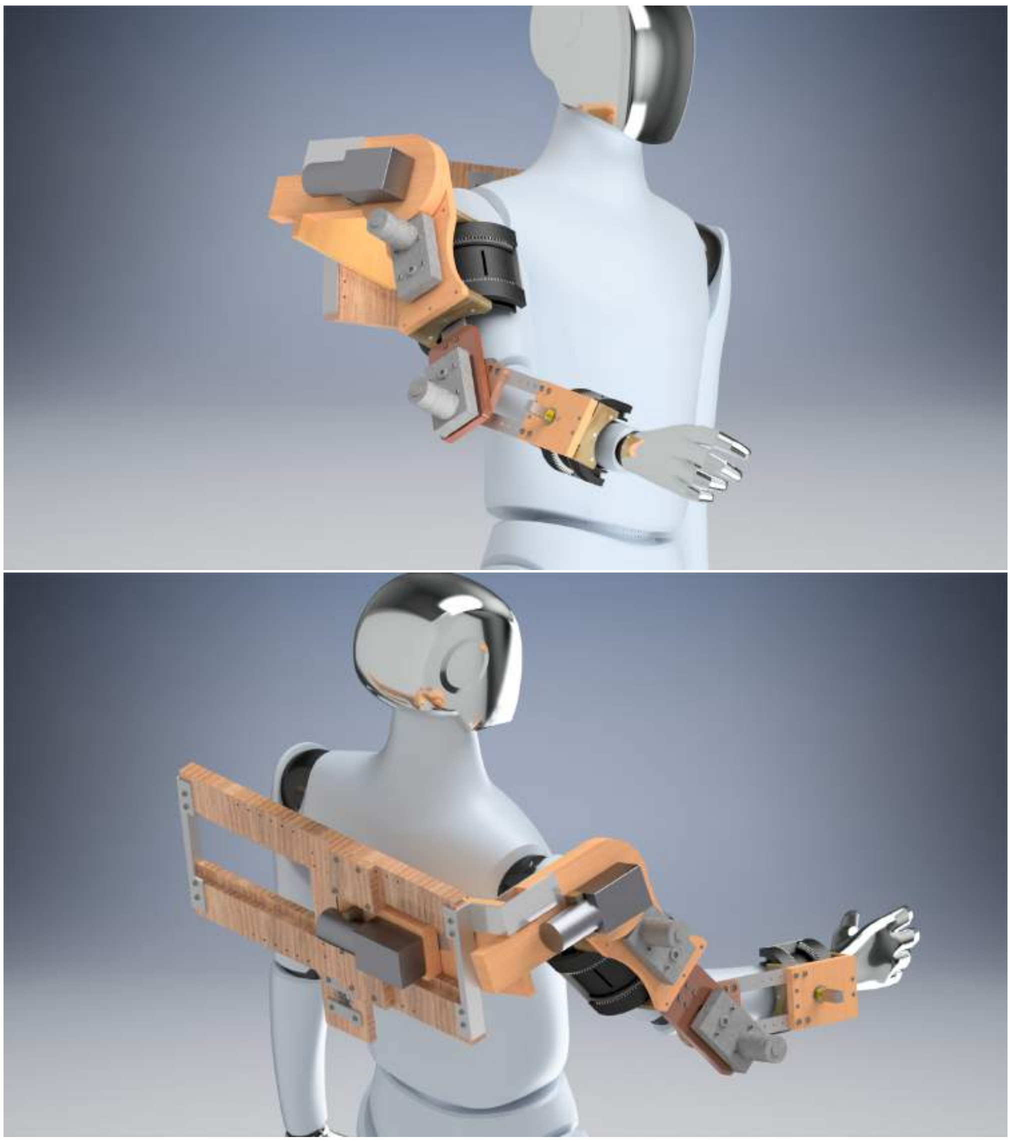

Figure 20: Right arm assembly

5.2 Final Design

This section shall discuss the final design of the mechanical system that has been constructed by the REFAUM team. Including discussions relating to the changes made between the initial design and the final product, as well as briefly outlining some of the manufacturing processes used to create the individual components of the system itself.

5.2.1 Wrist

The wrist was constructed closely following the original design. The brace was 3D printed out of ABS plastic, with the brace's gear printed as part of the piece. The smaller gears which turn the brace were water-jet cut out of 3mm aluminium plate, and the main wooden parts were water-jet cut from 12mm plywood. The pins connecting the motor to the gears were also 3D printed, however they were made bigger in the final design to improve the stability of the gears. The other change made to this subsystem involves the potentiometer mount configuration; rather than using a series of smaller gears, like what was done with the upper arm, a single multi-turn potentiometer was used. Figure 21 shows the final production of the wrist subsystem. To attach the wrist brace to the user a pair of skateboarding wrist guards were purchased, bolts were mounted to these guards to firmly attach them to the 3D printed wrist braces, although these have had some issues with interfering with the wrists' motion.

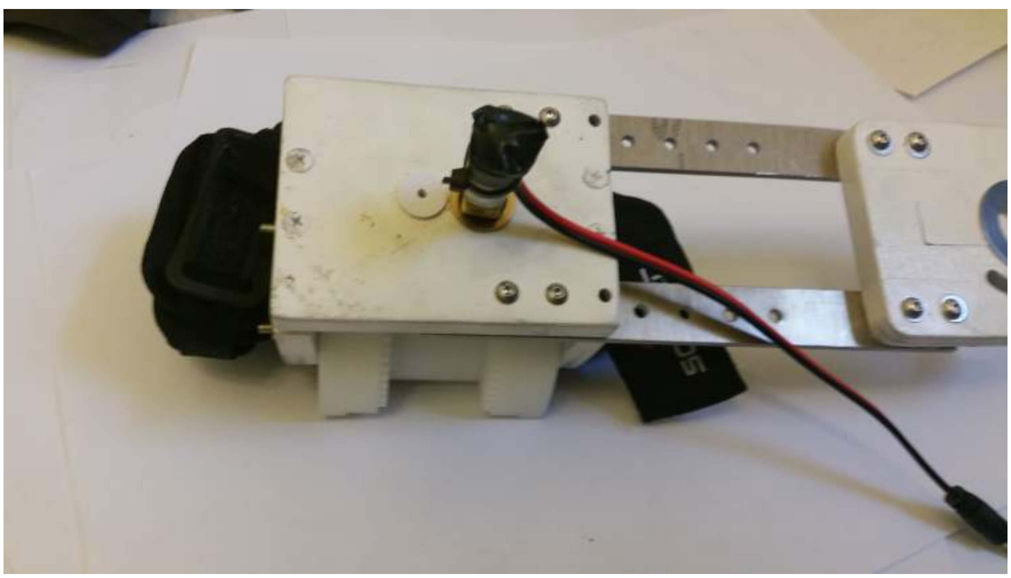

Figure 21: Final Wrist Subsystem

5.2.2 Pins

Every motor used in the project required a pin to connect it to the suit. For the wrist and upper arm systems, the pins could simply be 3D printed as they were not required to be load bearing. The pins for the elbow, shoulder, and back motors needed to be constructed from metal. To achieve this M20 bolts were machined down on the lathe by the workshop. A section was then flattened to the correct size and a grub screw were added to lock onto the motor pin. The result can be seen in figure 22.

Figure 22: Final Pins

5.2.3 Elbow

The elbow design has remained largely unchanged, however through testing with different materials it was found that 3d printed parts were strong enough to be used in place of the plywood. The aluminium connecting rods were then water-jet cut from a 3mm plate of aluminium. This subsystem can be seen in figure 23.

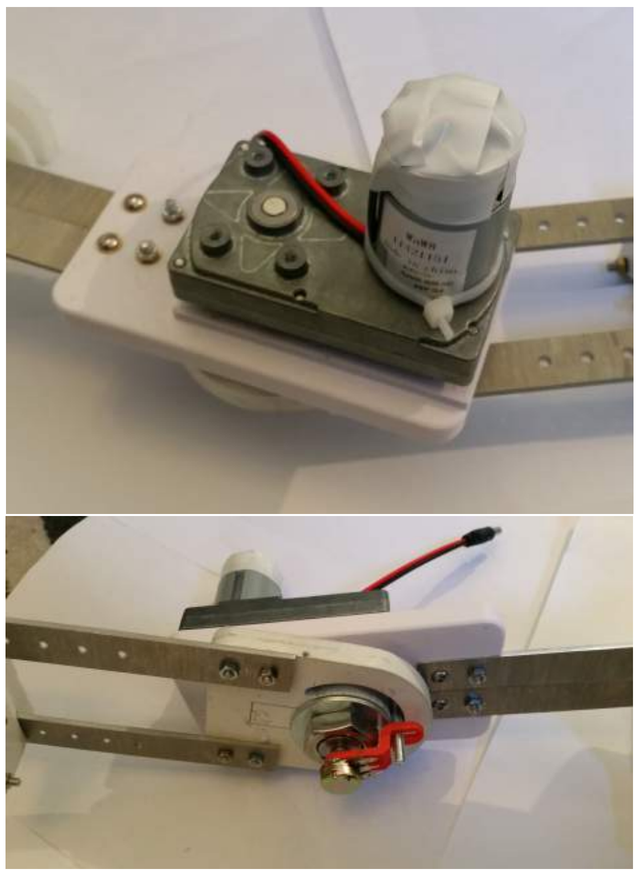

Figure 23: Final Elbow System

5.2.4 Upper Arm

The wooden pieces for the upper arm have been water-jet cut from plywood as planned. The main piece however has had some small redesigns to accommodate the potentiometer around the motor. Figure 24 shows the final upper arm subsystem; gear reduction is used to give the required potentiometer output. The large arm brace has been 3d printed, along with the motor pin and one of the gears. The other gear has been cut from aluminium as it is somewhat load bearing. Having one aluminium and one plastic gear allows the system to be more flexible, and helps to stop the plastic brace from wearing down in cases of jamming. Small stoppers have been placed at the end of the braces rail to limit the motion of the joint. Additionally small bolts were used to allow the brace to roll and were found to be quite effective.

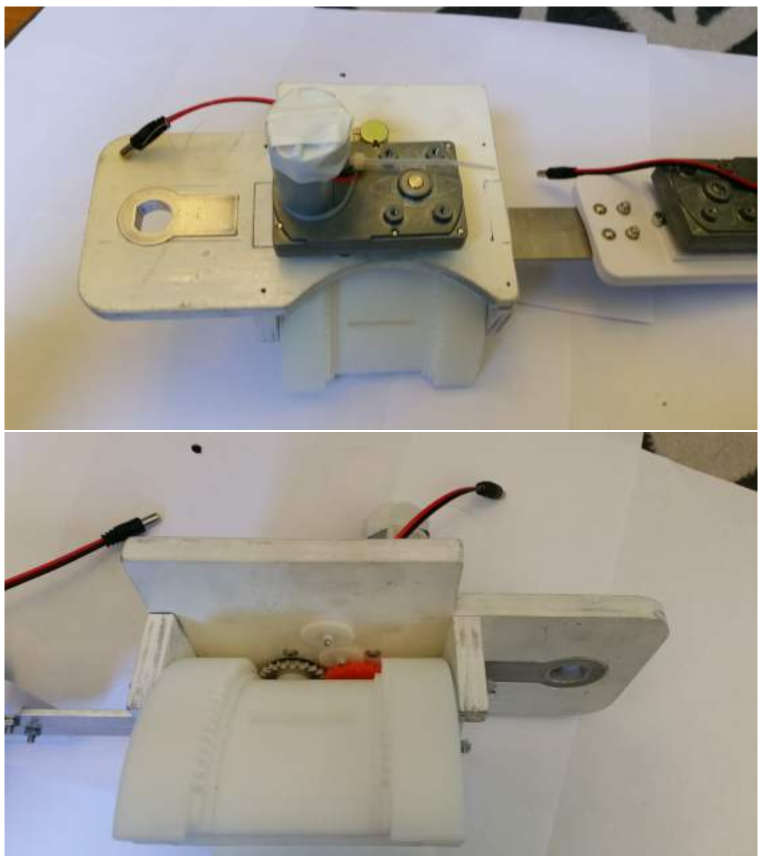

Figure 24: Final Upper Arm System

5.2.5 Shoulder

The final shoulder subsystem can be seen in figure 25, this has remained unchanged since the design embodiment section, and its wooden construction has been completed through the use of the water jet cutter. The metal corner braces were made with spare pieces of metal found in the workshop, and could be replaced with other parts to improve strength and adjustability in the future.

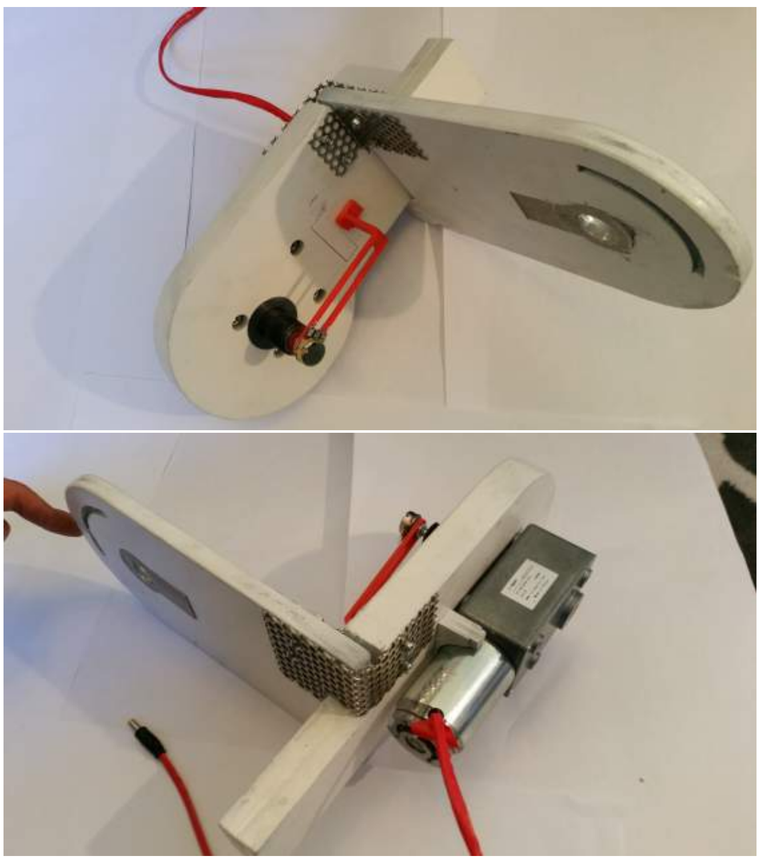

Figure 25: Final Shoulder System

5.2.6 Back

The back subsystem consists of two main parts: the motor holder, and the solid back piece. The overall subsystem can be seen in figure 26 including both parts. Again all wooden parts were created using the water jet cutter. The changes from the original design occur where the system connects to the chest mount. Some spacing was needed to move the 'T' piece away from the back, this has resulted in a large piece of wood between this piece and the solid part attaching to the vest. This has effectively solved the spacing problem, however adds a reasonable amount of unnecessary weight, in future projects a more permanent solution should be found.

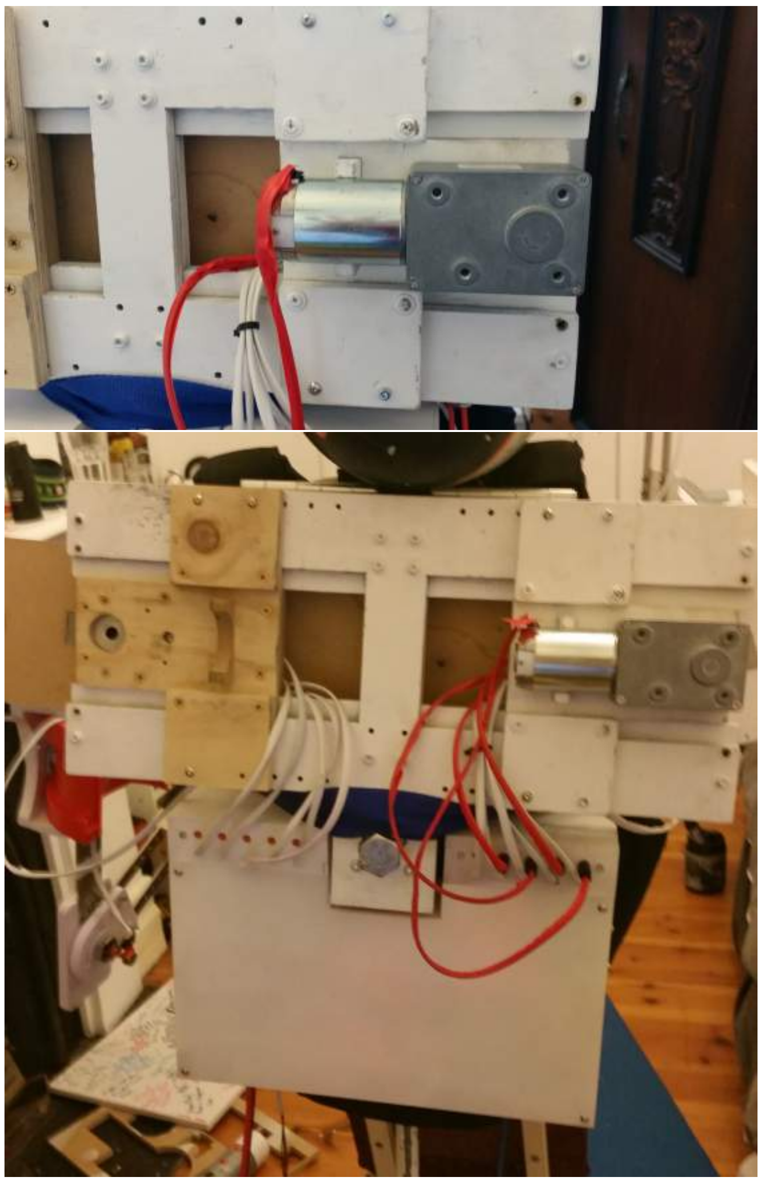

Figure 26: Final Back System

5.2.7 Chest Mount

The stab proof vest has been found to be a very effective attachment method, and has had no problem taking the weight of the REFAUM system. Extra straps have been added to this however to ensure that the back stays fixed to the vest firmly throughout operation. This can be seen in figure 27.

Figure 27: Final Chest Mount System

5.3 Summary

Overall the mechanical system has been able to achieve all desired degrees of freedom, and has been found to be strong enough to handle normal operation. The safety stops have all been tested at the motors maximum power and have all held. Some issues around comfort and weight have been discovered, and these could definitely be improved upon in future projects, this will be discussed in more detail in section 7.2. Figure 28 shows the final overall system.

Figure 28: Final Mechanical System

6 Control System

The control subsystem encompasses all software that was written for the project as well as the control theory implemented. This section shall discuss what software and control has been developed, how it works, and why it was made in the way it has been. It was decided early in the project that MATLAB and Simulink would be used for all of the software. This was due partially to the good control capabilities of Simulink, and the way MATLAB and Simulink can easily work with the Raspberry Pi. However, the main reason is the prevalence of this software in similar projects done previously. The lower body exoskeleton project at the University of Adelaide for example has used this for the software, and thus the use of it for this project will allow for drawing from the previous knowledge, and facilitate possible integration with other projects in the future.

6.1 Graphical User Interface

The graphical user interface (GUI) is the first thing that a user deals with when operating the REFAUM system and it defines how the user interacts with and controls the arm. The GUI had to be simple, easy to use, intuitive and safe. Figure 29 shows the opening page of the GUI. The GUI was developed using "Guide" which is an inbuilt MATLAB application. The program runs in three different modes: record, execute, and mirror. Each of these modes of operation is on its own tab so that a user cannot accidentally select options from the wrong mode. In figure 29 the tabs can be seen on the left, selecting one of these will take the user to that page of the GUI. There is also a large stop button there for safety, which will be available in all modes to ensure that the user can at any time stop all motors, and reset the GUI back to its initial state at any time.

Figure 29: GUI Main Page

6.1.1 Record Mode

The record mode allows a user to record and save custom move sets, the set up for this can be seen in figure 30. Once the 'Start' button is pressed, a connection is made between MATLAB and the Raspberry Pi, the program then enters a loop storing the input from each potentiometer with an associated time of recording. Once the movement is finished the user can select stop, and the movement will be processed and saved. The data is processed in two ways. It is firstly passed through a simple Simulink model with a low pass filter which 'smooths' out the data so that there are no sudden jumps in acceleration due to variations in the potentiometer recordings. After this the data is passed through what is known as the trajectory generation system. This sets the final trajectory by assessing the move set against the motors capabilities, and slowing down the movement if the suit will not be able to perform the actions fast enough. Once the data is processed the user will be prompted to enter a move name, the data from Simulink will be saved into a file with this name, and the move set will become available to select as an executable movement.

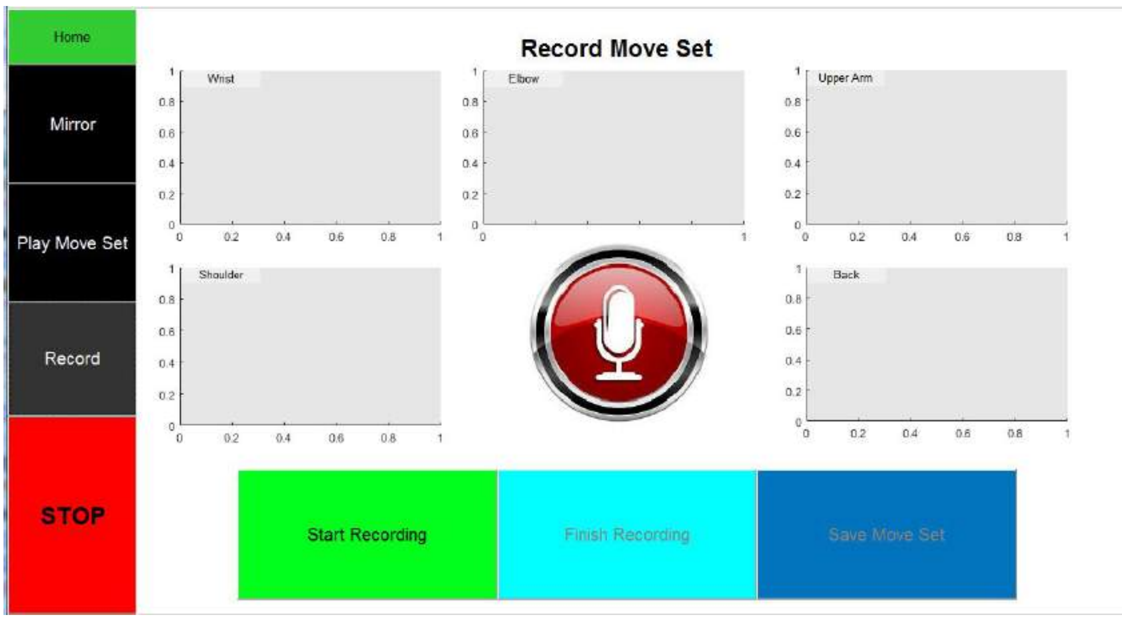

Figure 30: GUI Recording Tab

6.1.2 Execute Mode

The execution mode is where a move set is selected previewed and run. Figure 31 shows a preview of a sample move in this mode. A drop down menu displays all saved move sets for the user to select. Once a move is selected the preview and execute movement buttons become available. The move can be previewed as either a graph, which simply shows the position of each joint over time, or as an animated simulation in an external window similar to that of figure 32. The animation function was created using the Robotics Toolbox for MATLAB, written by Peter Corke (2011), and can be found in the appendices section L. Because low sampling rates were used for move-sets this year the animation program makes use of interpolation techniques, to estimate the states in between move-set data, increasing the overall performance and FPS of the animation. If a user decides to select 'Execute Movement' this will start the movement of the suit; the data from the selected file will be loaded into the MATLAB workspace, the Simulink control model will then be started which reads this data and executes the movement, this will be discussed in detail in section 6.2.

Figure 31: GUI Execute Tab

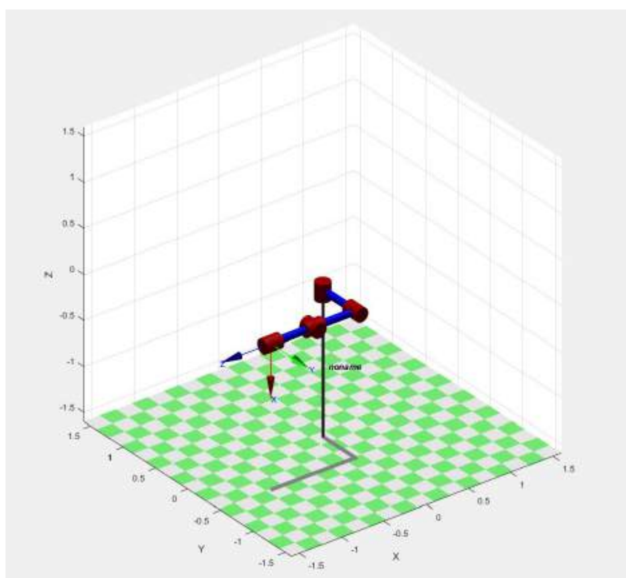

Figure 32: Move-Set Animation Window

6.1.3 Mirror Mode

The mirror mode makes the right arm of the exoskeleton mimic the position of the left arm. The GUI tab for this is very simple, as can be seen in figure 33 the page for the mirror mode consists of only a single button. When the 'Start' button is pressed the mirror move Simulink model will be started, and the mirroring will begin, the details of this control model will be discussed in section 6.4. As soon as the play button is pressed it will turn into a "Stop" button. The move mirroring will continue until a stop button is pressed, it can then be resumed at any time.

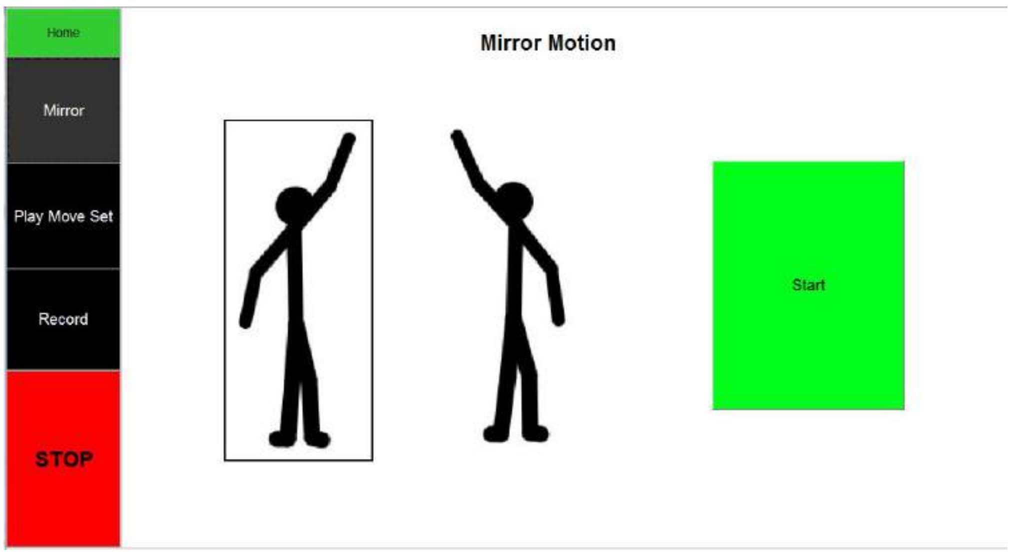

Figure 33: GUI Mirror Tab

6.2 Control Model

The Simulink model is what handles the control of the REFAUM, and is what interfaces with the motors and potentiometers through the Raspberry Pi in both the execution and mirror modes. There are two different models, one each for execution and mirroring, which apply similar control methodologies. There have been several iterations of how the control should operate, this section shall lay out the development of the control, the calculations and the final Simulink control model used.

6.2.1 Simulink Set-up

Simulink was used for all of the control models; however, difficulties were discovered when trying to interface the Simulink model with the Raspberry Pi. Simulink has inbuilt support packages for working with Raspberry Pi, however there were difficulties found when trying to interface these with MCP3008 ADC chip and the PWM generation chip. For this reason, an S-function, written in MATLAB code, was included in the Simulink models to handle all communication to the Pi; this effectively works as the plant, as it sends the PWM values to the motors, and receives the positions from the potentiometers in the one function. The S-function works by initializing all of the Pi variables at the start of the program, which are then stored while the model is running. It has functions that are called for each time it is needed to send or receive data, which simply uses MATLAB's Raspberry Pi support package to communicate data externally. As the model is not directly connected to the Pi it is unable to run in 'external mode' which is what would normally be used, and instead runs in 'normal mode' acting as a simulation, thus it is useful to use the Simulink real time synchronisation block to ensure that the movements are run at the correct speed.

To improve the speed when operating in this way it was decided that a LAN cable would connect directly from the operating computer to the Raspberry Pi to reduce delay in data transmission. Additionally the program would be run is discrete time to improve the consistency of the operating speed and to ensure that the movement could run in real time. Even over Ethernet there is still a reasonable amount of time taken to send and receive 5 separate signals, thus the frequency of 10Hz. This allows for all data to be passed and for the simulation to run in real time, while still being fast enough to perform accurate set point following.

6.2.2 Development of Control Model

The first iteration of the control model used a simple PID controller on each joint, treating each as a separate single input single output (SISO) system. It was found that trying to use derivative control directly on the discrete model ended up giving an output of either zero or infinity, and thus a unit delay and feedback loop were used instead to calculate an equivalent derivative value on the fly. The PID block using this loop can be seen in figure 34. As the set-point is constantly changing, it was not found to be useful to have integral control present since it was only slowing down the response of the system, thus this is operating as a PD controller however the integral has been left there with zero gain so adjustments can be made if steady state error removal becomes important in the future.

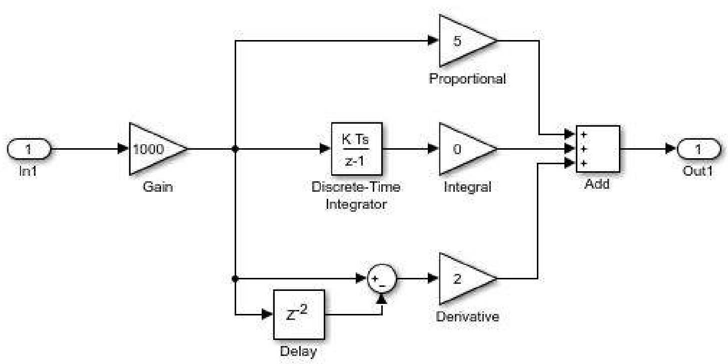

Figure 34: PID Controller

This simple closed loop PID controller was able to achieve reasonable good responses, and can even work quite well as an open loop control if the proportional component is switched off. There was however an issue with several of the joints in that for a the same PWM value the speed would be quite different depending on whether it was in the positive or negative direction. This was due to the extra torque needed in the positive direction to overcome gravity. To account for this an offset was added to the output in the S-function when operating in the positive direction. This was able to help solve this, however was not a robust fix as the direction that the weight was affecting the joint changed depending on the orientation of the suit. The other dynamic affects of the arm had also not been taken into account. This indicated that a simple SISO system would not be sufficient. Thus it was decided that model based control would be explored.

6.3 Model Based Control

To account for gravity and the dynamics of the arm, it was decided that model based control should be explored which would allow the control model to become multiple input, multiple output (MIMO) and have a model of the dynamics to work with. To achieve this, firstly the dynamics of the suit had to be calculated, this was achieved through the use of the Lagrangian method which uses the kinetic and potential energy of the subsystems to create a model for the torque of each joint. This used the method found in 'Introduction to Robotics' by John Craig (Craig 2014).

To calculate the toques the following equation is used:

$$\tau = \frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{\Theta}} - \frac{\partial \mathcal{L}}{\partial \Theta}$$

Where τ is a 5x1 vector of torques and $\mathcal{L}$ is the lagrangian defined by:

$$\mathcal{L}(\Theta, \dot{\Theta}) = k(\Theta, \dot{\Theta}) - u(\Theta)$$

Where u and k are the potential and kinetic energies of each joint respectively. These are calculated by:

$$u_i = -m_i \, {}^0g^T \, {}^0P_{C_i} + u_{ref_i}$$
$$k_i = \frac{1}{2} m_i v_{C_i}^T v_{C_i} + \frac{1}{2}{}^i \omega_i^T \, {}^{C_i}I_i^i \omega_i$$

For these calculations it was decided to neglect the rotational inertia and thus the inertial tensors (I were considered to be zero. This is obviously an oversimplification of the system which will definitely have inertial components, however after the initial calculation of the dynamics it was decided that the system would have to be simplified further, and hence this was not accounted for.

In order to calculate these energies the kinematics of the suit were first needed. For this the modified Denavit-Hartenberg (D-H) method was used. Figure 35 shows the how the axes are defined in the zero position for the D-H parameters. Each joint rotates about its z axis, with the back motor defined as joint 1 through to the wrist as joint 5.

Using the set up defined in figure 35 the following transformation matrices were found:

$$T_{01} = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & 0 \\ \sin(\theta_1) & \cos(\theta 1) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{12} = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & 0 \\ 0 & 0 & -1 & -d2 \\ \sin(\theta_2) & \cos(\theta_2) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{23} = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 & 0 \\ 0 & 0 & -1 & -d_3 \\ \sin(\theta_3) & \cos(\theta_3) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

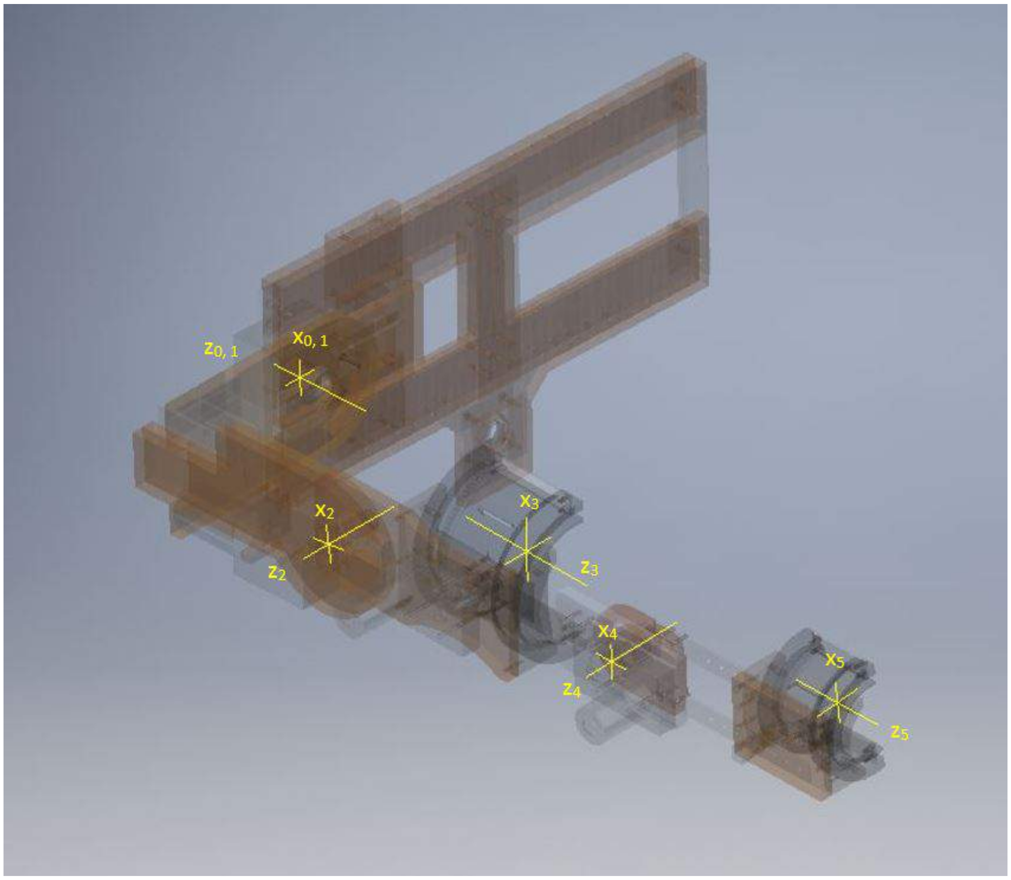

Figure 35: D-H Zero Position

$$T_{34} = \begin{bmatrix} \cos(\theta_4) & -\sin(\theta_4) & 0 & 0 \\ 0 & 0 & 1 & d_4 \\ -\sin(\theta_4) & -\cos(\theta_4) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{45} = \begin{bmatrix} \cos(\theta_5) & -\sin(\theta_5) & 0 & 0 \\ 0 & 0 & -1 & -d_5 \\ \sin(\theta_5) & \cos(\theta_5) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

From this the kinematic matrix of the end effector (wrist) is:

$$T_{05} = \begin{bmatrix} s_5(c_3s_1 - c_1c_2s_3) + c_5(c_4(s_1s_3 + c_1c_2c_3) - c_1s_2s_4) & c_5(c_3s_1 - c_1c_2s_3) - s_5(c_4(s_1s_3 + c_1c_2c_3) - c_1s_2s_4) & s_4(s_1s_3 + c_1c_2c_3) + c_1c_4s_2 & d_5(s_4(s_1s_3 + c_1c_2c_3) + c_1c_4s_2) + d_2s_1 + d_4(c_3s_1 - c_1c_2s_3) + d_3c_1s_2 \\ -c_5(c_4(c_1s_3 - c_2c_3s_1) + s_1s_2s_4) - s_5(c_1c_3 + c_2s_1s_3) & s_5(c_4(c_1s_3 - c_2c_3s_1) + s_1s_2s_4) - c_5(c_1c_3 + c_2s_1s_3) & c_4s_1s_2 - s_4(c_1s_3 - c_2c_3s_1) & d_3s_1s_2 - d_5(s_4(c_1s_3 - c_2c_3s_1) - c_4s_1s_2) - d_4(c_1c_3 + c_2s_1s_3) - d_2c_1 \\ c_5(c_2s_4 + c_3c_4s_2) - s_2s_3s_5 & -s_5(c_2s_4 + c_3c_4s_2) - c_5s_2s_3 & c_3s_2s_4 - c_2c_4 & -d_3c_2 - d_5(c_2c_4 - c_3s_2s_4) - d_4s_2s_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

By differentiating each joints kinematic transformation matrix with respect to time, the velocity matrix of each joint could be found. Then using this and the transformation matrices the energies can be calculated, and the Lagrangian could be determined. At this point the equation was beginning to become quite large as can be seen in the Lagrangian below:

$$
\begin{gathered}
\mathcal{L} = (m_3((h_3cos(\theta_2)sin(\theta_3)\dot{\theta_2} - d_3sin(\theta_2)\dot{\theta_2} + h_3cos(\theta_3)sin(\theta_2)\dot{\theta_3})^2 + (d_2cos(\theta_1)\dot{\theta_1}cos(\theta_1)cos(\theta_2)\dot{\theta_2} \\
+h_3cos(\theta_1)cos(\theta_3)\dot{\theta_1} - d_3sin(\theta_1)sin(\theta_2)\dot{\theta_1} - h_3sin(\theta_1)sin(\theta_3)\dot{\theta_3} - h_3cos(\theta_1)cos(\theta_2)cos(\theta_3)\dot{\theta_3} \\
+h_3cos(\theta_2)sin(\theta_1)sin(\theta_3)\dot{\theta_1} + h_3cos(\theta_1)sin(\theta_2)sin(\theta_3)\dot{\theta_2})^2 + (d_2sin(\theta_1)\dot{\theta_1} + d_3cos(\theta_1)sin(\theta_2)\dot{\theta_1} \\
+d_3cos(\theta_2)sin(\theta_1)\dot{\theta_2} + h_3cos(\theta_3)sin(\theta_1)\dot{\theta_1} + h_3cos(\theta_1)sin(\theta_3)\dot{\theta_3} - h_3cos(\theta_1)cos(\theta_2)sin(\theta_3)\dot{\theta_1} \\
-h_3cos(\theta_2)cos(\theta_3)sin(\theta_1)\dot{\theta_3} + h_3sin(\theta_1)sin(\theta_2)sin(\theta_3)\dot{\theta_2})^2))/2 + (m_2(d_2^2\dot{\theta_1}^2 + h_2^2\dot{\theta_1}^2 + h_2^2\dot{\theta_2}^2 \\
-h_2^2cos(\theta_2)^2\dot{\theta_1}^2 + 2d_2h_2cos(\theta_2)\dot{\theta_1}\dot{\theta_2}))/2 + (m_4((d_2cos(\theta_1)\dot{\theta_1} + d_3cos(\theta_1)cos(\theta_2)\dot{\theta_2} + d_4cos(\theta_1)cos(\theta_3)\dot{\theta_1} \\
-d_3sin(\theta_1)sin(\theta_2)\dot{\theta_1} - d_4sin(\theta_1)sin(\theta_3)\dot{\theta_3} - d_4cos(\theta_1)cos(\theta_2)cos(\theta_3)\dot{\theta_3} + h_4cos(\theta_1)cos(\theta_2)cos(\theta_4)\dot{\theta_2} \\
+d_4cos(\theta_2)sin(\theta_1)sin(\theta_3)\dot{\theta_1} + d_4cos(\theta_1)sin(\theta_2)sin(\theta_3)\dot{\theta_2} - h_4cos(\theta_4)sin(\theta_1)sin(\theta_2)\dot{\theta_1}+ \\
h_4cos(\theta_1)sin(\theta_3)sin(\theta_4)\dot{\theta_1} - h_4cos(\theta_1)sin(\theta_2)sin(\theta_4)\dot{\theta_4} + h_4cos(\theta_3)sin(\theta_1)sin(\theta_4)\dot{\theta_3} \\
+h_4cos(\theta_4)sin(\theta_1)sin(\theta_3)\dot{\theta_4} + h_4cos(\theta_1)cos(\theta_2)cos(\theta_3)cos(\theta_4)\dot{\theta_4} - h_4cos(\theta_2)cos(\theta_3)sin(\theta_1)sin(\theta_4)\dot{\theta_1} \\
-h_4cos(\theta_1)cos(\theta_3)sin(\theta_2)sin(\theta_4)\dot{\theta_2} - h_4cos(\theta_1)cos(\theta_2)sin(\theta_3)sin(\theta_4)\dot{\theta_3})^2 + (d_3sin(\theta_2)\dot{\theta_2} - d_4cos(\theta_2)sin(\theta_3)\dot{\theta_2} \\
-d_4cos(\theta_3)sin(\theta_2)\dot{\theta_3} + h_4cos(\theta_4)sin(\theta_2)\dot{\theta_2} + h_4cos(\theta_2)sin(\theta_4)\dot{\theta_4} + h_4cos(\theta_2)cos(\theta_3)sin(\theta_4)\dot{\theta_2} \\
+h_4cos(\theta_3)cos(\theta_4)sin(\theta_2)\dot{\theta_4} - h_4sin(\theta_2)sin(\theta_3)sin(\theta_4)\dot{\theta_3})^2 + (d_2sin(\theta_1)\dot{\theta_1} + d_3cos(\theta_1)sin(\theta_2)\dot{\theta_1} \\
+d_3cos(\theta_2)sin(\theta_1)\dot{\theta_2} + d_4cos(\theta_3)sin(\theta_1)\dot{\theta_1} + d_4cos(\theta_1)sin(\theta_3)\dot{\theta_3} - d_4cos(\theta_1)cos(\theta_2)sin(\theta_3)\dot{\theta_1} \\
-d_4cos(\theta_2)cos(\theta_3)sin(\theta_1)\dot{\theta_3} + h_4cos(\theta_1)cos(\theta_4)sin(\theta_2)\dot{\theta_1} + h_4cos(\theta_2)cos(\theta_4)sin(\theta_1)\dot{\theta_2} - h_4cos(\theta_1)cos(\theta_3)sin(\theta_4)\dot{\theta_3} \\
-h_4cos(\theta_1)cos(\theta_4)sin(\theta_3)\dot{\theta_4} + d_4sin(\theta_1)sin(\theta_2)sin(\theta_3)\dot{\theta_2} + h_4sin(\theta_1)sin(\theta_3)sin(\theta_4)\dot{\theta_1} - h_4sin(\theta_1)sin(\theta_2)sin(\theta_4)\dot{\theta_4} \\
+h_4cos(\theta_1)cos(\theta_2)cos(\theta_3)sin(\theta_4)\dot{\theta_1} + h_4cos(\theta_2)cos(\theta_3)cos(\theta_4)sin(\theta_1)\dot{\theta_4} - h_4cos(\theta_3)sin(\theta_1)sin(\theta_2)sin(\theta_4)\dot{\theta_2} \\
-h_4cos(\theta_2)sin(\theta_1)sin(\theta_3)sin(\theta_4)\dot{\theta_3})^2))/2 - gm_2(d_2sin(\theta_1) + h_2cos(\theta_1)sin(\theta_2)) - gm_3(d_2sin(\theta_1) + h_3(cos(\theta_3)sin(\theta_1) \\
-cos(\theta_1)cos(\theta_2)sin(\theta_3)) + d_3cos(\theta_1)sin(\theta_2)) + (h_1^2m_1\dot{\theta_1}^2)/2 - gm_4(h_4(sin(\theta_4)(sin(\theta_1)sin(\theta_3) + cos(\theta_1)cos(\theta_2)cos(\theta_3)) \\
+cos(\theta_1)cos(\theta_4)sin(\theta_2)) + d_2sin(\theta_1) + d_4(cos(\theta_3)sin(\theta_1) - cos(\theta_1)cos(\theta_2)sin(\theta_3)) + d_3cos(\theta_1)sin(\theta_2)) - gh_1m_1sin(\theta_1)
\end{gathered}
$$

To find the torques of each joint the Lagrangian then had to be differentiated with respect to each position, speed and with respect to time. After this it became apparent that the torque equations would be too computationally expensive to be performed at each time step with some running on for several pages. Despite this it was still found that there was value in the dynamic equation. It was decided that the main important factor that needed to be accounted for was weight and gravity. The form of joint space manipulator dynamics can be in general stated as:

$$\tau = M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta)$$

By extracting only the $G(\Theta)$ portion of the torque equation, a useful dynamic approximation for gravitational effects could be found which was only a few lines and could be feasibly computed in the control loop. This was achieved by simply taking the full torque equations and setting all angular velocities and accelerations to zero. Rather than implementing this strictly as model based control, the gravitational aspects of the dynamics were added to the PWM signal generated from the PID controller just to offset the weight of the limbs. The equations for the torques added are:

$$
\begin{aligned}
G_1 = &\quad gm_2(d_2c_1 - h_2s_1s_2) + gm_3(d_2c_1 + h_3(c_1c_3 + c_2s_1s_3) - d_3s_1s_2) + gm_4(d_2c_1 \\
&\quad +h_4(s_4(c_1s_3 - c_2c_3s_1) - c_4s_1s_2) + d_4(c_1c_3 + c_2s_1s_3) - d_3s_1s_2) + gh_1m_1c_1 \\
G_2 = &\quad gc_1(d_3m_3c_2 + d_3m_4c_2 + h_2m_2c_2 + h_4m_4c_2c_4 + d_4m_4s_2s_3 + h_3m_3s_2s_3 - h_4m_4c_3s_2s_4) \\
G_3 = &\quad -gm_4(d_4(s_1s_3 + c_1c_2c_3) - h_4s_4(c_3s_1 - c_1c_2s_3)) - gh_3m_3(s_1s_3 + c_1c_2c_3) \\
G_4 = &\quad gh_4m_4(c_4(s_1s_3 + c_1c_2c_3) - c_1s_2s_4) \\
G_5 = &\quad 0
\end{aligned}
$$

Where h represents the distance to the centroid of each joint, and s and c are shorthand for sine and cosine.

6.4 Final Control Models

The final control models used a very similar implementation to the initial SISO control models however with added aspects from the model based control algorithm. The final equation for the suit dynamics would have added several thousand lines of code for each time-step in the execution. This would have made the program far too slow to run in real time. For this reason only the aspects of the dynamics that were deemed to have a significant impact on the motion of the REFAUM were taken into account. This, along with the PID controller on each output created a more robust and accurate controller which was used for both control loops. The code for the input and output functions of the S-Function block including the dynamic model implementation can be found in appendix K.

6.4.1 Move Set Execution

The final control loop for the move set execution is shown in figure 36. The set points are read in via a MATLAB time series input which are provided by the GUI. The difference between this and the actual position are passed through a simple discrete PID controller to calculate an appropriate PWM signal to send. After this the signal is passed through the safety limiting function to ensure the joint stays within the specified bounds, and the saturation block which ensures that the speed will not be too high. The PWM values are then passed to the S-function, where they can be combined to effectively create the MIMO system that was aimed for. Inside the S-function the mass and position of each joint is accounted for and added to the final PWM signal sent to the motor controllers.

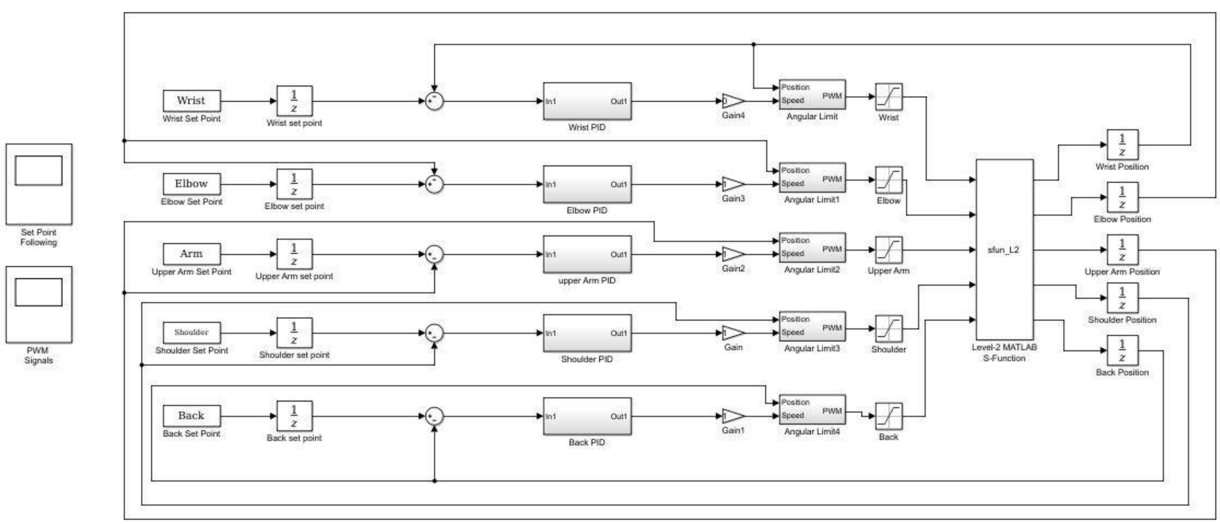

Figure 36: Closed Loop Control Model

6.4.2 Mirroring

The Simulink model for the mirroring function uses the same control methodology as the move execution however the set up is quite different. The Simulink model for the mirroring function can be seen in figure 37. The main difference between the two is the source of the set point; in the mirror controller the set point is read directly from the left arm's potentiometers which are also outputs from the S-function. It can also be seen that the mirror model has an additional user interface on the side. This is for the purposes of doing manual adjustments. The mirroring function requires one arm to mimic the other's position, however as the positions are read directly from the potentiometers, the arms may be at different positions despite giving the same reading. Thus, the manual adjustment allows a user to slowly move each motor in either direction and then 'zero' the difference to indicate that the arms are in the correct position. The subsystem in between the saturation and the S-function implements the switching between the two functions. The 'flip-flop' on each joint provides the zeroing functionality as it will subtract its value from the current difference, when the zero button is pushed for a joint the flip flop will update its value to be the current difference.

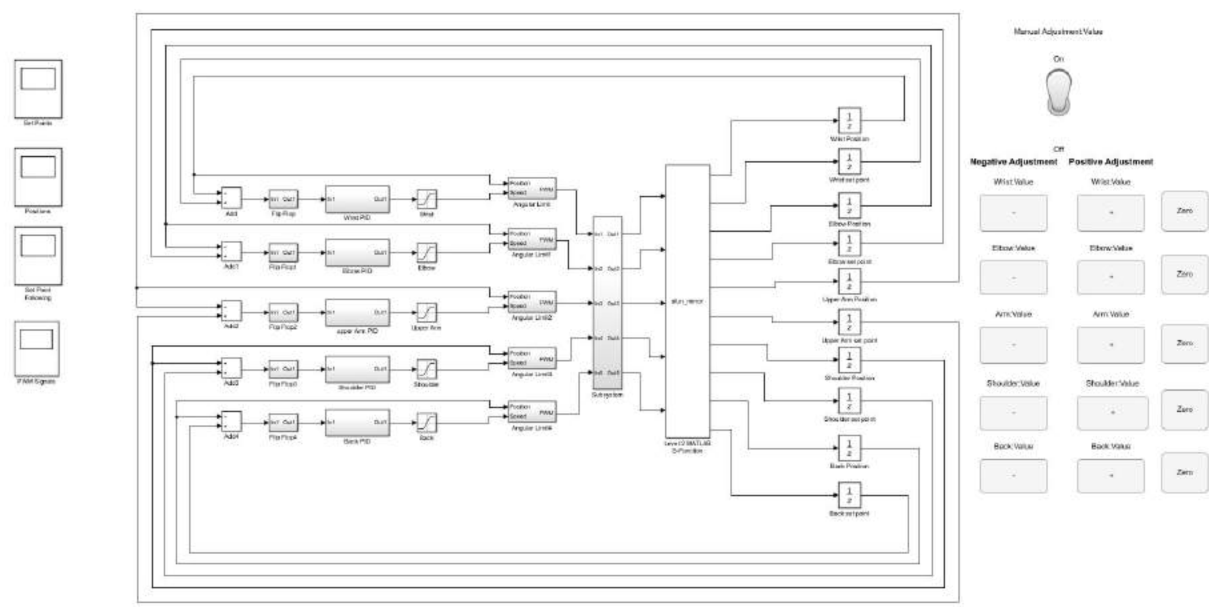

Figure 37: Mirror Image Control Loop

The mirror image function is set up so that it can be run indefinitely. The process will only end when stopped by the user, either through the Simulink model, GUI, or mechanical switch. It can however be paused at any time through the use of the manual adjustment switch

6.5 Summary

At the conclusion of this project, the software and control subsystem has been completed and achieved most of what was desired. The GUI provides a simple and convenient interface encapsulating all of the desired functionality for the project. Further options and functionality could be added in future projects; however, it has accomplished everything required for this years project.

For the purposes of this project precise and quick set point following is not crucial, as errors of a few degrees are unlikely to be noticed. The control models created have both resulted in set point following that is able to accomplish all requirements of the system. There are some further developments which would be recommended for future projects to improve the speed and portability of this part of the program however. Simulink supplies blocks which are designed to interface with the Raspberry Pi so that the program can be run externally. This would be good as it would allow a user to run the program without be attached to the computer.

7 Future Work

Although the 2017 REFAUM project has has come to a conclusion there are still several areas in each of the electrical, mechanical and control systems that could be improved or extended in future projects. This section of the report will focus on pin pointing these areas so future projects will know what issues to address in order to further improve the performance REFAUM system.

7.1 Electrical

The electrical system worked fine for the purposes of this year's project, however only the right arm of the exoskeleton was able to be powered. The system itself was designed to accommodate for the ten actuators required to power both arms but budget restrictions meant that the additional components couldn't be purchased. Future projects could easily look into powering the left arm of the exoskeleton by simply purchasing the additional DC motors/controllers along with the Raspberry Pi I/O expansion board required to control them. The only consideration that might have to be made with the addition of the extra powered exoskeleton arm involves the power system. Theoretically it should be able to provide power to both of the exoskeletons arms, under normal operating conditions, but as the additional components were never available this theory was never tested. With the possibility of future projects and the budgets that accompany them there are also some nice to have features that could be added to the electrical system. For instance, JST connectors could be used for the potentiometers allowing for easy removal also nylon cable covers could replace the electrical tape used by this year's project to provide a better cable management system. Additionally, the fan speed could be reduced by lowing the voltage supplied to them through the use of some more DC buck converters. As they are relatively loud when operating at maximum capacity.

In terms of extra features and elongated project scopes the following ideas could be useful in taking the system to the next level. The power supply could be completely replaced by a battery system removing the exoskeletons dependence on wall sockets entirely allowing the suit to be full mobile. If the Raspberry Pi Simulink block issues were ever ironed out, allowing the raspberry pi to perform all of the control functionalities by itself, then the host computer containing the GUI could be replaced with a wrist mounted touch screen. Again, taking the systems mobility to the next level.

7.2 Mechanical

Significant improvements will need to be made in future projects to reduce the weight and improve the overall comfort of the REFAUM's mechanical system. Before this could ever become a feasible commercial product most of the materials would need to be swapped for lighter ones. For the purposes of saving money, and ease of manufacture plywood was used for many parts of the suit. It is relatively light and strong compared to most woods, however at some points the amounts used were rather large creating a very bulky design. The weight could be significantly reduced if the suit were made from carbon fibre or if more of the parts were replaced with ergonomic designs made form aluminium.

Some flaws were also discovered in the later stages of the mechanical design which could warrant potential redesigns in future projects. The main fix that needs to be implemented is the alignment of the shoulder's roll axis with the arm and the other shoulder axes. Figure 38 shows the three axes for the three degrees-of-freedom of the shoulder; it can be seen that the axes intersect in different places. Since these three joints are trying to simulate a single three degree-of-freedom joint the rotational axes should all intersect at the same point, which should be the centre of the shoulder's rotation. This has also caused a small misalignment with the wrist roll, which should match the shoulder. The exoskeleton is still able to function with these flaws but overall comfort of the user is effected and therefore they should be fixed.

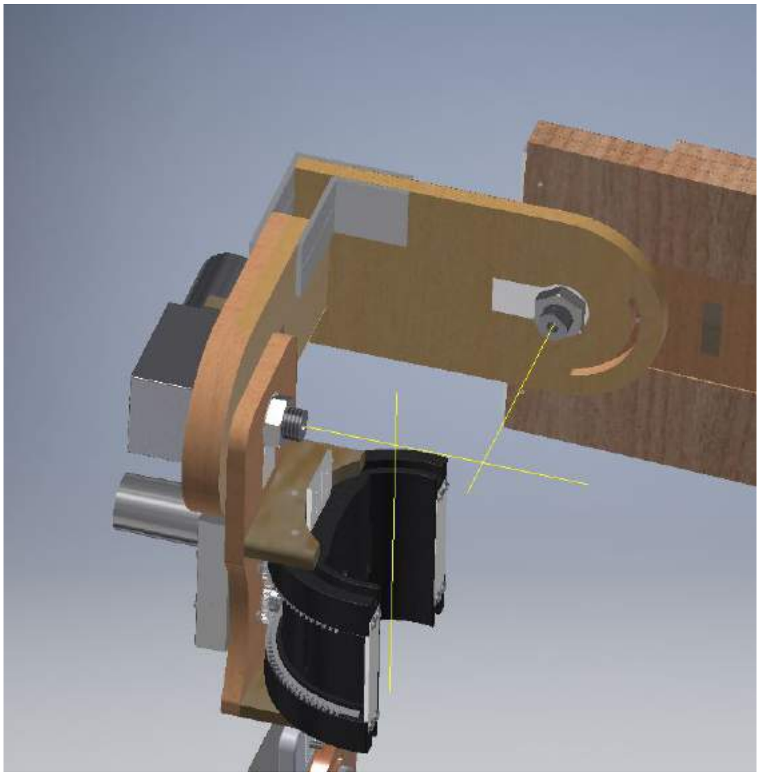

Figure 38: Shoulder Axes

7.3 Control

The control system is currently working well for its required purpose, however there are some developments which could be made for future projects. The main functionality that would be useful in future years is external software execution. This is the ability to run the control software directly on the Raspberry Pi rather than using it as a go between from the computer and the suit. The main reason this was not implemented this year was due to difficulties using the Simulink blocks provided with the Raspberry Pi. In particular it was difficult to get the blocks to control the PWM signals required to drive the motors as well as read the inputs from the ADC chips connected to the linear potentiometers. Additionally, the software itself could use some reworking if the Simulink blocks could be figured out, primarily to speed up the operation of the control models. As slow sample rates had to be used with the level 2 S-functions implemented in this year,s project.

8 Conclusion

During the course of 2017 the Robotic Exoskeleton For Assisted Upper-Body Motion, or "REFAUM", project was conducted. The project involved the design and build of the electrical, mechanical and control systems required to fully construct an upper body exoskeleton for use with assistive motion. Studies were conducted into human kinematics, dynamics and sizes as well as research papers relating to previous exoskeleton projects from both the University of Adelaide and the robotics industry over the past several decades. This information was used to inform the creation of the ten project goals assigned for completion throughout the year. Of these ten goals the REFAUM team was able to complete all but one of them, the extension goal relating to integration with the lower body exoskeleton project. Appropriate time management tools were utilised to plan for the construction of the mechanical and electrical systems. But due to unforeseen risks the workshop was unable to complete the construction of these systems in time and therefore a major compromise was made. This compromise involved having the REFAUM team members construct both of the mechanical and electrical systems themselves as this was the first year students were allowed to use to workshop. In doing this, significant delays were made to the rest of the project which resulted in the failed completion of the extension goal. Even with these complications and limitations imposed on the project by the budget the three primary systems of the exoskeleton: Electrical, mechanical and control were completed in order to create an effective prototype of the REFAUM system.

This prototype is capable of recording move-sets, using the user's left arm, and saving them as a .mat files for later use. Once created the move-sets can be animated through the GUI using an animation program, developed using the robotics toolbox for MATLAB, or executed on the physical system using control models developed in Simulink. Overall these functionalities allow the REFAUM system to be used for several different applications. Ranging from more serious activities, such as rehabilitation, all the way to more light-hearted ones for instance recreational activities. The prototype is still exactly that, a prototype, which means there are definitely some areas that could use upgrades or improvements in future years. The electrical system could upgraded by purchasing the additional components required to power the left arm of the exoskeleton or by replacing the host computer with a wrist mounted touch screen display. The mechanical system's comfort could be increased by performing some maintenance on the shoulder joint, to improve its overall orientation, or by reducing the weight of the system by using different construction materials. Finally, the control system could increase its operating speed by getting the Simulink blocks for the Raspberry Pi to work in addition to rewriting the code to move all calculations from the host computer to the Raspberry Pi. Implementing any of these improvements or upgrades would result in a more well-rounded REFAUM system for the future.

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Appendix

A Project Goals - SMART Format

G1: Research into Human Kinematics & Dynamics

Description:
Determine the full extent to which the average human adult can move their shoulder, elbow and wrist in terms of kinematic and dynamic movement.

Specifications:
Kinematics:
Determine the following:

- Angular range of motion relating to the shoulder's pitch, roll and yaw (3 D.O.F)
- Angular range of motion relating to the elbow's pitch (1 D.O.F)
- Angular range of motion relating to the wrist's roll (1 D.O.F)

Dynamics:
Determine the following:

- Maximum torque required to move the shoulder in each of the pitch, roll and yaw dimensions
- Maximum torque required to move the elbow in the pitch dimension
- Maximum torque required to rotate the wrist in the roll dimension

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- Values for the above specifications are found from legitimate sources and properly documented
- These values are then verified by comparing them to how our own bodies behave

Achievability:
Finding information on the kinematics and dynamics of human movement shouldn't be that difficult as an entire area of study has been dedicated to it, known as biomechanics. This information can be easily sourced from the Internet, books, research papers or previous honours project reports.

Relevance to Aims:
In order to design and build an upper body exoskeleton a firm understanding of how the human body behaves is essential. Quantifying the kinematics will assist with the design of the mechanical system whilst quantifying the dynamics will help with the design of the modular power subsystem.

Time Frame:
As other goals in this project depend on this one it is important that it is completed quickly. Therefore this goal should be worked on in the initial stages of the project and completed by: 19th of March

G2: Mechanical System Design

Description:
Design a mechanical system to replicate human upper body motion as close as possible, be comfortable to wear for long durations of time and fit a wide variety of users.

Specifications:
Kinematics:

- Cover 5 D.O.F overall, shoulder (pitch, roll, yaw), elbow (pitch) and wrist (roll)
- Achieve at least 80% of the angular range of motion for the shoulder, elbow and wrist determined from G1

Ergonomics:

- Weight limit: 10kg
- Adjustable limbs and chest harness required

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

Kinematics:

- Assembly drawings and or animations are produced in CAD confirming that the design meets the specifications mentioned above

Ergonomics:

- The overall weight of the design is estimated by using the volume and material information from the final designs list of parts and is less than 10kg
- The exoskeleton will be considered to be adjustable if the chest harness/limbs can be extended to fit all of our group members

Achievability:
Several projects revolving around the design of a mechanical system for human interaction have been accomplished in the past, both on-line and at the university. The university also has masters and PHD students that are currently focusing on the design and use of upper body exoskeletons. Therefore by researching literature relating to these previous projects, as well as making use of the other students studying upper body exoskeletons, we should be able to get a firm understanding of the necessary steps to take when considering the design of the mechanical system.

Relevance to Aims:
The mechanical system gives a way to establish a physical connection between the user and the exoskeleton. Without it there would be no way for the actuators and sensors to provide assistive motion to the user.

Time Frame:
This goal needs to be completed alongside G3 and G4 to make sure that all subsystems can be properly integrated before the final overall design is produced and then manufactured by the workshop. Therefore this goal should be worked on in the initial stages of the project and completed by: 14th of April

G3: Modular Actuator Subsystem Design

Description:
Design a modular actuator subsystem to provide the necessary torque to each of the mechanical system's joints in order to assist the users movement.

Specifications:

- Achieve at least 40% of the maximum torque required to move each of the joints (D.O.F) discovered in G1
- Design must be modular in that it can easily be connected or disconnected from the mechanical system.

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- Design calculations are produced showing that the actuators selected are able to provide the torque required in the above specifications
- Assembly drawings and or animations are produced using CAD to show how the modular actuator subsystem can be attached and removed from the mechanical system

Achievability:
Again several projects relating to the design of an actuator subsystem to power an upper body exoskeleton have been conducted in the past. Previously conducted research suggests that designing the actuator subsystem could be as simple as selecting motors and gear boxes strong enough to supply the required torques at each of the exoskeletons joints.

Relevance to Aims:
Assistive motion cannot be achieved if there is no actuator subsystem providing power to the exoskeletons joints. Also a modular design is preferred as it allows for the actuators to be decoupled when move sets are being recorded.

Time Frame:
Again this goal needs to be completed at the same time as G2 and G4 to make sure that all the subsystems can be properly integrated before the detailed design is produced and sent to the workshop for manufacture. Therefore this goal should be worked on in the initial stages of the project and completed by: 14th of April

G4: Sensor Subsystem Design

Description:
Design a sensor subsystem capable of measuring the position, velocity and acceleration of the exoskeletons joints during operation.

Specifications:

- Record angular motion (position, velocity & acceleration) for all of the mechanical system's joints (5 D.O.F) per arm

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- Sensors are purchased and tested to make sure they can achieve the angular ranges specified in G1

Achievability:
Designing this subsystem shouldn't be that hard as there are several different types of sensors available on the market. Also the velocity and acceleration of a particular joint could be found by using software to differentiate the values recorded from a single angular sensor over time.

Relevance to Aims:
The sensor subsystem is required for two main reasons. Firstly it provides information to the controller so closed loop feedback can be utilised. Secondly it allows for move sets to be recorded and translated by the trajectory generation system.

Time Frame:
Again this goal needs to be completed at the same time as G2 and G3 to make sure that all the subsystems can be properly integrated before the detailed design is produced and sent to the workshop for manufacture. Therefore this goal should be worked on in the initial stages of the project and completed by: 14th of April

G5: Build The Exoskeleton

Description:
Use the initial designs from the mechanical, modular actuator and sensor subsystems to come up with a final detailed design that is able to be manufactured by the workshop in a reasonable amount of time.

Specifications:

- Fully integrate mechanical, modular actuator and sensor subsystems
- Keep design as simple as possible
- Obtain approval from supervisor and workshop

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- CAD part and assembly drawings are produced showing the final detailed designs
- A work request form is signed by the project supervisor and the workshop confirms that the design is simple enough to be manufactured

Achievability:
As long as the workshop is included in the design process, during the early stages of the project, they should be able to provide the necessary feedback required to produce a manufacturable design as they have built several university projects in the past.

Relevance to Aims:
Again as this is a design & build project the actual exoskeleton has to be constructed at some point.

Time Frame:
The exoskeleton has to be manufactured ASAP otherwise full development and testing cannot be commenced. Therefore this goal is to be started directly after G2, G3 and G4 and completed no later than the 26th of May to make sure the workshop has enough time to build it.

G6: Electronic System Design

Description:
Design an electronic system capable of safely housing, connecting and powering all logic and actuator circuits.

Specifications:

- All electrical components relating to control should be contained in a non conductive control box
- All cables not located in the control box should be properly insulated for safety reasons
- The logic circuit should be provided with 5V and 2A
- The actuator circuit should be provided with 12V and 0-20A

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- CAD designs for control box are created containing mounts for all necessary electrical control components
- Sufficient insulation is obtained and applied to all electrical wiring located outside the control box
- A power supply capable of producing at least 12V and 20A is obtained for use with testing and demonstrations

Achievability:
A non conductive control box can easily be designed out of acrylic and mounted on the back of the exoskeleton where there is plenty of spare space. Wire insulation similar to that used on PC power supplies could be utilized to safely contain all external wiring, previous years projects have used this in the past. The university has access to several variable power supplies capable of 30V up to 25A therefore we should be able to borrow one from them and if not find our own from a local electronics store.

Relevance to Aims:
The electrical system is necessary to physically connect/power the sensor, actuator and control systems. All electronic components must be safely contained to prevent the user from getting electrocuted.

Time Frame:
This goal needs to be completed around the same time as G7 when the exoskeleton has been fully manufactured and assembled to allow time for testing. Therefore this goal should be worked on in the middle stages of the project and completed by: 24th of July

G7: Trajectory Generation Subsystem Design

Description:
Design a trajectory generation system capable of both animating and refining the data recorded from move-sets.

Specifications:

- Should be able to read in pre recorded move sets, from an external ".Mat" file, and refine them to provide the Simulink control model with a smooth trajectory to run on
- Should have the ability to display move sets as animations in both joint and Cartesian space
- Must be created using MATLAB

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- A program is created using MATLAB containing the necessary functions to execute the specifications made above

Achievability:
Smooth trajectories for the recorded move-sets should be able to be produced through the use of digital filters or optimisation algorithms. As for the animations the move-sets will be recorded in joint space which means they can be easily animated using the robotics toolbox for Matlab.

Relevance to Aims:
The trajectory generation subsystem is necessary to make sure that the Simulink controller can execute move-sets recorded by the sensor subsystem in a smooth and safe manner. The animations will also work as a good demonstration of what the exoskeleton should be doing during Ingenuity.

Time Frame:
This goal needs to be completed around the same time as G6 when the exoskeleton has been fully manufactured and assembled to allow time for testing. Therefore this goal should be worked on in the middle stages of the project and completed by: 24th of July

G8: Simulink Controller Design

Description:
Design a model based control system, using Simulink, that is capable of providing closed loop feedback control for the exoskeleton.

Specifications:

- Must be programmed using MATLAB and Simulink
- Should be able to support input from 10 sensors, one for each D.O.F
- Should be able to support output to 5 actuators for the exoskeletons right arm
- Has to use model based control for integration with future projects

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- A Simulink control model has been created and tested, using the final physical version of the exoskeleton, to meet all specifications listed above

Achievability:
Previous years honours project groups were able to design a Simulink control model for use with a lower body exoskeleton. Therefore by conducting research into their programs architecture we should be able to learn, adapt and create our own control system for the upper body exoskeleton.

Relevance to Aims:
The Simulink controller acts as the brain of the entire exoskeleton, and is required to bring everything together to produce a working system. Without it there wouldn't be anyway for the sensor or actuator subsystems to interact with each other.

Time Frame:
This goal has to be completed by the middle of semester 2, to allow enough time for detailed testing before ingenuity. Therefore this goal must be worked on in the later stages of the project and completed by: 15th of September

G9: Interface Design - GUI

Description:
Design and implement a GUI capable of giving the user a simple way to interact with the exoskeleton to record and execute move sets.

Specifications:

- Run on laptop using MATLAB
- Communicate to controller through LAN or Wi-Fi
- Ability to save and load move sets though a tool bar
- Ability to display move sets in joint and Cartesian space using the trajectory generation system
- Ability to start and stop recording a new move set
- Ability to execute currently loaded move set

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- A GUI has been designed and implemented, using MATLAB, with the ability to execute all of the functions specified above

Achievability:
Several projects have implemented their own GUI's in past honours projects so it is possible. Also MATLAB has its own pre built functions relating to GUI's that we could look into instead of designing it from scratch.

Relevance to Aims:
We want to have a way to record and execute move sets, this goal aims to make that process easier and more user friendly.

Time Frame:
This goal has to be completed before ingenuity and after the rest of the exoskeleton has been tested and confirmed working. Therefore this goal should be worked on in the final stages of the project and completed by: 31st of October

E1: Integration with Lower Body Exoskeleton

Description:
Determine a way to physically attach this years upper and lower body exoskeletons for demonstration purposes at the end of the year during Ingenuity.

Specifications:

- At least 50% of the upper body exoskeletons weight must be transferred through the lower body exoskeleton to the ground

Measurable Outcomes:
This goal will be considered complete when the following conditions are met:

- A mechanism has been put in place that is able to transfer the specified load from the upper body exoskeleton to the lower body exoskeleton

Achievability:
Designing a mechanism to connect both projects should be relatively simple, in comparison to the rest to the project. So as long as the project teams talk about it in the early stages of the design process this goal should be able to be completed before the presentation at ingenuity.

Relevance to Aims:
Having some of the weight taken off of our system will greatly improve the ergonomics of the overall design and make it easer for the user to wear for longer durations of time. It also allows for easier integration between these two projects in the future.

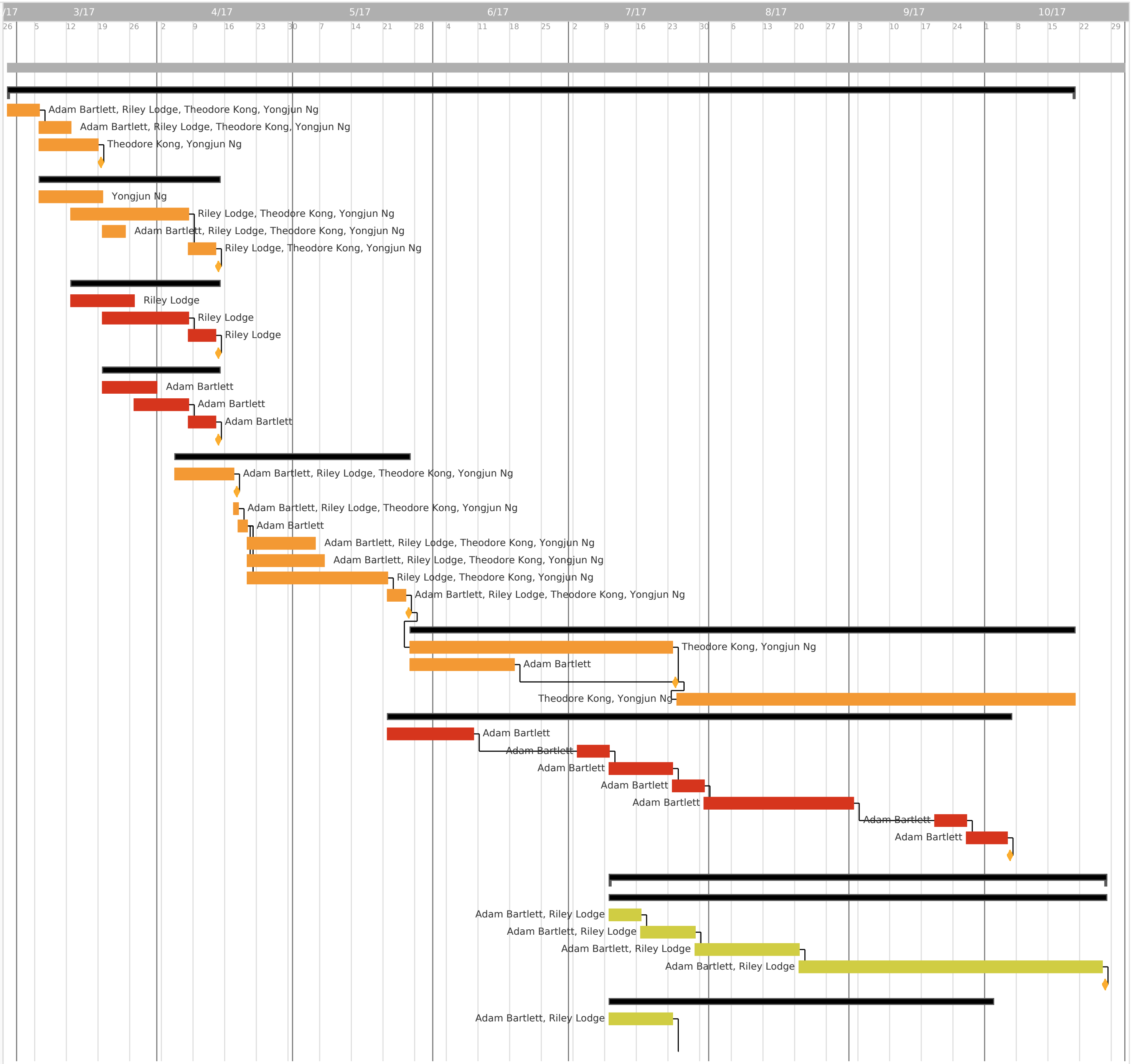
Time Frame:
As previously stated this goal has to be completed by ingenuity. Therefore it should be worked on in the middle stages of the project and completed a couple of weeks before ingenuity: 31st of October

B Gantt Chart

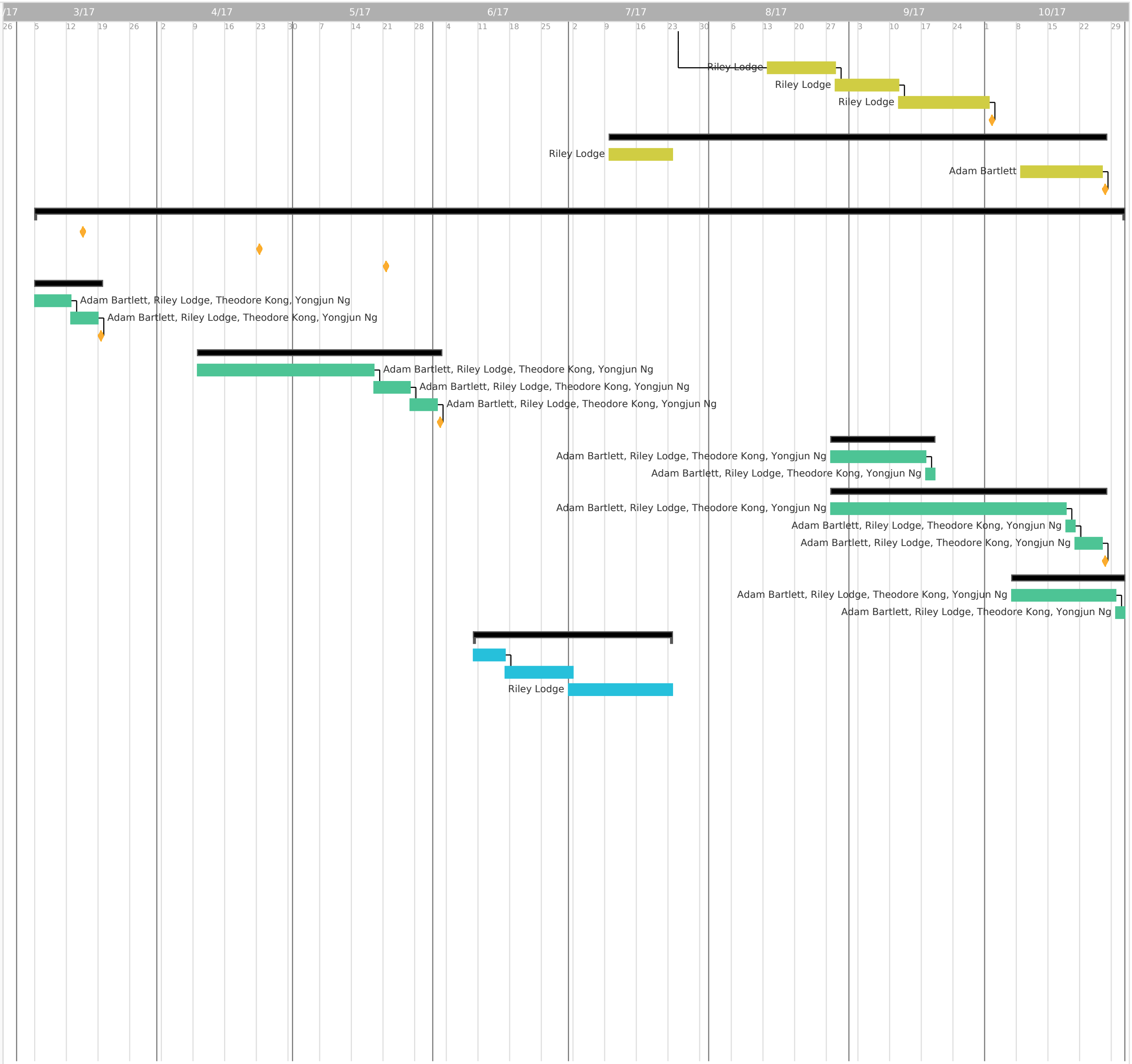
See the next page...

2366 - REFAUM

Task	start	end
Hardware Design & Build	**27/02/17**	**20/10/17**
Requirements Elicitation	27/02	05/03
Specification Definitions	06/03	12/03
Research	06/03	18/03
G1	19/03	19/03
Mechanical System	**06/03/17**	**14/04/17**
Research	06/03	19/03
Initial Concepts	13/03	07/04
Workshop Kick-off Meeting	20/03	24/03
Comparative Analysis	08/04	13/04
Recommended Initial Design (G2)	14/04	14/04
Modular Power Subsystem	**13/03/17**	**14/04/17**
Research	13/03	26/03
Initial Designs & Calculations	20/03	07/04
Comparative Analysis	08/04	13/04
Recommended Initial Design (G3)	14/04	14/04
Sensor Subsystem	**20/03/17**	**14/04/17**
Research	20/03	31/03
Initial Design	27/03	07/04
Comparative Analysis	08/04	13/04
Recommended Initial Design (G4)	14/04	14/04
Detailed Design	**05/04/17**	**26/05/17**
Integration	05/04	17/04
Overall Recommended Initial Desi...	18/04	18/04
Workshop Design Review	18/04	18/04
Decision on 1 or 2 Arms for Build	19/04	20/04
Modification/Update of Design	21/04	05/05
Verifications/Calculations/Simulati...	21/04	07/05
CAD	21/04	21/05
Obtain Approval For Build	22/05	25/05
Submit Drawings (G5)	26/05	26/05
Build	**27/05/17**	**20/10/17**
Construction	27/05	23/07
Purchase Additional Parts	27/05	18/06
Assemble	24/07	24/07
Maintenance/Modification	25/07	20/10
Electrical System	**22/05/17**	**06/10/17**
Research	22/05	09/06
Initial Design	03/07	09/07
Prototype	10/07	23/07
Testing	24/07	30/07
Modification/Optimisation	31/07	01/09
Control Box Design	20/09	26/09
Control Box Construction	27/09	05/10
Final Design (G6)	06/10	06/10
Control System	**10/07/17**	**27/10/17**
GUI	**10/07/17**	**27/10/17**
Research	10/07	16/07
Initial Design	17/07	28/07
Testing	29/07	20/08
Modification/Optimization	21/08	26/10
Final Design (G9)	27/10	27/10
Simulink Control Models	**10/07/17**	**02/10/17**
Research	10/07	23/07



Initial Design	14/08	28/08
Testing	29/08	11/09
Modification/Optimisation	12/09	01/10
Final Design (G8)	02/10	02/10
Trajectory Generation Subsystem	**10/07/17**	**27/10/17**
Move-Set Optimisation	10/07	23/07
Animation Program	09/10	26/10
Final Design (G7)	27/10	27/10
Deliverables	**05/03/17**	**31/10/17**
Library Workshop Session	15/03	15/03
IP Declaration Submission	23/04	23/04
Risk Assessment Submission	21/05	21/05
Project Charter	**05/03/17**	**19/03/17**
Draft	05/03	12/03
Final	13/03	18/03
Submission	19/03	19/03
Preliminary Report	**10/04/17**	**02/06/17**
Draft	10/04	18/05
Review	19/05	26/05
Final	27/05	01/06
Submission	02/06	02/06
Seminar	**28/08/17**	**19/09/17**
Preperation	28/08	17/09
Presentation	18/09	19/09
Final Report	**28/08/17**	**27/10/17**
Draft	28/08	18/10
Review	19/10	20/10
Final	21/10	26/10
Submission	27/10	27/10
Ingenuity	**07/10/17**	**31/10/17**
Preperation	07/10	29/10
Presentation	30/10	31/10
Other	**10/06/17**	**23/07/17**
Swot Week	10/06	16/06
Exam Break	17/06	01/07
Riley Possibly Unavailable	01/07	23/07



C Work Breakdown Structure

Resources Required:

(a) 3D Printing

(b) Workshop

(c) Library

(d) CAD

(e) MATLAB

(f) Robotics Lab

(g) Meeting Room

(h) Previous Project Reports

Key:

- **RA:** Resource Allocated, A = Adam, E = Edmund, R = Riley, T = Theodore, G = Whole Team
- **RR:** Resource Required, will have letters relating to resources specified above

Work Breakdown Structure:

WBS	RA	RR
1.0: Hardware Design & Build		
1.1: Requirements Elicitation	G	
1.2: Specification Definitions	G	
1.3: Research		c)
1.3.1: Kinematics and Dynamics of Human Movement	E	
1.3.2: Potential use of Orthopaedic Brackets	T	
1.4: Mechanical System		
1.4.1: Research		c)
1.4.1.1: Ergonomics	E	
1.4.2: Initial Concepts		d)
1.4.2.1: Shoulder	T	
1.4.2.2: Elbow	T	
1.4.2.3: Wrist	T	
1.4.2.4: Ergonomics		
1.4.2.4.1: Back Mount	E	
1.4.2.4.2: Humerus Mount	E	
1.4.2.4.3: Forearm Mount	E	
1.4.3: Workshop Kick-off Meeting	G	b), g)
1.4.4: Comparative Analysis		
1.4.4.1: Criteria Selection	E, R, T	
1.4.4.2: Screening & Scoring Tables	E, R, T	
1.4.4.3: Workshop Design Review	E, R, T	b), g)
1.4.4.4: Modification/Hybridization	E, R, T	
1.4.5: Recommended Initial Design [Milestone]		

1.5: Modular Power Subsystem		
1.5.1: Research		c)
1.5.1.1: Power Types	R	
1.5.1.2: Pros & Cons of Types	R	
1.5.1.3: Recommended Power Type	R	
1.5.2: Initial Designs & Calculations		d)
1.5.2.1: Shoulder	R	
1.5.2.2: Elbow	R	
1.5.2.3: Wrist	R	
1.5.3: Comparative Analysis		
1.5.3.1: Criteria Selection	R	
1.5.3.2: Screening & Scoring Tables	R	
1.5.3.3: Workshop Design Review	R	b), g)
1.5.3.4: Modification/Hybridization	R	
1.5.4: Recommended Initial Design [Milestone]		
1.6: Sensor Subsystem		
1.6.1: Research		c)
1.6.1.1: Sensors	A	
1.6.2: Initial Designs		d)
1.6.2.1: Shoulder	A	
1.6.2.2: Elbow	A	
1.6.2.3: Wrist	A	
1.6.3: Comparative Analysis		
1.6.3.1: Criteria Selection	A	
1.6.3.2: Screening & Scoring Tables	A	
1.6.3.3: Modification/Hybridization	A	
1.6.4: Recommended Initial Design [Milestone]		
1.7: Detailed Design		
1.7.1: Integration	G	
1.7.2: Overall Recommended Initial Design	G	
1.7.3: Workshop Design Review	G	b), g)
1.7.4: Decide on 1 or 2 Arms for Build		
1.7.4.1: Look at Budget	A	
1.7.4.2: Look at Time	A	
1.7.4.3: Make Decision	A	
1.7.5: Modification/Update Design	G	
1.7.6: Verifications/Calculations/Simulations	G	e)
1.7.7: CAD		d)
1.7.7.1: Models	E, R, T	
1.7.7.2: Manufacturing Drawings		
1.7.7.2.1: Parts	E, R, T	
1.7.7.2.2: Assemblies	E, R, T	
1.7.8: Obtain Approval for Build		
1.7.8.1: Supervisor Approval	G	
1.7.8.2: Workshop Approval	G	
1.7.8.3: Work Request Form	A	
1.7.9: Submit Drawings [Milestone]		

1.8: Build		a), b)
1.8.1: Construction	E, T	
1.8.2: Purchase Additional Parts	A	
1.8.3: Assemble [Milestone]		
1.8.4: Maintenance/Modification	E, T	
1.9: Electrical System		
1.9.1: Research		c)
1.9.1.1: Electronics	A	
1.9.1.2: Power Supplies	A	
1.9.2: Initial Design		
1.9.2.1: Power Supply		
1.9.2.1.1: Logic Circuit (5V, 2A)	A	
1.9.2.1.2: Actuator Circuit (12V, 0-20A)	A	
1.9.2.2: Logic Circuit		
1.9.2.2.1: Controller	A	
1.9.2.2.2: PWM Generator	A	
1.9.2.2.3: ADC	A	
1.9.2.3: Actuator Circuit		
1.9.2.3.1: Motor Controllers	A	
1.9.2.3.2: Fans	A	
1.9.3: Prototype	A	f)
1.9.4: Testing	A	e), f)
1.9.5: Modification/Optimisation	A	f)
1.9.6: Control Box Design	A	d)
1.9.7: Control Box Construction	A	a), b), f)
1.9.8: Final Design [Milestone]		
2.0: Control System		
2.1: GUI		
2.1.1: Research		c)
2.1.1.1: How To Use GUI's In MATLAB	A, R	
2.1.2: Initial Design	A, R	e)
2.1.3: Testing	A, R	e)
2.1.4: Modification/Optimisation	R	e)
2.1.5: Final Deign [Milestone]		
2.2: Simulink Control Models		
2.2.1: Research		h)
2.2.1.1: Previous Years Set-up	A, R	
2.2.2: Initial Design		e)
2.2.2.1: Execute Move-Set: Control Model	R	
2.2.2.2: Record Move-Set: Control Model	R	
2.2.2.3: Mirror Mode: Control Model	R	
2.2.3: Testing	R	e)
2.2.4: Modification/Optimisation	R	e)
2.2.5: Final Deign [Milestone]		
2.3: Trajectory Generation Subsystem		
Move-set Optimisation	R	e)

Animation Program	A	e)
3.0: Deliverables		
3.1: Minutes	R	
3.2: Library Workshop Session	G	
3.3: IP Declaration	G	
3.4: Risk Assessment	A	
3.5: Project Charter		
3.5.1: Executive Summary	R	
3.5.2: Project Introduction		
3.5.2.1: Background	R	c)
3.5.2.2: Motivation	R	c)
3.5.2.3: Literature Review	R	c)
3.5.2.4: Aims	R	
3.5.3: Stakeholders	T	
3.5.4: Goals	A	
3.5.5: Resources Required	T	
3.5.6: WBS/Gantt Chart	A	
3.5.7: Project Risk Management	E	
3.5.8: Budget	A	
3.5.9: Conclusion	R	
3.5.10: Submission [Milestone]	A	
3.6: Preliminary Report		
3.6.1: Executive Summary	R	
3.6.2: Introduction	R	
3.6.3: Management	A	
3.6.4: Literature Review		c)
4.6.4.1: Human Kinematics & Dynamics	E	
4.6.4.2: Control Strategy	A	
3.6.5: Mechanical System	E, R, T	
3.6.6: Electrical System	A	
3.6.7: Control System	A	
3.6.8: Future Work	A, R	
3.6.9: Conclusion	R	
3.7: Seminar		
3.7.1: Preparation	G	
3.7.2: Presentation	G	
3.8: Final Report		
3.8.1: Executive Summary	R	
3.8.2: Introduction	R	
3.8.3: Management	A	
3.8.4: Literature Review	A, R, E	c)
3.8.5: Electrical System	A	
3.8.6: Mechanical System	E, R, T	
3.8.7: Control System	R	
3.8.8: Future Work	A, R	
3.8.9: Conclusion	A	
3.9: Ingenuity		

3.9.1: Preparation	G	
3.9.2: Presentation	G	

Table 5: Work Breakdown Structure

D Risk Assessment

D.1 Project Risks

The following project risks have been assigned severity, likelihood and overall risk ratings according to the risk matrix presented in figure 39 below.

Severity

Likelihood		1 - Insignificant	2 - Minor	3 - Moderate	4 - Major	5 - Catastrophic
A -	Almost certain	High(H)	High(H)	Extreme(X)	Extreme(X)	Extreme(X)
B -	Likely	Moderate(M)	High(H)	High(H)	Extreme(X)	Extreme(X)
C -	Possible	Low(L)	Moderate(M)	High(H)	Extreme(X)	Extreme(X)
D -	Unlikely	Low(L)	Low(L)	Moderate(M)	High(H)	Extreme(X)
E -	rare	Low(L)	Low(L)	Moderate(M)	High(H)	High(H)

Extreme (X) – Act immediately to eliminate the risk or at the very least mitigate it. Requires constant surveillance.

High (H) – Act immediately to mitigate the risk. Requires frequent surveillance.

Medium (M) – Reasonable steps should be taken to mitigate risk. Requires less frequent surveillance.

Low (L) – Mitigate/survey if necessary.

Figure 39: Project Risk Matrix

R001: Budget Exceeded
Description: Expenditures are not closely watched and the project runs out of funding before it is completed.

Severity: Major(4) **Likelihood:** Possible(C) **Risk:** Extreme(X)

Mitigation Strategy: Use a spreadsheet to keep track of the budget and make sure an items are only purchased once the team is 100% sure they are required.

New Severity: Major(4) **New Likelihood:** Rare(E) **New Risk:** High(H)

R002: Insufficient Time Allocation
Description: The time allocated to perform a certain task is not enough to complete it resulting in a delay to the entire project. This could potentially result in some of the project goals not being completed.

Severity: Major(4) **Likelihood:** Likely(B) **Risk:** Extreme(X)

Mitigation Strategy: Make use of appropriate Milestones and a Gantt chart to manage the time line of the project. When allocating time for tasks on the Gantt chart make use of Hofstadter's law to make sure more time is given then necessary to allow for unforeseen events.

New Severity: Major(4) **New Likelihood:** Unlikely(D) **New Risk:** High(H)

R003: Ergonomics of The Design
Description: A design is manufactured that doesn't actually fit the intend user requiring a rebuild of the components involved.

Severity: Moderate(3) **Likelihood:** Possible(C) **Risk:** High(H)

Mitigation Strategy: Perform extensive research into ergonomics and make sure the final design has adjustable joints and straps wherever necessary.

New Severity: Moderate(3) **New Likelihood:** Rare(E) **New Risk:** Medium(M)

R004: Sickness
Description: A team member becomes sick and spreads it to everyone else in the group reducing overall productivity.

Severity: Catastrophic(5) **Likelihood:** Almost Certain(A) **Risk:** Extreme(X)

Mitigation Strategy: Make sure the infected group remains isolated from the group until they are better. Communication between team members can still occur it will just have to be online rather than face to face.

New Severity: Insignificant(1) **New Likelihood:** Almost Certain(A) **New Risk:** High(H)

R005: Faulty Parts
Description: Faulty motors or sensors are purchased form a store so parts have to be repurchased.

Severity: Major(4) **Likelihood:** Possible(C) **Risk:** Extreme(X)

Mitigation Strategy: Make sure research is conducted towards where parts are being purchased from and keep all receipts so items can be returned if necessary.

New Severity: Minor(2) **New likelihood:** Unlikely(D) **New Risk:** Low(L)

R006: Communication failure
Description: Team members become confused with tasks assigned to them resulting in the wrong problems being addressed. These problems will need to be readdressed properly therefore wasting project time.

Severity: Moderate(3) **Likelihood:** Likely(B) **Risk:** High(H)

Mitigation Strategy: Have individual reports from team members at the start of every meeting in order to explain what has been accomplished in the past week. Make sure that any issues found are dealt with accordingly so the project can get back on track.

New Severity: Moderate(3) **New likelihood:** Unlikely(D) **New Risk:** Medium(M)

R007: Device Safety
Description: The control system behaves unexpectedly and the motors try to bend the users arm the wrong way resulting in physical injury.

Severity: Catastrophic(5) **Likelihood:** Possible(C) **Risk:** Extreme(X)

Mitigation Strategy: Design in hardware countermeasures in the form of mechanical stops to prevent this from ever happening.

New Severity: Catastrophic(5) **New likelihood:** Rare(E) **New Risk:** High(H)

R008: Lack of skills
Description: A team member might not have the required knowledge to complete a task related to their subsystem.

Severity: Moderate(3) **Likelihood:** Possible(C) **Risk:** High(H)

Mitigation Strategy: Make sure team members get help either from each other or any of the supervisors if stuck.

New Severity: Insignificant(1) **New likelihood:** Possible(C) **New Risk:** Low(L)

R009: Goals Not Met
Description: Unable to achieve specified goals throughout project due to unforeseen issues.

Severity: Minor(2) **Likelihood:** Possible(C) **Risk:** Medium(M)

Mitigation Strategy: Hold multiple weekly meetings to make sure the project is heading in the right direction. If something unforeseen comes up deal with it promptly (Note: goals are aloud to change explanations just have to be provided in subsistent reports).

New Severity: Minor(2) **New likelihood:** Rare(E) **New Risk:** Low(L)

R010: File Deletion
Description: Files or folders are accidentally deleted from the group repository.

Severity: Catastrophic(5) **Likelihood:** Likely(B) **Risk:** Extreme(X)

Mitigation Strategy: Back up repository every week and make sure files are stored in multiple locations.

New Severity: Minor(2) **New likelihood:** Likely(B) **New Risk:** High(H)

R011: Workshop Construction Delayed
Description: The workshop is delayed due to other honours projects and therefore can't complete the mechanical and electrical systems of the exoskeleton in time for the testing of the control system

Severity: Major(4) **Likelihood:** Likely(B) **Risk:** Extreme(X)

Mitigation Strategy: Make sure to hand in electrical and mechanical system designs well before their due date so they can be placed near the top of the workshops queue.

New Severity: Major(4) **New likelihood:** Possible(C) **New Risk:** High(H)

D.2 Safety Risks

D.2.1

See the next page...

HAZARD MANAGEMENT – RISK ASSESSMENT(LONG FORM)

Stage 1:	Hazard Identification	Residual risk rating L, M, H, VH	L
Name or description of the activity(s) to be assessed	Building and testing of an upper body exoskeleton for use with assistive teaching for rehabilitative purposes		
Area, School/Branch Building/Room	School of Mechanical Engineering, Robotics Lab		
Workers completing the risk assessment. Name and contact details	Adam Bartlett	Mobile/Phone	0422 969 537
	Riley Lodge	Mobile/Phone	0431 522 869
	Ho Tin Kong	Mobile/Phone	0403 290 937
	Yongjun Ng	Mobile/Phone	0404 633 926

- This template or equivalent template can be used. Please note that this list is not exhaustive, but can be used as the basis for your initial hazard identification.
- If you tick yes to any of the hazards listed below, then the hazard is to be transferred and addressed on **Appendix C2.**
  Where a number of activities have the same hazards, they may be grouped together on the same assessment and the same control measures applied to each.

Consider – is there potential for, or identified exposure to any of the following, as part of a process/activity

Physical/Environmental Hazards		Plant and Equipment hazards	
☐	Animals (e.g. hazardous wild animals, bees, snakes)	☐	Mobile lifting equipment or farm machinery
☐	Confined space entry (e.g. pit, tank, silo, entry through a hatch)	☐	Pressurised vessels/systems (e.g. autoclave, boiler)
☐	Fall from a height (e.g. ladder, elevated platform, cliff, scaffolding)	☐	Hazardous levels of heat or vibration (to whole or part body)
☐	Fire (potential for uncontrolled fire due to ignition sources)	☐	Hazardous plant (e.g. lathes, lasers, microtomes, cryostats,
☐	Flying or moving items/plant/vehicles, falling object(s)		or operations could result in amputation, eye injury, serious
☐	Hazardous terrain or environment including wet/slippery surfaces		laceration, crushing injury)
☐	Lighting/visibility is compromised and hazardous	**Radiation hazards**	
☐	Noise or sound levels > 85dB(A) or peak level of greater than	☐	Sealed sources or unsealed sources
	135 dB(C) for any period of time	☐	Artificial sources (UV)
☐	Temperature or weather extremes (e.g. hypothermia, major burns)	**Biological hazards (e.g. via inhalation, contact, digestion)**	
☐	Isolation (e.g. work in a remote area, difficult to access work site,	☐	Contamination (e.g. pathogens, body fluids)
	or a rescue effort would be difficult in the event of an emergency.	☐	Animal handling (e.g. bites, allergies)
☐	Boating and/or Diving (e.g. risk of drowning)	☐	Other
Communications		**Chemical hazards**	
☐	Communication problems (e.g. by virtue of location or isolation)	☐	Explosive substances
Electrical		☐	Flammable substances, gas, airborne contaminants
☒	Electric shock	☐	Toxic or asphyxiate gas (e.g. CO_2 including dry ice, liquid N_2)
Ergonomic/Hazardous Manual activity/task(s)		☐	Respiratory irritants (e.g. nanotech, dust, asbestos)
☐	Work requiring repetitive force or movement	☐	Chemical spraying (e.g. agricultural, pesticides)
☒	Sustained force/posture or awkward posture	☐	Prohibited and restricted carcinogens requiring a permit
☐	Working with animals, unpredictable/unbalanced loads	☐	Hazardous chemicals (not included above)
☐	Transfer of item(s) up or down stairs, using both hands or	☐	Other
	requiring the use of lifting equipment from one level to another	**Activity combines a number of different hazards, and**	
Stress/Duress hazards		**the impact/results of interaction is unknown e.g. mixing**	
☐	Personal threat e.g. aggressive behaviour, abuse, threat, assault	**chemicals or recognised as a risk e.g. water and electricity.**	
	(includes home visits)	☐	Specify -
☐	Fatigue e.g. from excessive work related mental/physical exertion	**High Risk Travel**	
Remote work location or working in isolation		☐	Destination is rated DFAT 3 or 4 (High/Very High)
☐	Medical emergency, difficult to administer/obtain first aid	**High risk work licence required in accordance with WHS Regs**	
	gain assistance e.g. access to medical facilities	☐	Boom-type elevating work platform, scaffolding, dogging,
Other			crane and hoist operation, reach stackers, forklift operation,
☒	Moving and rotating parts		pressure equipment operation.
☐			
☐		☐	No hazards identified. No risk assessment required.

HAZARD MANAGEMENT

Stage 2 and Stage 3 – Risk Assessment and Control

Record the potential hazards/issues identified in Hazard Identification Process on Appendix C1 **and** **When and where the hazard is present (i.e. when is the worker exposed?)**	**Inherent risk assessment rating** Before controls are implemented (Refer to the risk assessment Tables – Appendix C3) L, M, H, VH	**List the control measures implemented (i.e. in place)** • Control measures are to be in accordance with the Hierarchy of Control. Refer to Appendix C3 for examples. • Choose the control(s) that most effectively eliminate the hazard or minimises the risk. • Record the control measures in place under the relevant control measure (e.g. list in order under the following headings - substitution, isolation, engineering, administrative, Personal Protective Equipment). • Ensure that control measures do not introduce new hazards.	**Residual risk rating** After controls in place The highest rating is to be transferred to the top of page C1.
Electric shock – User could sustain a small electrical shock from coming in contact with either the motors, motor drivers, power supply or the controller electronics. (12V 0-5A)	M	Substitution – 12V motors have been selected over 24V motors as they lower the power of the electric shock that the user could sustain. Isolation – Insulation has been used to properly cover all physical cables and motor mounts whilst the controller electronics have been safely contained within a nonconductive control box.	L
Ergonomics – It is possible for the motors to move in ways the human body cannot therefore putting unwanted strain on the user's joints.	H	Engineering – Mechanical stops have been put in place (bolts and pins) to restrict the motion of the exoskeleton's joints so they can only move in the same way as the user's limbs. Engineering – Software protection has also been put in place by using feedback from the sensors to restrict the motion of the exoskeletons limbs.	L
Ergonomics – The weight of the exoskeleton could discomfort the user if worn for a long amount of time during testing.	M	Isolation – A full chest harness, and belts, have been selected to hold the weight of the entire exoskeleton. This chest harness restricts the user's movement and acts as a brace to make sure their spine remains straight during testing exercises. It is also able to pass the majority of the systems weight through the user's hips to make it easier for them to wear for longer durations of time. Administrative – During testing sessions the user should take regular breaks from wearing the device anytime they start to feel uncomfortable.	L
Moving and rotating parts – Motors and gears have to be used to power the exoskeleton. It is possible that the user could get a part of their body stuck or pinched in these parts resulting in minor injuries.	M	Isolation – 3D printed protective covers have been designed to ensure the user isn't able to directly access the gears or motor shafts. Engineering – The motors selected for powering the exoskeleton only move at slow speeds so it would be very hard for the user to actually injure a part of their body.	L

Moving and rotating parts – The control subsystem could malfunction and start making the exoskeleton behave erratically in which case you would want to have an emergency shutdown feature in place.	M	Engineering – An emergency stop button has been included in the electronic subsystems design. In the case of an emergency it can be pressed to cut off all power being provided to the exoskeleton.	L

Staff related activities (Note – Low and Medium Residual Risk does not require Manager/Supervisor authorisation)			Student related activities		
Author	Name and Signature		Author Adam Bartlett	Name and Signature	Adam Bartlett [signature] 16/05/17
High Residual Risk – Authorised by Manager/Supervisor	Name and Signature/authority		Low and Medium Residual Risk – Authorised by Manager/Supervisor	Name and Signature/authority	[signature] Tien-Fu Lu
High Residual Risk – Authorised by Head of School/Branch	Name and Signature/authority		High Residual Risk – Authorised by Head of School/Branch	Name and Signature/authority	
Very High Residual Risk – Authorised by VC&P	Name and Signature/authority		Very High Residual Risk – Authorised by VC&P	Name and Signature/authority	

HAZARD MANAGEMENT

RISK ASSESSMENT TABLES

Three essential steps are taken:

1. The probability or likelihood of an incident occurring is evaluated;
2. The severity of the potential consequences is calculated or estimated;
3. Based on these two factors, the risks are assigned priority for risk control through the use of a risk rating.

Risk assessment involves examining and evaluating the likelihood/severity/consequence in order to prioritise and implement adequate controls. The risk matrix has been adopted based on the principles of AS/NZS ISO 31000 (2009) Risk Management – Principles and Guidelines and Code of Practice "How to Manage Work Health and Safety Risks (2012).

Likelihood Table

CATEGORY	DESCRIPTION
Almost certain	There is an expectation that an event/incident will occur.
Likely	There is an expectation that an event/incident **could occur** but not certain to occur.
Slight	This expectation lies somewhere in the midpoint between "could" and "improbable".
Unlikely	There is an expectation that an event/incident is doubtful or **improbable** to occur.
Rare	There is no expectation that the event/incident will occur.

Consequences Table

CATEGORY	DESCRIPTION
Severe	Injury resulting in death, permanent incapacity.
Major	Injury requiring extensive medical treatment, hospitalisation, or activities could result in a Notifiable occurrence.
Moderate	Injury requires formal medical treatment (hospital outpatient/doctors visit etc), activities could result in an Improvement Notice.
Minor	Injury requires first aid.
Negligible	Injury requires minor first aid (e.g. bandaid), or result in short term discomfort (e.g. bruise, headache, muscular aches etc), no medical treatment.

Risk matrix

Likelihood	Consequences				
	Negligible	Minor	Moderate	Major	Severe
Almost Certain	Medium	High	Very High	Very High	Very High
Likely	Medium	Medium	High	Very High	Very High
Slight	Low	Medium	High	High	Very High
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Low	Medium	Medium

<u>**If the level of risk is assessed as high or very high**</u>

- ☐ Stop the activity; or
- ☐ Tag out the plant/equipment; or
- ☐ Secure any chemical; and
- ☐ Determine if the activity is to:
  - ☐ continue; or
  - ☐ cease

in consultation with your Manager/Supervisor.

Follow the process in 3.5.6.1 where the risk cannot be reduced to medium or low.

Appendix C4 (Page 4 of 4)

HAZARD MANAGEMENT

HIERARCHY OF RISK CONTROL

Hierarchy of control			Examples of control measures	
HIGHEST	Level 1	Elimination	• Not introducing the hazard into the workplace. • Designing out the hazards before they are introduced. • Removing the hazard completely. • Not conducting the activity.	MOST
	If this is not practicable then	↓		
	Level 2 Where it is not reasonably practicable to eliminate the hazards and associated risks.	Substitution	• Replacing or substituting the hazard with something safer.	
		Isolation	• Isolating the hazard from the people by distance or using barriers.	
		Engineering	• Installing/using a control measure of a physical nature, including a mechanical device or process e.g. trolleys, hoists, guards, residual current devices, fume-hoods, extraction/ventilation systems, RCD protection.	
		↓		
LEVEL OF HEALTH AND SAFETY PROTECTION	Level 3 These control measures do not control the hazard at the source. They rely on human behaviour and supervision, and used on their own tend to be the least effective in minimising risks.	Administrative	• Documenting a standard operating procedure (SOP) and include in the induction program for all staff required to perform the activity • Developing a proficiency based training program if required by the risk assessment (see definitions) (Workers may be trained against the SOP Appendix E or other assessment criteria.) • Training workers to use control measures implemented when carrying out the activity • Introducing a second operator • Providing signage or warning labels • Restricting access • Maintenance and testing programs • Changing the work organisation e.g. relocating equipment or items, rotating workers between different activities	RELIABILITY OF CONTROL MEASURES
LOWEST	Exposure is only limited if the worker wears and uses the PPE correctly.	Personal Protective Equipment (PPE)	Requiring the use of one or more of the following: • ear protection (ear muffs) • respirators • face masks • hard hats/helmet • gloves, aprons • eye protection (glasses, shield, visor) • non-slip footwear • appropriate clothing	LEAST

For further examples and explanation on the Hazard Management and Risk Control process, please refer to the Code of Practice for How to manage WHS Risks (2011).

D.2.2 Safe Operating Procedure

See the next page...

Appendix E

HAZARD MANAGEMENT – SAFE OPERATING PROCEDURE (SOP)

NAME OF THE TASK/ACTIVITY	**2366: REFAUM – TESTING/DEMO WITHOUT USER**	**DATE: 26/10/17**
LOCATION	THE UNIVERSITY OF ADELAIDE – ENG SOUTH, ROBOTICS LAB AND WORKSHOP ADELAIDE CONVENTION CENERE – INGENUITY BOOTH	
RISK ASSESSMENT (RA) NAME & NUMBER	**2366: Building and testing of an upper body exoskeleton for use with assistive teaching for rehabilitative purposes**	
Residual risk rating on the RA	☒ Low ☐ Medium ☐ High ☐ Very High	
Hazards identified on the RA	**Electric Shock, Sustained force/posture or awkward pose, Moving and rotating parts**	

PERSONAL PROTECTIVE EQUIPMENT

Operation of the REFAUM system requires the use of closed-toe shoes and tight-fitting clothing.

DESCRIBE, IN SEQUENCE, STEPS TO COMPLETE THE ACTIVITY SAFELY

STOP!

<u>DO NOT OPERATE THE REFAUM SYSTEM</u> IF YOU HAVE NOT BEEN AUTHORISED TO DO SO BY THE DESIGN TEAM.

Preparation – Work Area Check:

- ❑ Area is easily accessible for the operator.
- ❑ Area is free from debris, fluids and or any other tripping hazards.
- ❑ Area does not interfere with walkways, doors or emergency exits.
- ❑ Area is free of unauthorised personnel.

Preparation – REFAUM System Set-up:

- ❑ Place the stand inside the work area, in a position that allows for safe movement of the exoskeleton's limbs.
- ❑ Properly secure the stand with weights to ensure it remains stationary.
- ❑ Carefully place the REFUAM system onto the stand making sure the Velcro straps of the vest are tightly secured.
- ❑ Secure the additional blue straps around the exoskeleton.
- ❑ <u>Familiarise yourself with the location of the two switches capable of turning off the exoskeleton in case of an emergency. The first of which is a toggle switch located on the bottom left of the control box (Up = ON, Down = OFF) whilst the second one is the power switch on the front right hand side of the PSU (- = ON, O = OFF).</u>
- ❑ Make sure the toggle switch on the electrical system is turned off (Down = OFF).
- ❑ Place the PSU somewhere out of the way where it can easily be accessed by the operator.
- ❑ Make sure the PSU is switched off.
- ❑ Connect the power cable form the control box to the PSU. Make sure that the terminals have been properly secured and covered with electrical tape.
- ❑ Plug the PSU into a standard 240V mains power socket.
- ❑ Plug in the Ethernet cable from the host computer to the control box. If required (i.e. not using Wi-Fi).
- ❑ Put up a boundary around the REFAUM system using tape or barricades to keep unwanted personnel away during operation.

Pre – Operational Safety Checks:

- ❑ Visually inspect the REFAUM system to make sure none of the components or wires are damaged in any way. Any unsafe equipment should be reported to the appropriate staff members.
- ❑ Ensure the toggle and PSU switches are off.
- ❑ Be aware of other activities happening within the immediate area.
- ❑ Ensure no trip hazards are present and the operator has easy access to the suit.

Operation:

- ❑ Switch on the PSU.
- ❑ Turn on the REFAUM system by flicking the toggle switch on the control box (Up = ON).
- ❑ Wait 30 seconds for the Raspberry Pi to boot up.
- ❑ Start up the GUI on the host computer.
- ❑ Select the desired mode of operation and follow the required steps listed below.
- ❑ NEVER LEAVE THE REFAUM SYSTEM RUNNING WHILE UNATTENDED.
- ❑ At any point during operation the suit can be turned off by: Pressing the red "STOP" button in the bottom right-hand corner of the GUI, flicking the toggle switch on the control box to the off position (Down = OFF) or by turning off the PSU.

Operation – Recording:
- ❑ Select the "Record" tab in the GUI.
- ❑ Make sure the area surrounding the REFAUM system is clear.
- ❑ Click the "Start Recording" button on the GUI.
- ❑ Move the left arm of the exoskeleton to record the desired move-set.
- ❑ When finished click the "Finish Recording" button on the GUI.
- ❑ The move-set can then be saved by pressing the "Save Move-Set" button on the GUI.

Operation – Executing:
- ❑ Select the "Play Move Set" tab in the GUI.
- ❑ Select the desired move-set to be recorded from the drop-down menu on the GUI.
- ❑ Click "preview" to see an animation on the host computer of what the move-set should look like.
- ❑ If the move-set is ok and the area around the exoskeleton is clear press the "Execute Move-set" button on the GUI to execute the move-set.
- ❑ The move-set will go until completion unless the "Stop Movement" button on the GUI is pressed.

Operation – Mirror Image:
- ❑ Select the "Mirror" tab in the GUI.
- ❑ Make sure the area surrounding the REFAUM system is clear.
- ❑ Click the "Start" button to put the exoskeleton into the mirror image mode.
- ❑ Move the left arm of the exoskeleton, the right arm should replicate its motion.
- ❑ When finished click the "Stop" button on the GUI to turn off the mirror image mode.

Pack Up:
- ❑ Close the GUI, and clear the MATLAB workspace.
- ❑ Turn off the REFUAM system by flicking the toggle switch on the control box (Down = OFF).
- ❑ Switch off the PSU.
- ❑ Unplug the PSU from the wall socket.
- ❑ Remove the control box's power cable from the PSU.
- ❑ Remove the Ethernet cable from the control box, if used.
- ❑ Unbuckle the straps securing the exoskeleton.
- ❑ Place the REFAUM system in a secure area making sure not to damage any or the wires, motors or control box.

Emergency Stop Requirements:
The REFUAM system must be switched off, by flicking the toggle switch on the bottom left hand side of the control box (Up = ON, Down = OFF) or the PSU power button (- = ON, O = OFF) to their respective off positions, if any of the following situations occur:
- ❑ Motors malfunction or get stuck on the mechanical stops.
- ❑ Any of the exoskeletons limbs become unattached.
- ❑ If the stand falls over or looks like is about too.
- ❑ If any weird sounds or other observations are made that seem out of the ordinary.

Prepared by				
People involved in the drafting of this SOP	Adam Bartlett, Riley Lodge			
Person authorising the SOP	Name:	Tien-Fu Lu		Signature Tien Lu
	Position:	Project Supervisor		Date: 27/10/17

This Safe Operating Procedure must be reviewed after any incident/injury associated with this activity or when a risk assessment is reviewed.

E Budget

See the next page...

Direct Costs:

Item	Quantity	Cost	Total Cost	Date	Group Member	Retailer
Elastic Strap	2	$5.99	$11.98	18/04/2017	Adam Bartlett	eBay - happytime31
Airsoft Stab Proof Vest	1	$48.96	$48.96	19/04/2017	Adam Bartlett	eBay - worldwidekeyseller_gotobuy
Large Motor	2	$88.48	$176.96	5/05/2017	Adam Bartlett	eBay - tidefeel
Medium Motor	2	$28.42	$56.84	5/05/2017	Adam Bartlett	eBay - remotor
Small Motor	1	$9.19	$9.19	5/05/2017	Adam Bartlett	eBay - yuniquee
5 x 10K Potentiometer	1	$2.00	$2.00	5/05/2017	Adam Bartlett	eBay - winddeal
5 x Small Motor Controller	1	$26.99	$26.99	5/05/2017	Adam Bartlett	eBay - smartdigi
Raspberry Pi 3 Model B Kit	1	$96.95	$96.95	5/05/2017	Adam Bartlett	eBay - learcnc
2 x 40mm DC Fan	2	$1.94	$3.88	19/05/2017	Adam Bartlett	eBay - go_vovotrade
PCA9685 PWM Generator	1	$7.95	$7.95	15/06/2017	Adam Bartlett	eBay - bitb99
Large Motor Controller	2	$24.45	$50.55	15/06/2017	Adam Bartlett	eBay - robotshop_inc
MCP3008 ADC	1	$8.95	$8.95	18/07/2017	Adam Bartlett	eBay - learcnc
I2C Converter	1	$9.95	$9.95	19/07/2017	Adam Bartlett	eBay - aus3d-shop
10 x Miniature Needle Roller Bearing	1	$13.07	$13.07	26/07/2017	Adam Bartlett	eBay - speed_mart
10 x M20 Hex Lock Nut	1	$31.50	$31.50	26/07/2017	Adam Bartlett	eBay - thefastenerwarehouse1
10 x Thrust Needle Roller Bearing	1	$19.62	$19.62	26/07/2017	Adam Bartlett	eBay - speed_mart
10 x Self Lubricating Bearing Sleeve	2	$5.68	$11.36	26/07/2017	Adam Bartlett	eBay - solaluna88
100 x M4 Bolt	1	$28.80	$28.80	26/07/2017	Adam Bartlett	eBay - thefastenerwarehouse1
Hinge	2	$2.21	$4.42	14/08/2017	Adam Bartlett	Bunnings
2m 25A R&B Wire	1	$8.70	$8.70	27/09/2017	Adam Bartlett	Jaycar
40 x Male Header Pins	1	$0.95	$0.95	27/09/2017	Adam Bartlett	Jaycar
5 x DC Jacks	1	$12.30	$12.30	1/10/2017	Adam Bartlett	eBay - valuefinding
White Zortrax ABS	1	$46.00	$46.00	12/10/2017	Adam Bartlett	3dprintergear
25A Toggle Switch	1	$1.35	$1.35	18/10/2017	Adam Bartlett	eBay - amazing-trading
10 x Port Lever Terminal Block	1	$4.79	$4.79	18/10/2017	Adam Bartlett	eBay - xingchunqing1984
DC Buck Converter	1	$3.49	$3.49	18/10/2017	Adam Bartlett	eBay - koala-ok

3 x Large Terminal Block	1	$5.60	$5.60	18/10/2017	Adam Bartlett	eBay - wind-speed168
30 x PCB Mount Terminal Block	1	$2.67	$2.67	18/10/2017	Adam Bartlett	eBay - happyleucky
Assorted PCB Protoboards	1	$6.90	$6.90	18/10/2017	Adam Bartlett	eBay - cyperworm
MCP3008 ADC	1	$8.95	$8.95	18/10/2017	Adam Bartlett	eBay - learcnc
Electrical Tape	1	$2.95	$2.95	27/10/2017	Adam Bartlett	Jaycar
25m Roll - Light Hook Up Wire - Red	1	$5.50	$5.50	27/10/2017	Adam Bartlett	Jaycar
25m Roll - Light Hook Up Wire - Black	1	$5.50	$5.50	27/10/2017	Adam Bartlett	Jaycar
25m Roll - Light Hook Up Wire - Green	1	$5.50	$5.50	27/10/2017	Adam Bartlett	Jaycar
8G USB	1	$11.95	$11.95	27/10/2017	Adam Bartlett	Jaycar
3m, 15A Red Wire	1	$3.75	$3.75	27/10/2017	Adam Bartlett	Jaycar
3m, 15A Black Wire	1	$3.75	$3.75	27/10/2017	Adam Bartlett	Jaycar
10m, 7.5A Red Wire	1	$5.50	$5.50	27/10/2017	Adam Bartlett	Jaycar
10m, 7.5A Black Wire	1	$5.50	$5.50	27/10/2017	Adam Bartlett	Jaycar
		Grand Total:	$771.52			

In-Kind Costs:

Item	Estimated Cost	Supplier
ABS	$40	3D printing workshop
Acrylic	$60	Mech Eng workshop
Nuts & Bolts	$20	Mech Eng workshop
MATLAB/Simulink Licence	$500	Technology services
13.8V, 20A PSU	$100	Group member
Grand Total:	$720	

Salary Costs:

Team Member	Task Completed	Hourly Rate	Hours Worked	Cost
Workshop	Pin Manufacturing	50	6	$300
		Sub Total:	6	$300

Adam	Entire Project	50	670	$31,950
Edmund	Entire Project	50	343	$17,150
Riley	Entire Project	50	667	$26,300
Theodore	Entire Project	50	528	$26,400
		Sub Total:	2208	$110,400
		Grand Total:	2214	$110,700

F Movement Figures

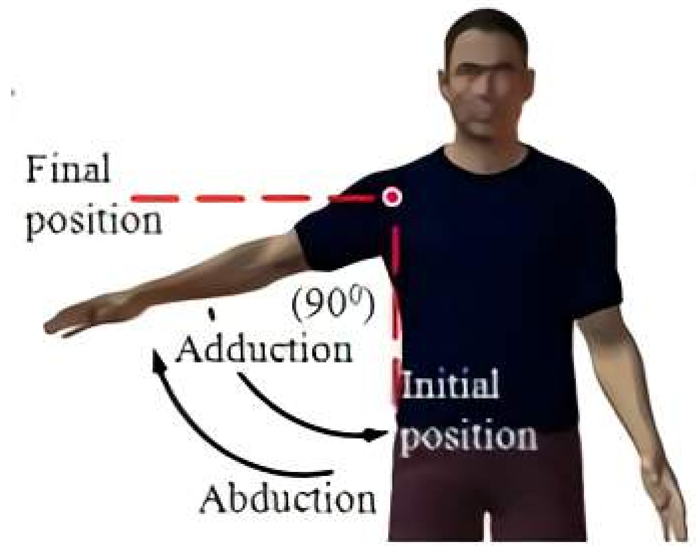


Figure 40: Shoulder Yaw - x-axis (R.A.R.C. Gopura, et al. 2010, pp56)

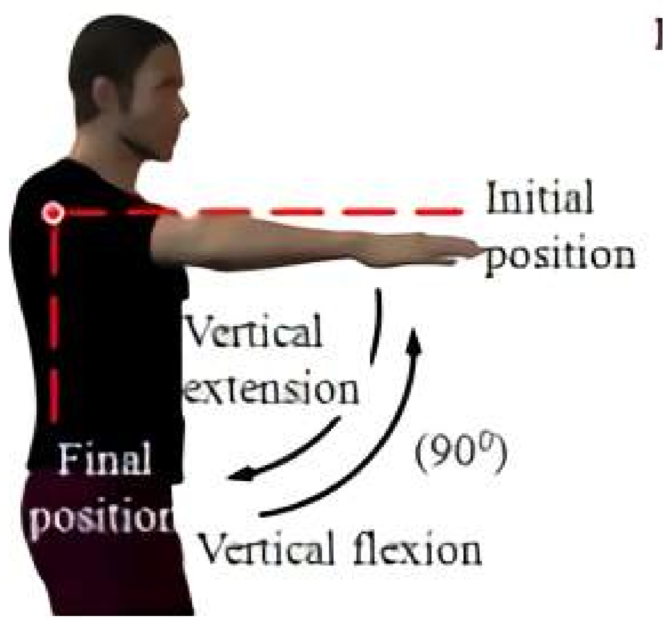


Figure 41: Shoulder Pitch - y-axis (R.A.R.C. Gopura, et al. 2010, pp56)

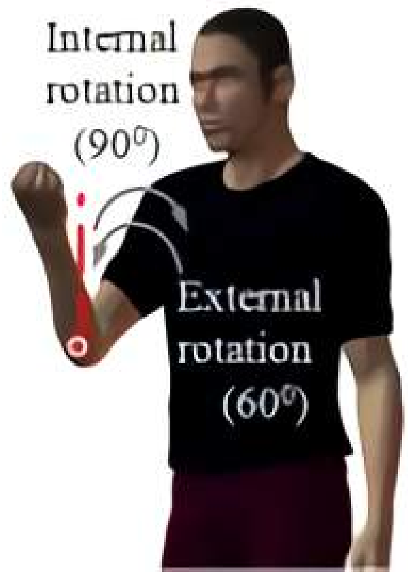


Figure 42: Shoulder Roll - z-axis (R.A.R.C. Gopura, et al. 2010, pp56)

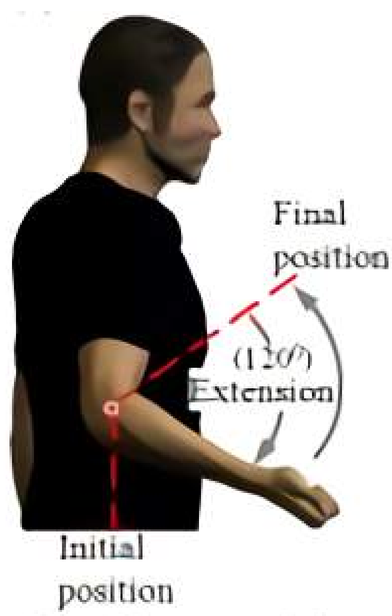


Figure 43: Elbow Pitch - z-axis (R.A.R.C. Gopura, et al. 2010, pp56)

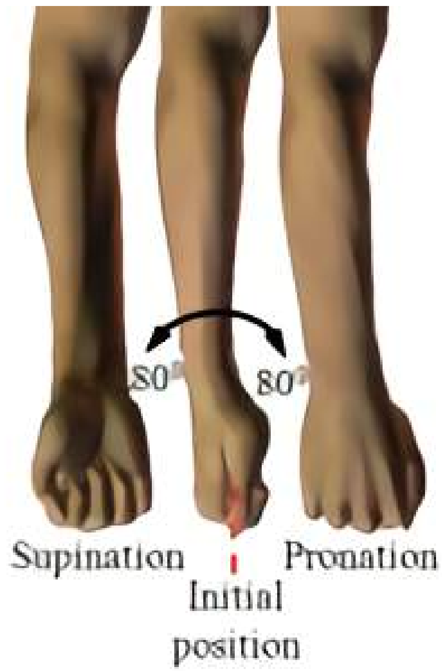
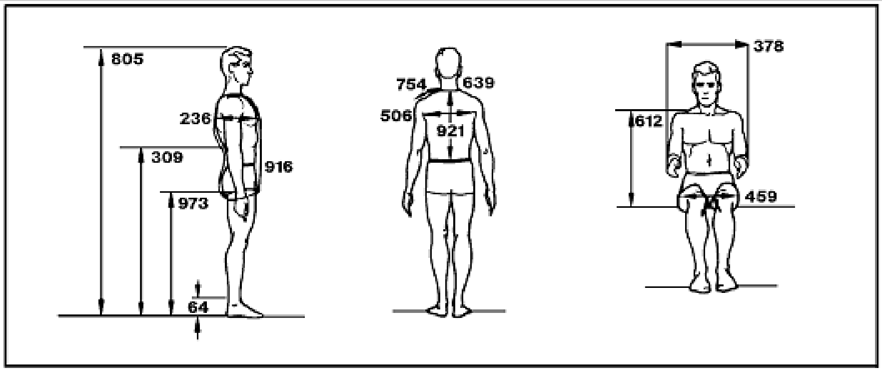


Figure 44: Wrist Roll: z-axis (R.A.R.C. Gopura, et al. 2010, pp56)

G NASA Anthropometry



Microgravity notes	No.	Dimension	5th percentile	50th percentile	95th percentile
1	916	Vertical trunk circumference	158.7 (62.5)	170.7 (67.2)	182.6 (71.9)
2 1	612	Midshoulder height, sitting	60.8 (23.9)	65.4 (25.7)	70.0 (27.5)
	459	Hip breadth, sitting	34.6 (13.6)	38.4 (15.1)	42.3 (16.6)
1	921	Waist back	43.7 (17.2)	47.6 (18.8)	51.6 (20.3)
	506	Interscye	32.9 (13.0)	39.2 (15.4)	45.4 (17.9)
	639	Neck circumference	35.5 (14.0)	38.7 (15.2)	41.9 (16.5)
	754	Shoulder length	14.8 (5.8)	16.9 (6.7)	19.0 (7.5)
	378	Forearm-forearm breadth	48.8 (19.2)	55.1 (21.7)	61.5 (24.2)

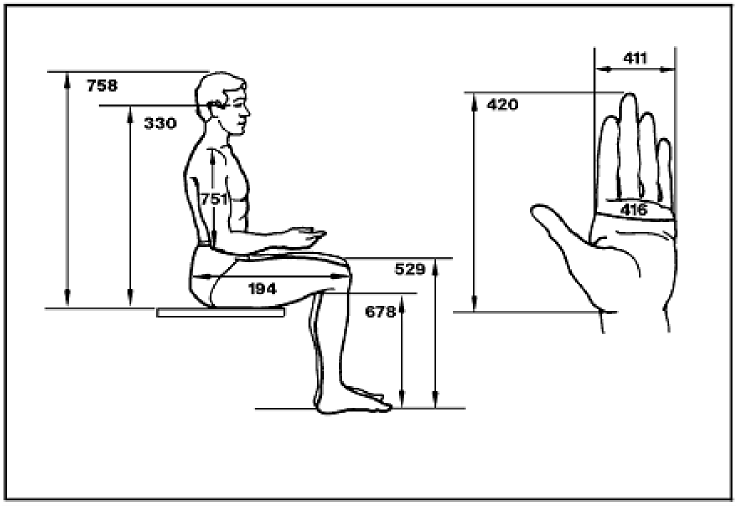
Values in cm with inches in parentheses

Notes:

a) Gravity conditions - the dimensions apply to a 1-G condition only. Dimension expected to change significantly due to microgravity are marked.

b) Measurement data - the numbers adjacent to each of the dimension are reference codes. the same codes are in Volume II of Reference 16. Reference 16, Volume II, provides additional data for these measurements plus an explanation of the measurement technique.

Notes for application of dimensions to microgravity conditions:



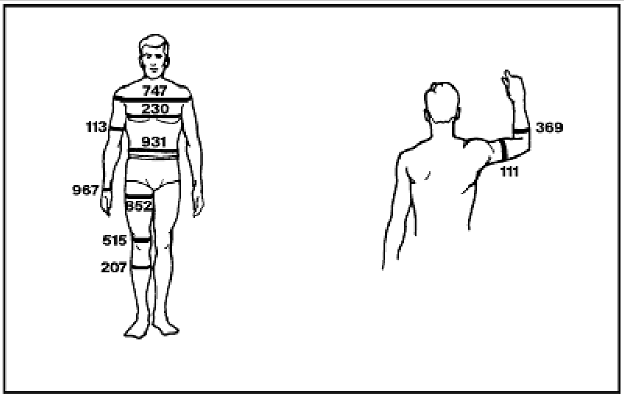
Microgravity notes	No.	Dimension	5th percentile	50th percentile	95th percentile
2 1	758	Sitting height	88.9 (35.0)	94.2 (37.1)	99.5 (39.2)
2 1	330	Eye height, sitting	76.8 (30.3)	81.9 (32.2)	86.9 (34.2)
4	529	Knee height, sitting	52.6 (20.7)	56.7 (22.3)	60.9 (24.0)
	678	Popliteal height	40.6 (16.0)	44.4 (17.5)	48.1 (19.0)
	751	Shoulder-elbow length	33.7 (13.3)	36.6 (14.4)	39.4 (15.5)
	194	Buttock-knee length	56.8 (22.4)	61.3 (24.1)	65.8 (25.9)
	420	Hand length	17.9 (7.0)	19.3 (7.6)	20.6 (8.1)
	411	Hand breadth	8.2 (3.2)	8.9 (3.5)	9.6 (3.8)
	416	Hand circumference	20.3 (8.0)	21.8 (8.6)	23.4 (9.2)

Notes:

a) Gravity conditions - the dimensions apply to a 1-G condition only. Dimension expected to change significantly due to microgravity are marked.

b) Measurement data - the numbers adjacent to each of the dimension are reference codes. the same codes are in Volume II of Reference 16. Reference 16, Volume II, provides additional data for these measurements plus an explanation of the measurement technique.

Notes for application of dimensions to microgravity conditions:



Microgravity notes	No.	Dimension	5th percentile	50th percentile	95th percentile
	747	Shoulder circumference	109.5 (43.1)	119.2 (46.9)	128.8 (50.7)
	230	Chest circumference	89.4 (35.2)	100.0 (39.4)	110.6 (43.6)
6	931	Waist circumference	77.1 (30.3)	89.5 (35.2)	101.9 (40.1)
5	852	Thigh circumference	52.5 (20.7)	60.0 (23.6)	67.4 (26.5)
5	515	Knee circumference	35.9 (14.1)	39.4 (15.5)	42.9 (16.9)
5	207	Calf circumference	33.9 (13.3)	37.6 (14.8)	41.4 (16.3)
	113	Biceps circumference, relaxed	27.3 (10.7)	31.2 (12.3)	35.1 (13.8)
	967	Wrist circumference	16.2 (6.4)	17.7 (7.0)	19.3 (7.6)
	111	Biceps circumference, flexed	29.4 (11.6)	33.2 (13.1)	36.9 (14.5)
	369	Forearm circumference, relaxed	27.4 (10.8)	30.1 (11.8)	32.7 (12.9)

Notes:

a) Gravity conditions - the dimensions apply to a 1-G condition only. Dimension expected to change significantly due to microgravity are marked.

b) Measurement data - the numbers adjacent to each of the dimension are reference codes. the same codes are in Volume II of Reference 16. Reference 16, Volume II, provides additional data for these measurements plus an explanation of the measurement technique.

Notes for application of dimensions to microgravity conditions:

H PWM Generator - MATLAB Libraries

H.1 Initialisation Function

```
% PWM Generator initialisation function
% By Adam Bartlett, ID: a1646071
function i2cpwm = i2cpwm_init(Rasp_pi)

    % Create i2c object
    i2cpwm = i2cdev(Rasp_pi, 'i2c-1', '0x40');

    % Set all 4 PWM rails to 0
    write(i2cpwm, [hex2dec('FA'), hex2dec('0')]);
    write(i2cpwm, [hex2dec('FB'), hex2dec('0')]);
    write(i2cpwm, [hex2dec('FC'), hex2dec('0')]);
    write(i2cpwm, [hex2dec('FD'), hex2dec('0')]);


    % Make changes to MODE1 & MODE2
    write(i2cpwm, [hex2dec('01'), hex2dec('04')]);
    write(i2cpwm, [hex2dec('00'), hex2dec('01')]);
    pause(0.005)

    % Read MODE1 register into matlab under "mode1"
    mode1 = readRegister(i2cpwm, hex2dec('00'));

    % Update and Write mode1 to PWM generator
    mode1 = mode1 & (bitcmp(hex2dec('10'), 'int8'));
    write(i2cpwm, [hex2dec('FA'), mode1]);
    pause(0.005);

end
```

H.2 Set Frequency Function

```
% PWM Generator frequency set function
% By Adam Bartlett, ID: a1646071
function i2cpwm_freq(freq, i2cpwm)

    % Ajust prescale value
    prescaleval = 25000000.0;
    prescaleval = prescaleval / 4096.0;
    prescaleval = prescaleval / freq;
    prescaleval = prescaleval - 1.0;
    prescale = floor(prescaleval + 0.5);

    % Save current MODE1 register
    oldmode = readRegister(i2cpwm, hex2dec('00'));

    % Generate new mode for MODE1 register
    newmode = bitor((bitand(oldmode, hex2dec('7F'))), hex2dec('10'));

    % Update registers
    write(i2cpwm, [hex2dec('00'), newmode]);
    write(i2cpwm, [hex2dec('FE'), floor(prescale)]);
    write(i2cpwm, [hex2dec('00'), oldmode])
    pause(0.005)
    write(i2cpwm, [hex2dec('00'), bitor(oldmode, hex2dec('80'))])

end
```

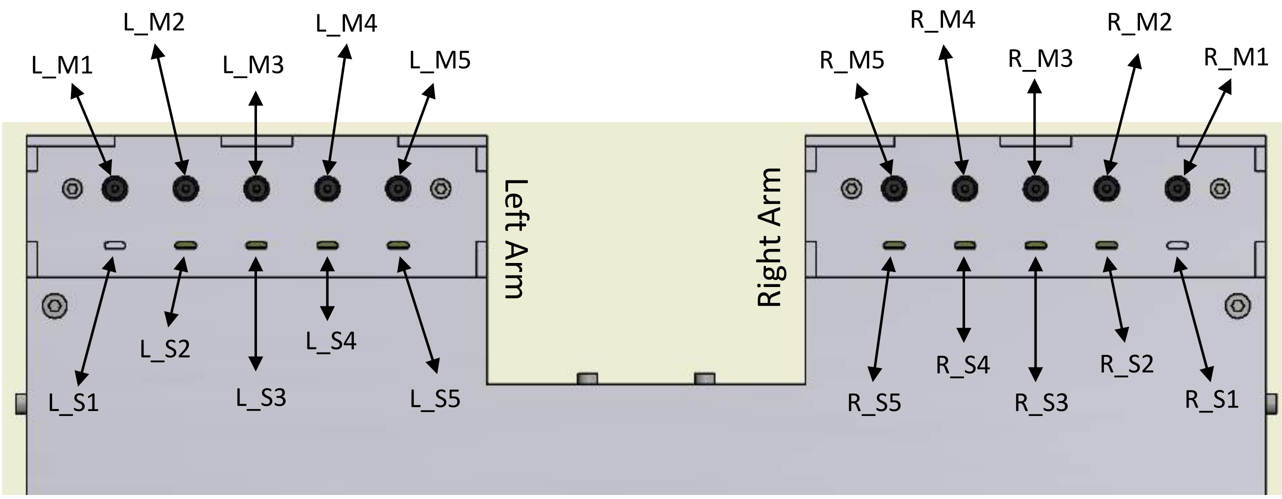
H.3 Set Motor Speed Function

```
% PWM Generator set motor speed function
% By Adam Bartlett, ID: a1646071
function i2cpwm_set(motor_num, pwm_val, i2cpwm)


    if(motor_num == 0) % PWM Channel: 0 [Shoulder: Pitch]
        write(i2cpwm, [hex2dec('06') 0]);
        write(i2cpwm, [hex2dec('07') 0]);

        write(i2cpwm, [hex2dec('08') bitand(pwm_val, hex2dec('FF'))]);
        write(i2cpwm, [hex2dec('09') bitshift(pwm_val, -8)]);

    elseif(motor_num == 1) % PWM Channel: 1 [Shoulder: Yaw]
        write(i2cpwm, [hex2dec('0A') 0]);
        write(i2cpwm, [hex2dec('0B') 0]);

        write(i2cpwm, [hex2dec('0C') bitand(pwm_val, hex2dec('FF'))]);
        write(i2cpwm, [hex2dec('0D') bitshift(pwm_val, -8)]);

    elseif(motor_num == 2) % PWM Channel: 2 [Shoulder: Roll]
        write(i2cpwm, [hex2dec('0E') 0]);
        write(i2cpwm, [hex2dec('0F') 0]);

        write(i2cpwm, [hex2dec('10') bitand(pwm_val, hex2dec('FF'))]);
        write(i2cpwm, [hex2dec('11') bitshift(pwm_val, -8)]);

    elseif(motor_num == 3) % PWM Channel: 3 [Elbow: Pitch]
        write(i2cpwm, [hex2dec('12') 0]);
        write(i2cpwm, [hex2dec('13') 0]);

        write(i2cpwm, [hex2dec('14') bitand(pwm_val, hex2dec('FF'))]);
        write(i2cpwm, [hex2dec('15') bitshift(pwm_val, -8)]);

   elseif(motor_num == 4) % PWM Channel: 4 [Wrist: Roll]
        write(i2cpwm, [hex2dec('16') 0]);
        write(i2cpwm, [hex2dec('17') 0]);

        write(i2cpwm, [hex2dec('18') bitand(pwm_val, hex2dec('FF'))]);
        write(i2cpwm, [hex2dec('19') bitshift(pwm_val, -8)]);
    else
        % Do nothing
    end

end
```

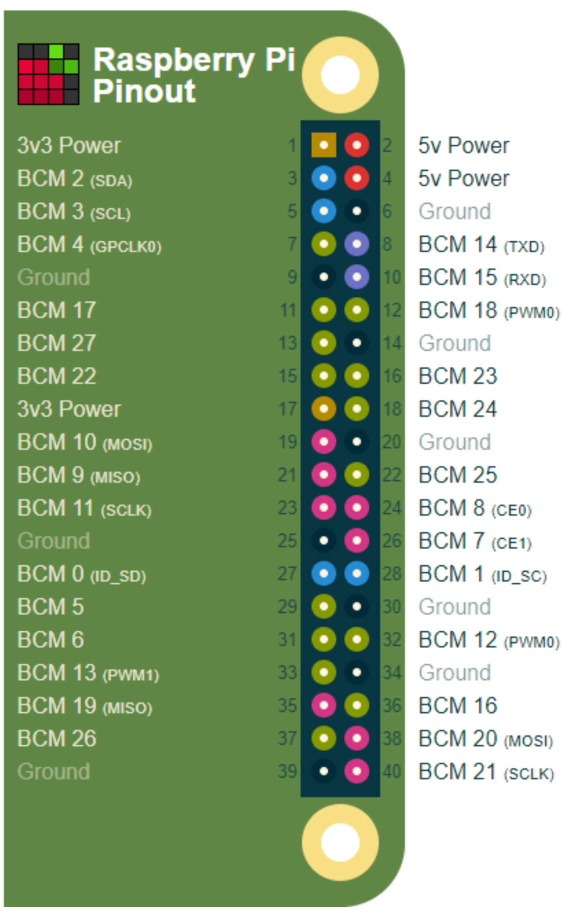
I Electrical System - Component Key

See the next page...

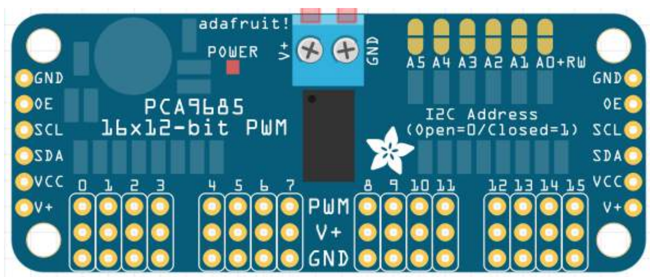
Control Box – I/O Ports



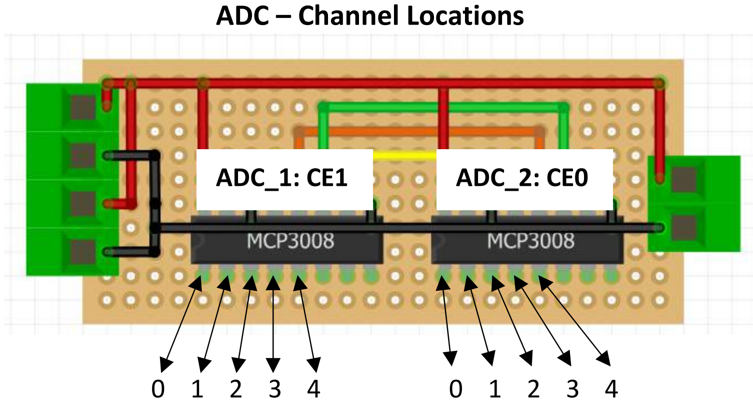
Raspberry Pi – GPIO Pin Locations



PWM – Channel Locations



ADC – Channel Locations



Key: Right Arm

Shoulder Pitch:

Motor: R_M1

- Direction = BCM 17
- Speed = PWM_0

Sensor: R_S1

- ADC_1: CE1 = Channel 0

Shoulder Yaw:

Motor: R_M2

- Direction = BCM 25
- Speed = PWM_1

Sensor: R_S2

- ADC_1: CE1 = Channel 1

Shoulder Roll:

Motor: R_M3

- In1 = BCM 5
- In2 = BCM 6
- Speed = PWM_3

Sensor: R_S3

- ADC_1: CE1 = Channel 2

Elbow Pitch:

Motor: R_M4

- In3 = BCM 27
- In4 = BCM 22
- Speed = PWM_2

Sensor: R_S4

- ADC_1: CE1 = Channel 3

Wrist Roll:

Motor: R_M5

- In3 = BCM 23
- In4 = BCM 24
- Speed = PWM_4

Sensor: R_S5

- ADC_1: CE1 = Channel 4

Key: Left Arm

Shoulder Pitch:

Motor: L_M1

- N/A

Sensor: L_S1

- ADC_2: CE0 = Channel 0

Shoulder Yaw:

Motor: L_M2

- N/A

Sensor: L_S2

- ADC_2: CE0 = Channel 1

Shoulder Roll:

Motor: L_M3

- N/A

Sensor: L_S3

- ADC_2: CE0 = Channel 2

Elbow Pitch:

Motor: L_M4

- N/A

Sensor: L_S4

- ADC_2: CE0 = Channel 3

Wrist Roll:

Motor: L_M5

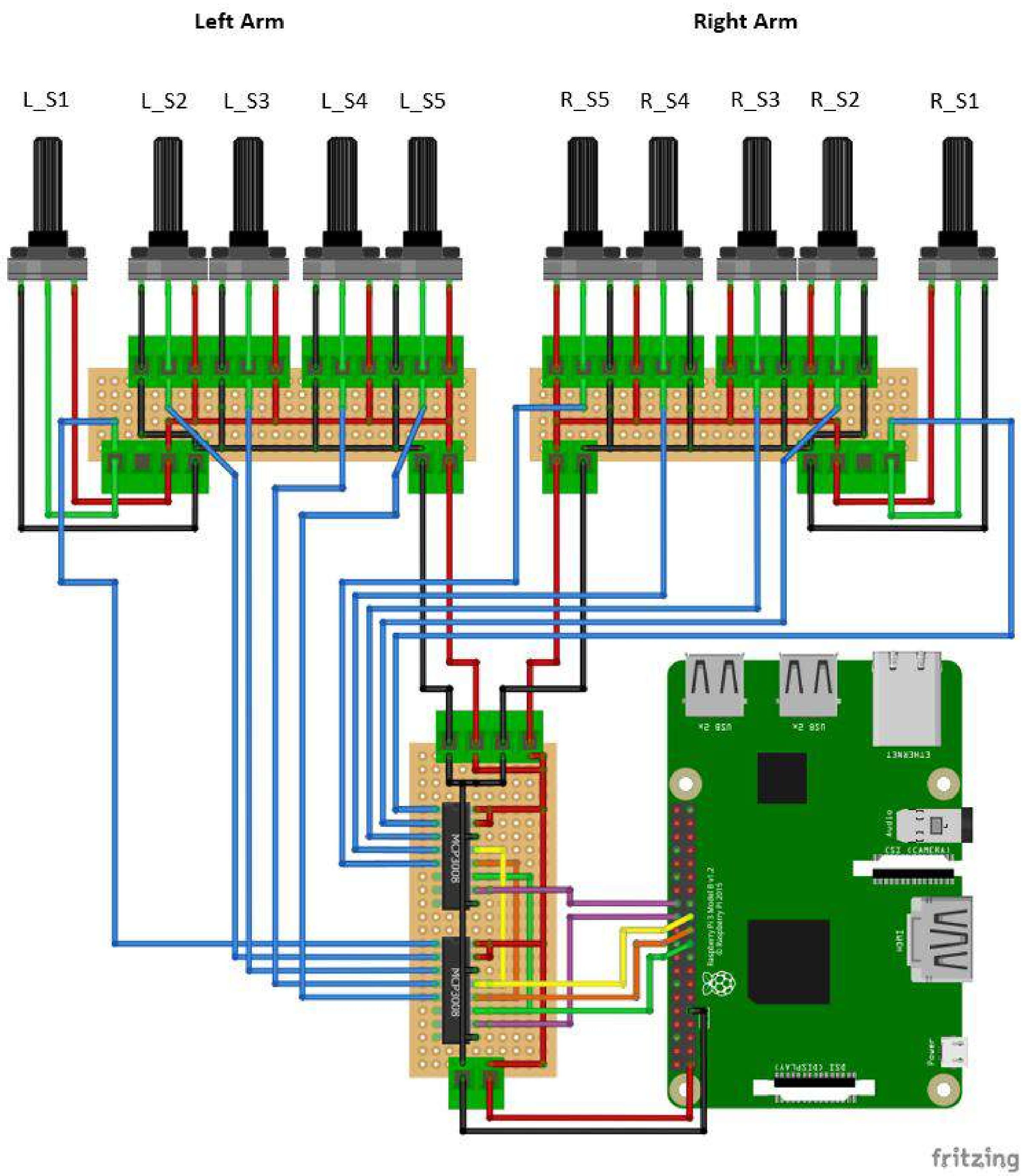
- N/A

Sensor: L_S5

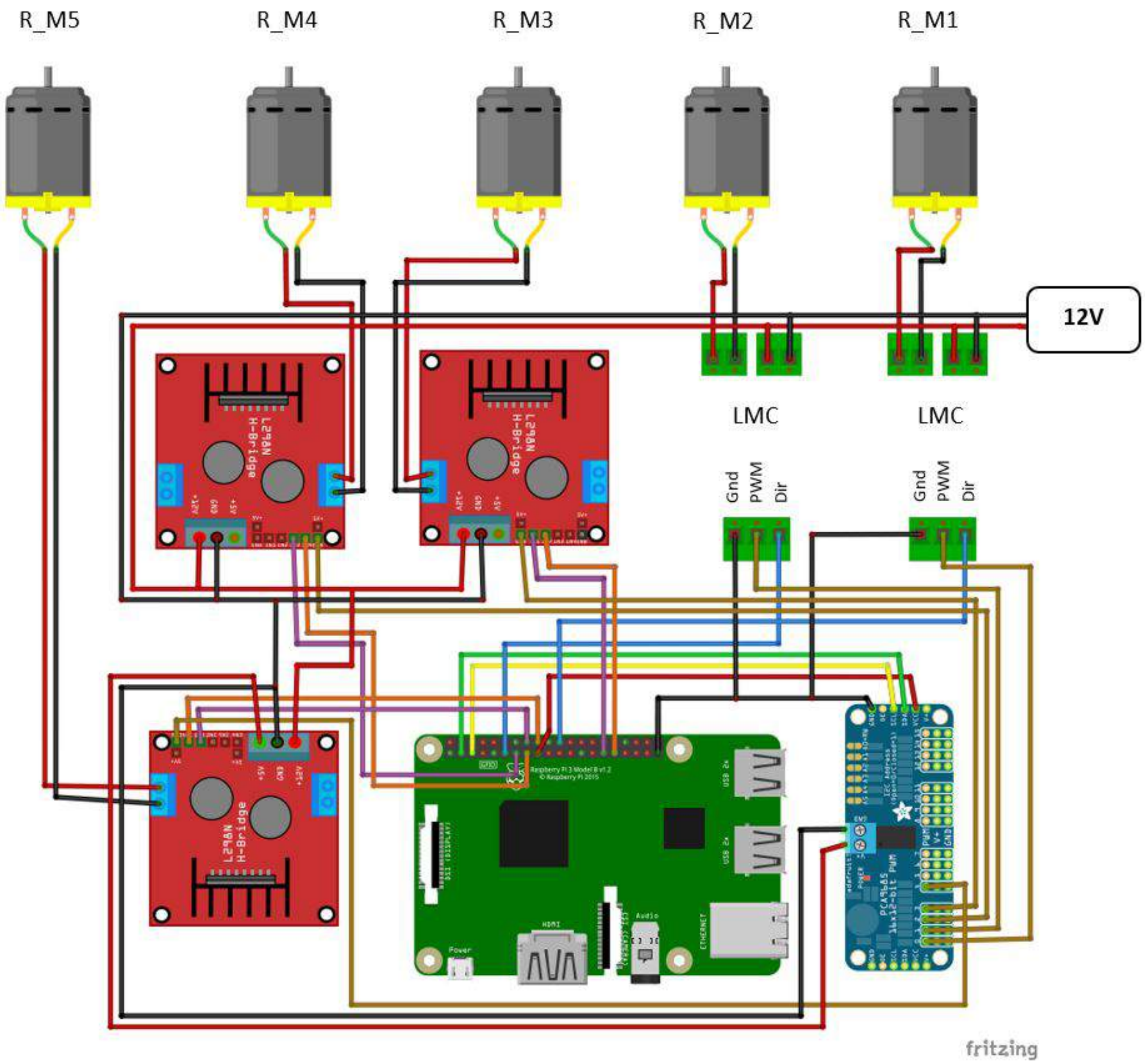
- ADC_2: CE0 = Channel 4

J Electrical System - Wiring

J.1 Sensor Configuration



J.2 Motor Configuration



K Matlab Control Code

K.1 S-Function Output

```
%%
%% Outputs:
%%   Functionality    : Called to generate block outputs in
%%                      simulation step
%%   Required         : Yes
%%   C-MEX counterpart: mdlOutputs
%%
function Outputs(block)
global config;
global offsets;
global G;
global initial;

t = [0 0 0 0 0];
m = [.2 .6 .8 1 1.3];
d = [ .17 .15 .08 .27];
h = [ 0.9 0.8 0.04 0.13];
g=9.8;
for i=1:5
    t(i) = readVoltage(config.mcp3008_2,i-1);
    block.OutputPort(11-2*i).data = t(i);
    block.OutputPort(2*i).data = 3.2 - readVoltage(config.mcp3008_1,5-i)+offsets(i);
end
t(1) = 1.46*t(1) - initial(1);
t(2) = 1.46*t(2) - initial(2) - pi/4;
t(3) = 3*t(3) - initial(3);
t(4) = 1.46*t(4) - initial(4);



G(1)=  g* m(2)*(d(2)*cos(t(1))- h(2)*sin(t(1))*sin(t(2))) + g* m(3)*(d(2)*cos(t(1))+ h↙
(3)*(cos(t(1))*cos(t(3))+ cos(t(2))*sin(t(1))*sin(t(3))) - d(3)*sin(t(1))*sin(t(2)))↙
+ g* m(4)*(d(2)*cos(t(1))+ h(4)*(sin(t(4))*(cos(t(1))*sin(t(3))- cos(t(2))*cos(t(3))↙
*sin(t(1))) - cos(t(4))*sin(t(1))*sin(t(2))) + d(4)*(cos(t(1))*cos(t(3))+ cos(t(2))↙
*sin(t(1))*sin(t(3))) - d(3)*sin(t(1))*sin(t(2))) + g* h(1)*m(1)*cos(t(1));
G(2)=  g* cos(t(1))*(d(3)*m(3)*cos(t(2))+ d(3)*m(4)*cos(t(2))+ h(2)*m(2)*cos(t(2))+ h↙
(4)*m(4)*cos(t(2))*cos(t(4))+ d(4)*m(4)*sin(t(2))*sin(t(3))+ h(3)*m(3)*sin(t(2))*sin(t↙
(3))- h(4)*m(4)*cos(t(3))*sin(t(2))*sin(t(4)));
G(3)=  - g* m(4)*(d(4)*(sin(t(1))*sin(t(3))+ cos(t(1))*cos(t(2))*cos(t(3))) - h(4)*sin↙
(t(4))*(cos(t(3))*sin(t(1))- cos(t(1))*cos(t(2))*sin(t(3)))) - g* h(3)*m(3)*(sin(t(1))↙
*sin(t(3))+ cos(t(1))*cos(t(2))*cos(t(3)));
G(4)=  g* h(4)*m(4)*(cos(t(4))*(sin(t(1))*sin(t(3))+ cos(t(1))*cos(t(2))*cos(t(3))) -↙
cos(t(1))*sin(t(2))*sin(t(4)));
G(5) =  0;

 block.OutputPort(11).data = G(4);
```

K.2 S-Function Update

See the next page...

```
%end Outputs

%%
%% Update:
%%   Functionality    : Called to update discrete states
%%                      during simulation step
%%   Required         : No
%%   C-MEX counterpart: mdlUpdate
%%
function Update(block)


global config;
%**************** Control Motors Here ***************************%

global G;




for i=1:5
    setPoint(i) = (block.InputPort(i).Data + sign(block.InputPort(i).Data)*G(i)*100);
end


%% Get/Update Direction

    % Wrist
    if(setPoint(1) > 0)
        % Go CCW
        writeDigitalPin(config.mypi, 24, 0);
        writeDigitalPin(config.mypi, 23, 1);
    else
        % Go CW
        writeDigitalPin(config.mypi, 23, 0);
        writeDigitalPin(config.mypi, 24, 1);
    end
    if(abs(setPoint(1)) <300)
        setPoint(1)=0;
    end


    % Elbow
    if(setPoint(3) > 0)
        % Go CCW
        writeDigitalPin(config.mypi, 22, 0);
        writeDigitalPin(config.mypi, 27, 1);
    else
        % Go CW
        writeDigitalPin(config.mypi, 27, 0);
        writeDigitalPin(config.mypi, 22, 1);
    end

    if(abs(setPoint(3)) <300)
        setPoint(3)=0;
```

```
    end


    % Arm
    if(setPoint(2) > 0)
        % Go CCW
        writeDigitalPin(config.mypi, 5, 0);
        writeDigitalPin(config.mypi, 6, 1);
    else
        % Go CW
        writeDigitalPin(config.mypi, 6, 0);
        writeDigitalPin(config.mypi, 5, 1);
    end

    if(abs(setPoint(2)) <300)
        setPoint(2)=0;
    end


    % Shoulder
    if(setPoint(4) > 0)
        % Go CCW
        writeDigitalPin(config.mypi, 25, 1);

    else
        % Go CW
        writeDigitalPin(config.mypi, 25, 0);
    end
    if(abs(setPoint(4)) <420)
        setPoint(4)=0;
    end


    % Back
    if(setPoint(5) > 0)
        % Go CCW
        writeDigitalPin(config.mypi, 17, 1);

    else
        % Go CW
        writeDigitalPin(config.mypi, 17, 0);
    end
    if(abs(setPoint(5)) <420)
        setPoint(5)=0;
    end


    for i=1:5
        i2cpwm_set(5-i,floor(abs(setPoint(i))), config.i2cpwm)
    end
```

L Animation Function - MATLAB Code

See the next page...

```
% Move-Set Animation Function
% By Adam Bartlett, ID: a1646071
function animate(Back, Shoulder, Arm, Elbow, Wrist)

    % Collect initial move-set data:
        % Joint Data:
        SB_i = Back.Data;
        SS_i = Shoulder.Data;
        SW_i = Arm.Data;
        E_i = Elbow.Data;
        W_i = Wrist.Data;

        % Time Data:
        time_i = Back.Time;
        SIZE = size(time_i');

    %% Find Zero Positions: Assuming not given yet
        zero_pos = [SB_i(1), SS_i(1), SW_i(1), E_i(1), W_i(1)];

    %% Increase size of move-set through interpolation
        % This helps make the animation look smoother

        % Variables
        int_SB = [];
        int_SS = [];
        int_SW = [];
        int_E = [];
        int_W = [];
        TIME = [];

        flag = 1;
        k = 1;

        % Interpolate
        for i = 1:(SIZE(2)*2 - 1)

            if(flag == 1) % Odd = Normal value

                int_SB(i) = SB_i(k);
                int_SS(i) = SS_i(k);
                int_SW(i) = SW_i(k);
                int_E(i) = E_i(k);
                int_W(i) = W_i(k);

                TIME(i) = time_i(k);

                k = k + 1;
                flag = 0;

            else % Even = Interpolated value

                int_SB(i) = (SB_i(k) + SB_i(k - 1))/2;
                int_SS(i) = (SS_i(k) + SS_i(k - 1))/2;
                int_SW(i) = (SW_i(k) + SW_i(k - 1))/2;
                int_E(i) = (E_i(k) + E_i(k - 1))/2;
```

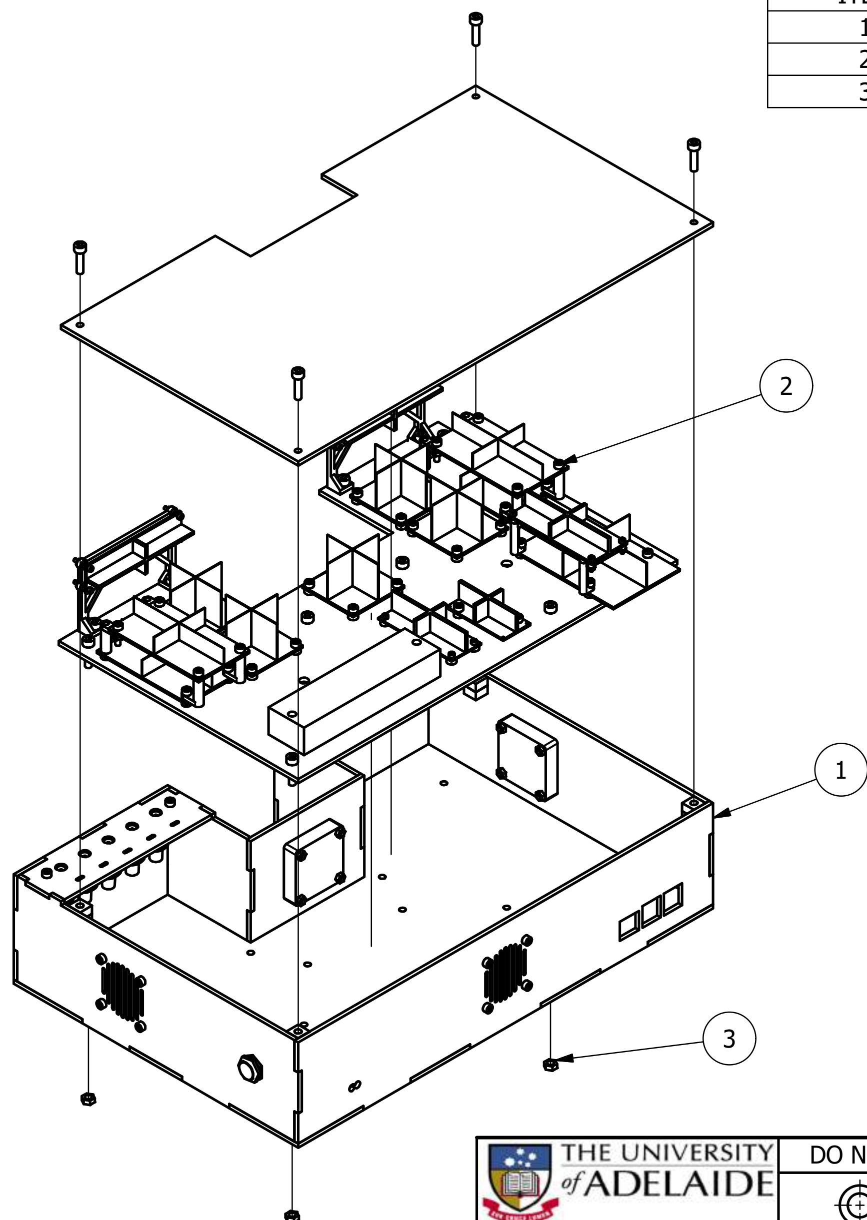
```
                int_W(i) = (W_i(k) + W_i(k - 1))/2;

                TIME(i) = (time_i(k) + time_i(k - 1))/2;

                flag = 1;
            end
        end

    %% Convert joint data from voltage to radians
    for i = 1:(SIZE(2)*2 - 1)

        SB(i) = ((int_SB(i) - zero_pos(1))*83.414 + 11.697)*(pi/180);
        SS(i) = ((int_SS(i) - zero_pos(2))*83.414 - 78.303)*(pi/180);   % Offset by 90
degrees to get to our defined real position
        SW(i) = ((int_SW(i) - zero_pos(3))*83.414 + 11.697)*(pi/180);
        E(i) = ((int_E(i) - zero_pos(4))*83.414 + 11.697)*(pi/180);
        W(i) = ((int_W(i) - zero_pos(5))*83.414 + 11.697)*(pi/180);

    end
    move_set = [SB' SS' SW' E' W'];

    %% Determine FPS of move-set
    rec_Fps = [];
    for i = 2:(SIZE(2)*2 - 1)
        rec_Fps(i) = TIME(i) - TIME(i - 1);
    end
    FPS = round((1/(mean(rec_Fps))));

    %% Initialise the robotics toolbox
    startup_rvc;

    % Link Lengths:
    d2 = 0.5;
    d3 = 0.5;
    d4 = 0;
    d5 = 0.5;

    % D&H Parameters
    L(1) = Link([0 0 0 0],'modified');
    L(2) = Link([0 d2 0 pi/2],'modified');
    L(3) = Link([0 d3 0 pi/2],'modified');
    L(4) = Link([0 d4 0 -pi/2],'modified');
    L(5) = Link([0 d5 0 pi/2],'modified');

    %Create the robot by using the SerialLink command form the RVC toolbox
    R = SerialLink(L, 'name','REFAUM');

    %% Animate the move-set
    R.plot(move_set, 'fps', FPS, 'noname', 'trail', '.')

end
```

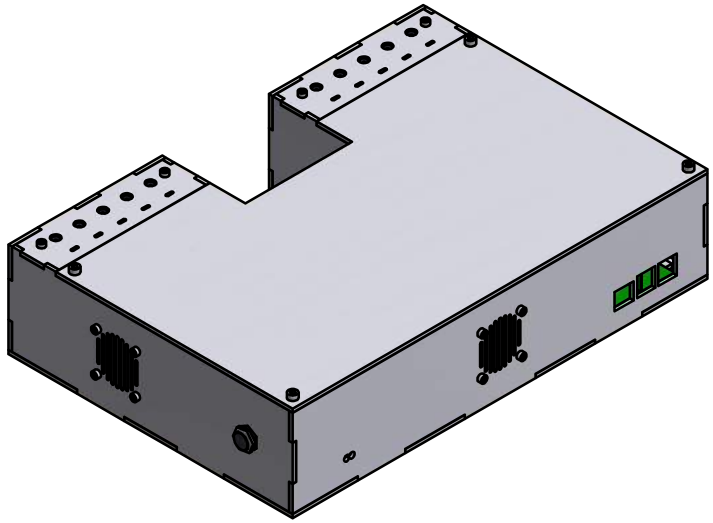
M CAD

M.1 Control Box: Assembly

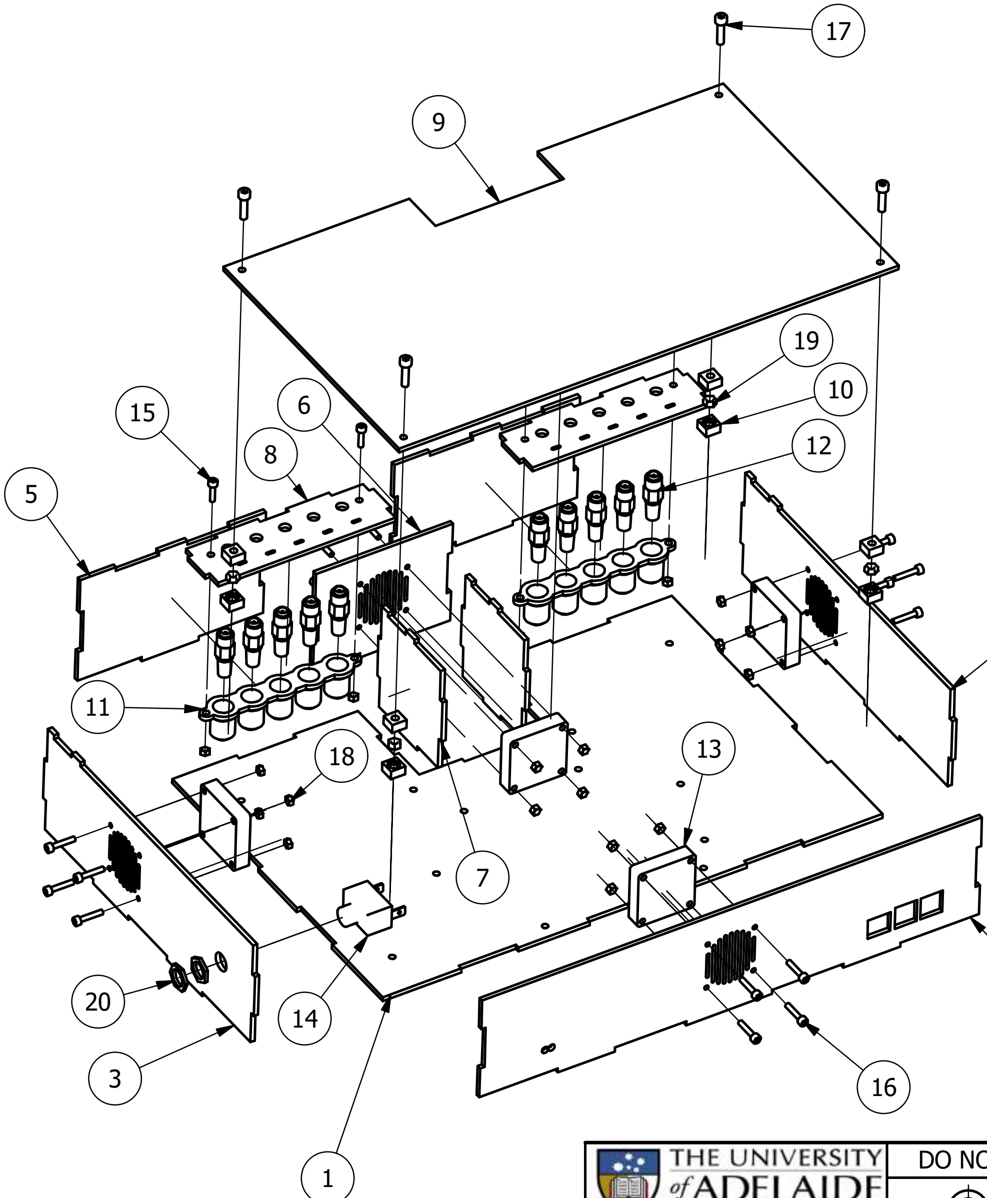
See the next page...

PARTS LIST			
ITEM	PART NUMBER	DESCRIPTION	QTY
1	CTR-01-00	Initial Control Box Assembly	1
2	CTR-02-00	Component Assembly	1
3	AS 1112 – M4	Nut, Hexagon, M4	6



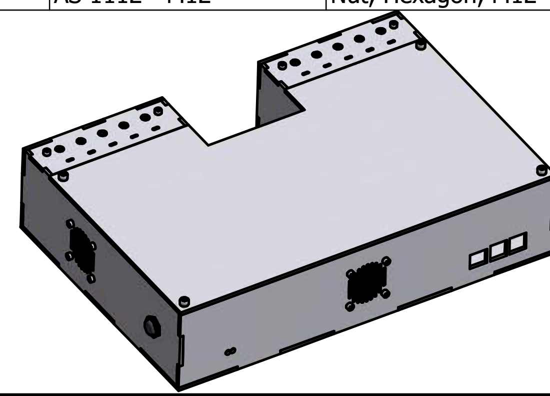


THE UNIVERSITY of ADELAIDE	DO NOT SCALE	DESIGNED Adam Bartlett	DATE 28/09/2017	PROJECT Project #2366 - REFAUM
	THIRD ANGLE PROJECTION	DRAWN Adam Bartlett	DATE 9/10/2017	TITLE Final Control Box Assembly
UNLESS STATED OTHERWISE GENERAL TOLERANCE: LINEAR: ± 0.3 ANGULAR: ± 1° REMOVE BURRS & SHARP EDGES 3.2 ALL OVER.	DIMENSIONS IN MILIMETERS	CHECKED Riley Lodge	DATE 9/10/2017	PART NUMBER CTR-00-00 — REVISION 1
	DRAWING STANDARD AS1100	APPROVED Riley Lodge	DATE 9/10/2017	
		MATERIAL		QTY 1 — MASS N/A — SCALE 1:3 — SHEET 1 of 1 — A3



PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
1	CTR-01-01	Base Plate	1
2	CTR-01-02	Rear Panel	1
3	CTR-01-03	Left Side Panel	1
4	CTR-01-04	Right Side Panel	1
5	CTR-01-05	Front Panel	2
6	CTR-01-06	U Rear Panel	1
7	CTR-01-07	U Side Panel	2
8	CTR-01-08	IO Shield	2
9	CTR-01-09	Lid	1
10	CTR-01-10	Lid Mount	8
11	CTR-01-11	DC Plug Rack	2
12	DC Jack	Female DC Jack	10
13	40mm Fan	12V DC Fan, 40mm	4
14	Toggle Switch	12V, 25A Toggle Switch	1
15	ISO 4762 - M3 x 12	Bolt, Hex Socket Cap, M3 x 12	4
16	ISO 4762 - M3 x 16	Bolt, Hex Socket Cap, M3 x 16	16
17	ISO 4762 - M4 x 16	Bolt, Hex Socket Cap, M4 x 16	4
18	AS 1112 - M3	Nut, Hexagon, M3	20
19	AS 1112 - M4	Nut, Hexagon, M4	4
20	AS 1112 - M12	Nut, Hexagon, M12	2



THE UNIVERSITY of ADELAIDE

UNLESS STATED OTHERWISE
GENERAL TOLERANCE:
LINEAR: ± 0.3
ANGULAR: ± 1°
REMOVE BURRS & SHARP EDGES
3.2 ALL OVER.

DO NOT SCALE

THIRD ANGLE PROJECTION

DIMENSIONS IN MILIMETERS

DRAWING STANDARD AS1100

DESIGNED	Adam Bartlett	DATE	28/09/2017
DRAWN	Adam Bartlett	DATE	9/10/2017
CHECKED	Riley Lodge	DATE	9/10/2017
APPROVED	Riley Lodge	DATE	9/10/2017
MATERIAL			

PROJECT Project #2366 - REFAUM

TITLE Initial Control Box Assembly

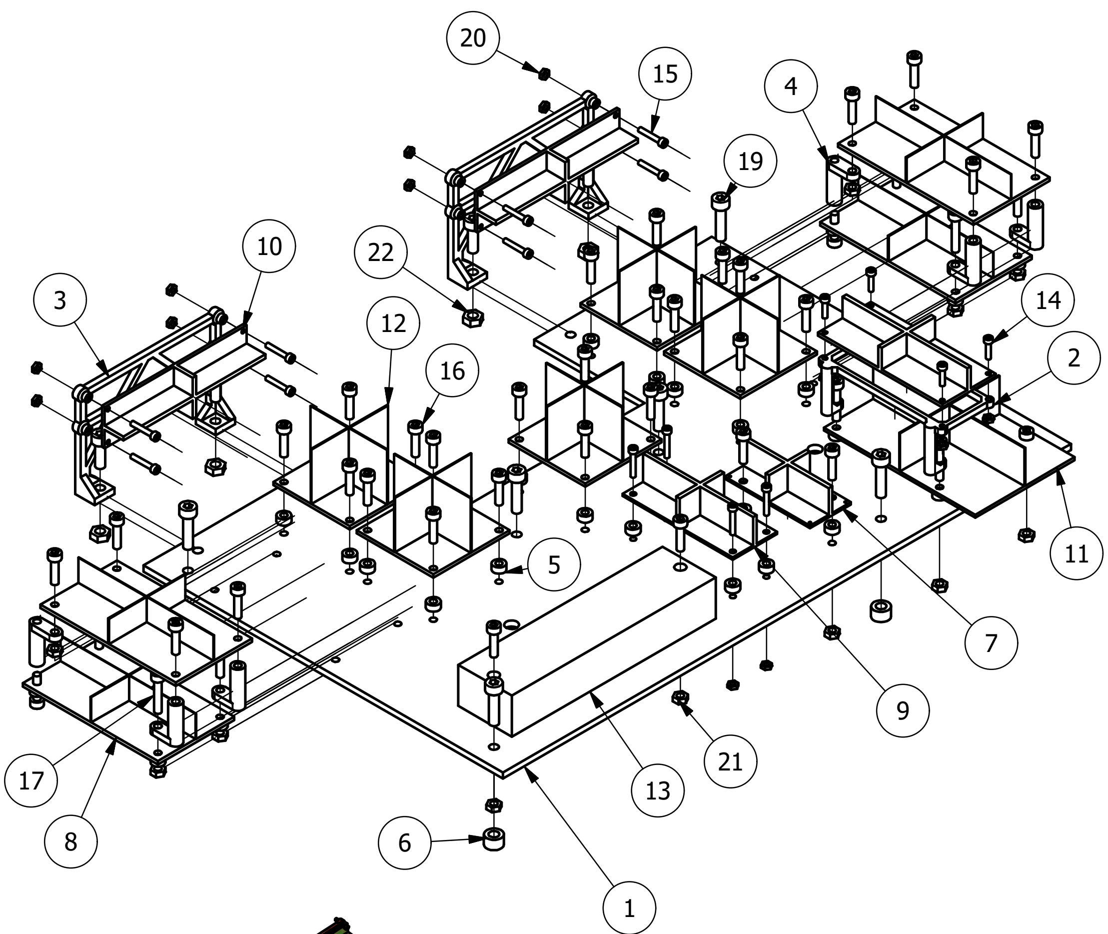
PART NUMBER CTR-01-00

REVISION 1

QTY	MASS	SCALE	SHEET	
1	N/A	1:3	1 of 1	A3

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
1	CTR-02-01	Floor	1
2	CTR-02-02	ADC Mount	2
3	CTR-02-03	POT Mount	2
4	CTR-02-04	Large Motor Controller Mount	8
5	CTR-02-05	M3 Mount 3mm	38
6	CTR-02-06	M4 Mount 5mm	6
7	DC Buck Converter	DC Buck Converter	1
8	Large Motor Controller	Large Motor Controller	4
9	PWM Generator	PWM Generator	1
10	Potentiometer Output	Potentiometer Output	2
11	Raspberry Pi 3	Raspberry Pi 3	1
12	Small Motor Controller	Small Motor Controller	5
13	Terminal Block	Terminal Block	1
14	ISO 4762 - M2 x 8	Bolt, Hex Socket Cap, M2 x 8	4
15	ISO 4762 - M2 x 12	Bolt, Hex Socket Cap, M2 x 12	12
16	ISO 4762 - M3 x 12	Bolt, Hex Socket Cap, M3 x 12	38
17	ISO 4762 - M3 x 16	Bolt, Hex Socket Cap, M3 x 16	6
18	ISO 4762 – M4 x 12	Bolt, Hex Socket Cap, M4 x 12	4
19	ISO 4762 – M4 x 16	Bolt, Hex Socket Cap, M4 x 16	6
20	AS 1112 - M2	Nut, Hexagon, M2	16
21	AS 1112 – M3	Nut, Hexagon, M3	36
22	AS 1112 – M4	Nut, Hexagon, M4	4

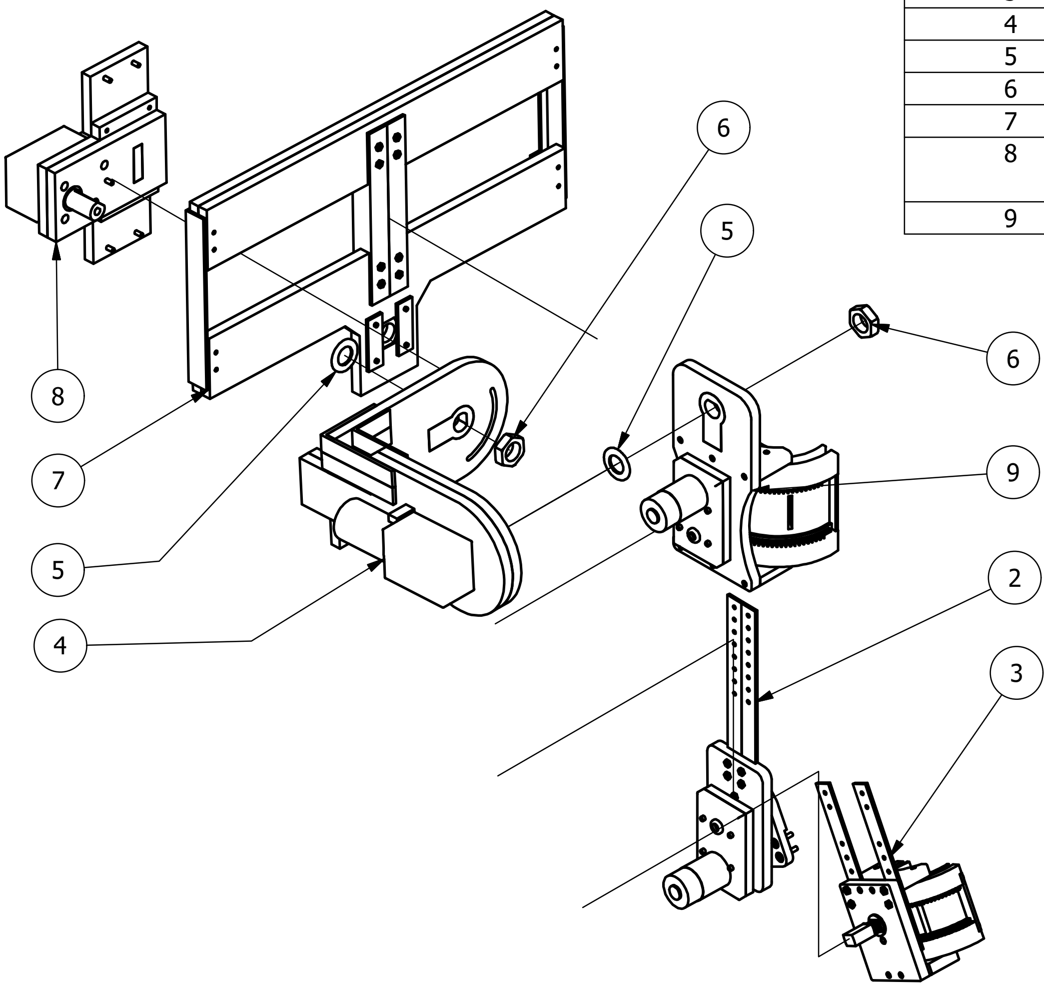


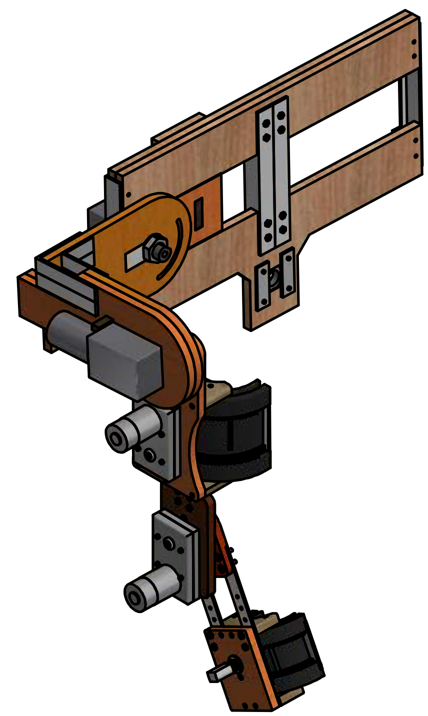
THE UNIVERSITY of ADELAIDE	DO NOT SCALE	DESIGNED Adam Bartlett — DATE 28/09/2017	PROJECT Project #2366 - REFAUM
	THIRD ANGLE PROJECTION	DRAWN Adam Bartlett — DATE 9/10/2017	TITLE Component Assembly
UNLESS STATED OTHERWISE GENERAL TOLERANCE: LINEAR: ± 0.3 ANGULAR: ± 1˚ REMOVE BURRS & SHARP EDGES 3.2 ALL OVER.	DIMENSIONS IN MILIMETERS	CHECKED Riley Lodge — DATE 9/10/2017	PART NUMBER CTR-02-00 — REVISION 1
	DRAWING STANDARD AS1100	APPROVED Riley Lodge — DATE 9/10/2017	QTY 1 — MASS 0.345 kg — SCALE 1:2 — SHEET 1 of 1 — A3
		MATERIAL	

M.2 Exoskeleton: Assembly

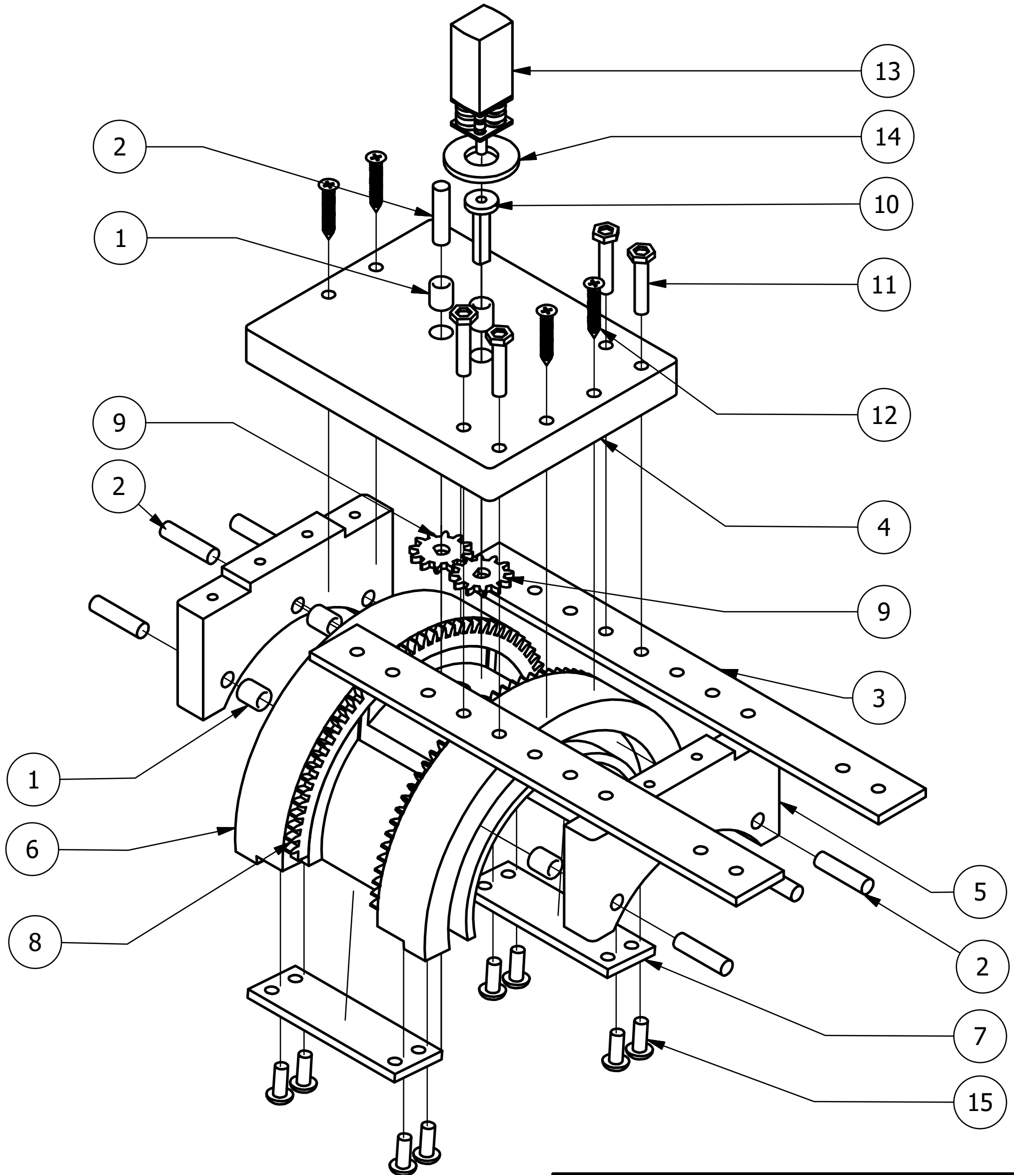
See the next page...

PARTS LIST			
ITEM	PART NUMBER	DESCRIPTION	QTY
2	01-02	Elbow sub assembly	1
3	01-01	Wrist sub assembly	1
4	01-04	Shoulder Assembly (right)	1
5	20x35x2mm Thrush bearing		2
6	M20 lock nut		2
7	01-05	Upper back sub assembly	1
8	01-06	Back motor holder sub assembly	1
9	01-03	Upper arm sub assembly	1



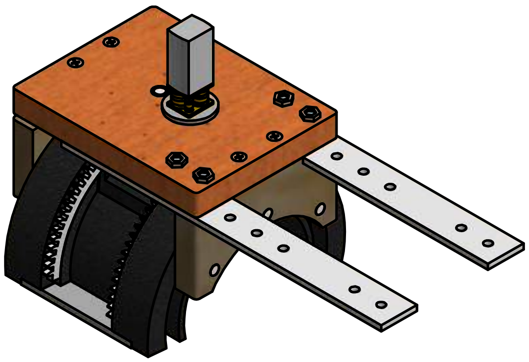


THE UNIVERSITY of ADELAIDE	DO NOT SCALE	DESIGNED Various	DATE 22/05/2017	PROJECT Upper body exoskeleton
UNLESS STATED OTHERWISE GENERAL TOLERANCE: LINEAR: ± 0.3 ANGULAR: ± 1˚ REMOVE BURRS & SHARP EDGES 3.2 ALL OVER.	THIRD ANGLE PROJECTION	DRAWN Riley Lodge	DATE 20/05/2017	TITLE Overall assembly (Right)
	DIMENSIONS IN MILIMETERS	CHECKED	DATE	PART NUMBER 01 — REVISION 1
	DRAWING STANDARD AS1100	APPROVED	DATE	QTY 1 — MASS N/A — SCALE 1:1 — SHEET 1 of 1 — A3
		MATERIAL		



PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
1	Bearing sleeve		8
2	5x20mm aluminium rod		7
3	01-01-04	Wrist to elbow connector	2
4	01-01-01	Main wrist piece	1
5	01-01-02	Wrist bracket	2
6	01-01-06	Wirst brace	1
7	01-01-05	Wrist brace reinforcement	2
8	01-01-08		2
9	01-01-07	Small wrist gear	2
10	01-01-03	Wirst Pin	1
11	M4 20mm bolt		4
12	M4 20mm screw		4
13	Wrist motor		1
14	10mm washer		1
15	M4 10mm bolt		8



THE UNIVERSITY of ADELAIDE

UNLESS STATED OTHERWISE
GENERAL TOLERANCE:
LINEAR: ± 0.3
ANGULAR: ± 1˚
REMOVE BURRS & SHARP EDGES
3.2 ALL OVER.

DO NOT SCALE

THIRD ANGLE PROJECTION

DIMENSIONS IN MILIMETERS

DRAWING STANDARD AS1100

DESIGNED	Riley Lodge	DATE	18/05/2017
DRAWN	Riley Lodge	DATE	20/05/2017
CHECKED		DATE	
APPROVED		DATE	
MATERIAL			

PROJECT Upper body exoskelton

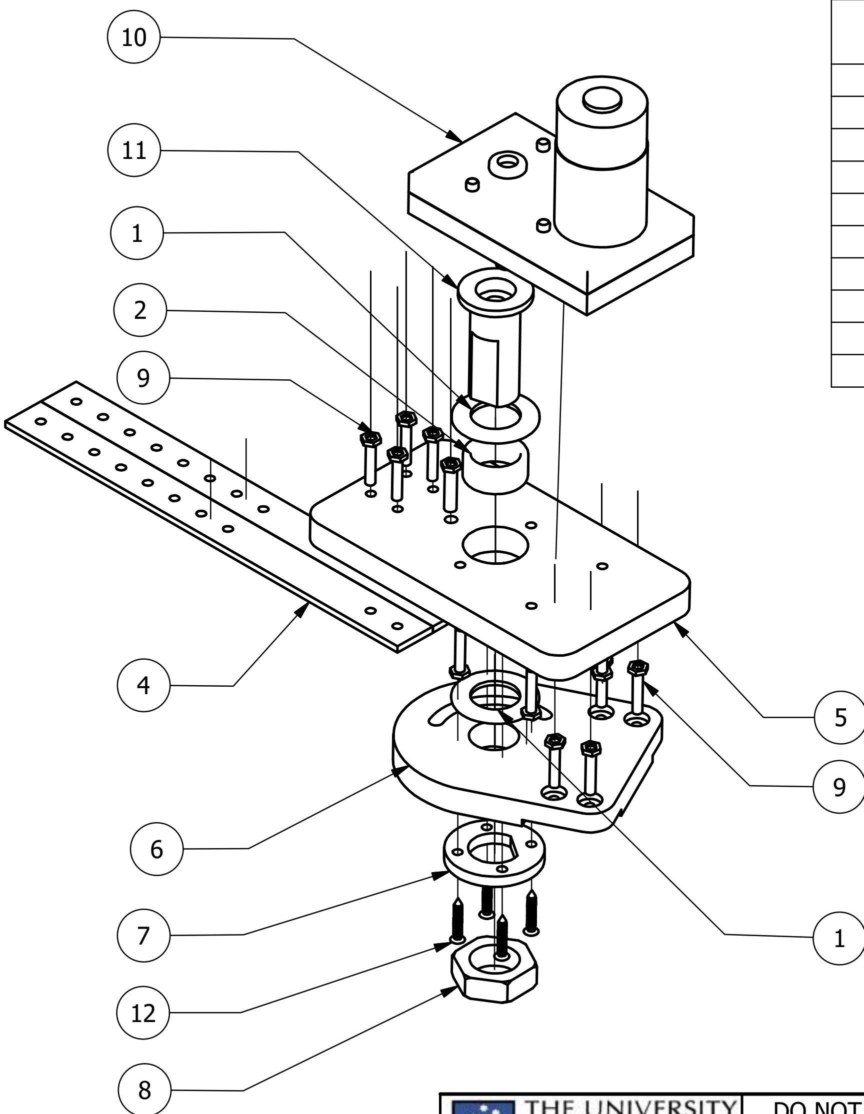
TITLE Wrist sub assembly

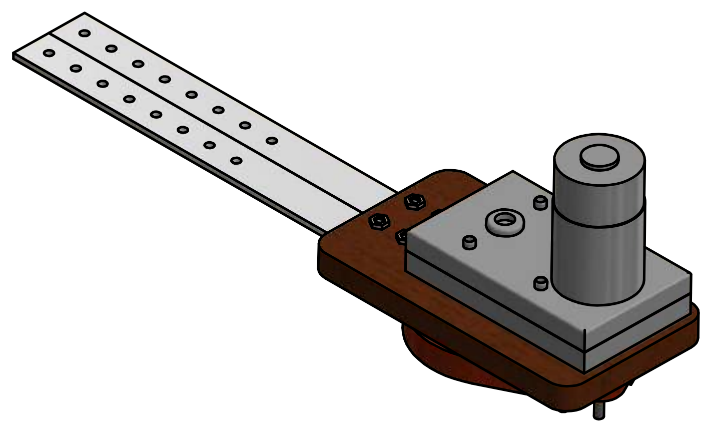
PART NUMBER WID-01-01

REVISION 1

QTY	MASS	SCALE	SHEET	
1	N/A	1:1	1 of 1	A3

PARTS LIST			
ITEM	PART NUMBER	DESCRIPTION	QTY
1	20x35x2mm Thrush bearing		2
2	20x26x12mm Needle roller bearing		1
3	M5 20mm bolt		1
4	01-02-03	Elbow to upper arm conector	2
5	01-02-01	Upper Elbow Piece	1
6	01-02-02	Lower Elbow Piece	1
7	01-02-05	Elbow pin lock	1
8	M20 lock nut		1
9	M4 20mm bolt		12
10	Medium Motor		1
11	01-02-04	Elbow Pin	1
12	M4 20mm screw		4





THE UNIVERSITY of ADELAIDE

UNLESS STATED OTHERWISE
GENERAL TOLERANCE:
LINEAR: ± 0.3
ANGULAR: ± 1°
REMOVE BURRS & SHARP EDGES
3.2 ALL OVER.

DO NOT SCALE

THIRD ANGLE PROJECTION

DIMENSIONS IN MILIMETERS

DRAWING STANDARD AS1100

DESIGNED	Riley Lodge	DATE	18/05/2017
DRAWN	Riley Lodge	DATE	20/05/2017
CHECKED		DATE	
APPROVED		DATE	
MATERIAL			

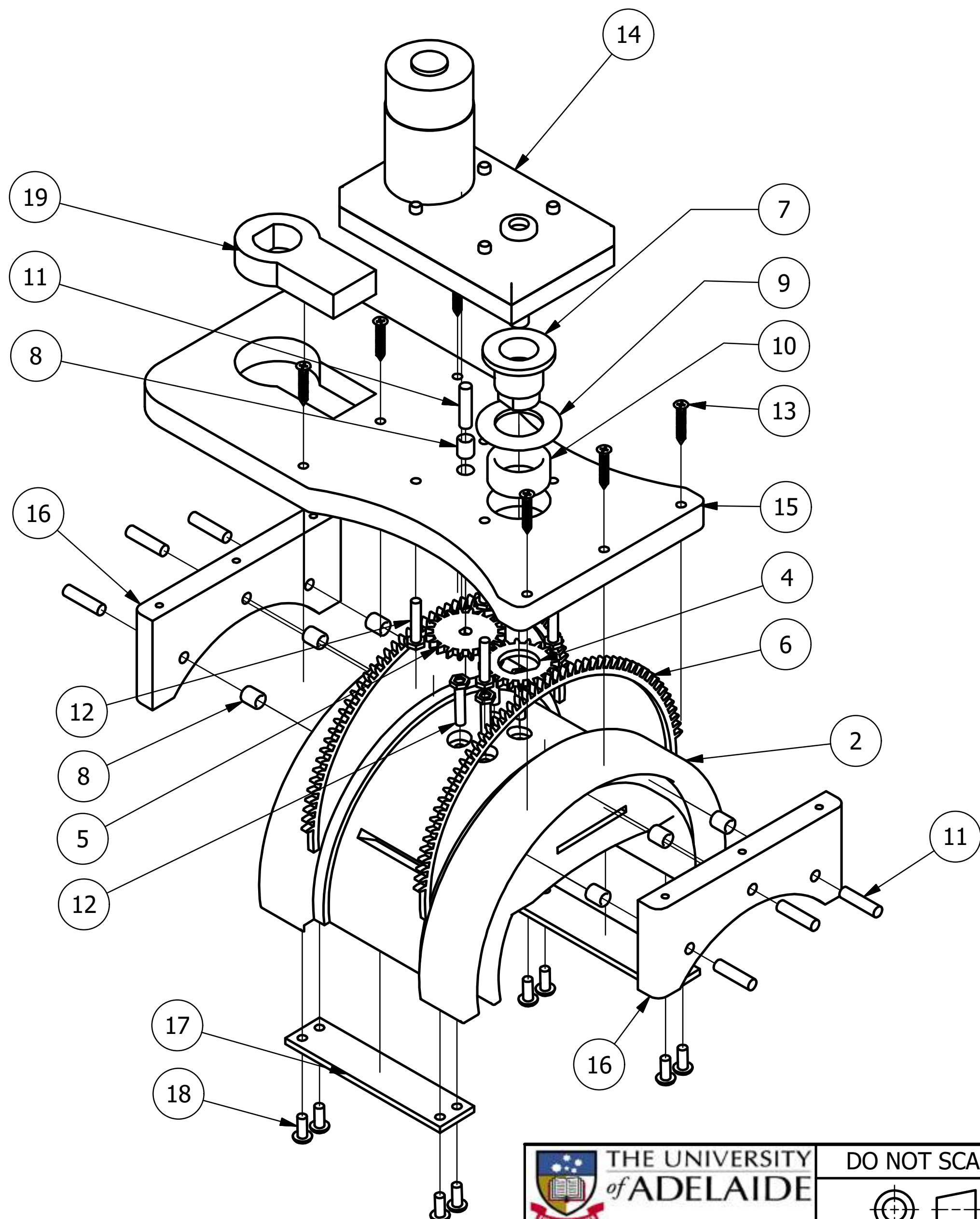
PROJECT Upper body exoskeleton

TITLE Elbow Sub Assembly (Right)

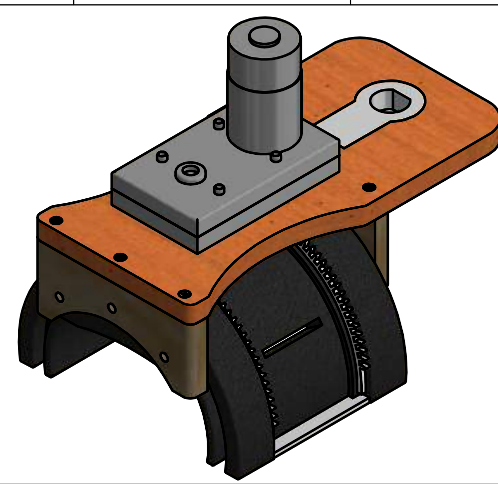
PART NUMBER WID-01-02

REVISION 1

QTY 1 | MASS N/A | SCALE 1:1 | SHEET 1 of 1 | A3



PARTS LIST			
ITEM	PART NUMBER	DESCRIPTION	QTY
2	01-03-05	Upper Arm brace	1
4	01-03-07	Upper arm motor gear	1
5	01-03-06	Upper arm potentiometer gear	1
6	01-03-08	Upper arm large gear	2
7	01-03-03	Upper arm motor pin	1
8	Bearing sleeve		7
9	20x35x2mm Thrush bearing		1
10	20x26x12mm Needle roller bearing		1
11	5x20mm aluminium rod		7
12	M4 20mm bolt		8
13	M4 20mm screw		6
14	Medium Motor		1
15	01-03-01	Upper arm main piece	1
16	01-03-02	Upper arm bracket	2
17	01-03-04	Arm brace reinforcement	2
18	M4 10mm bolt		8
19	01-04-05	Shoulder connector	1



THE UNIVERSITY of ADELAIDE

UNLESS STATED OTHERWISE
GENERAL TOLERANCE:
LINEAR: ± 0.3
ANGULAR: ± 1˚
REMOVE BURRS & SHARP EDGES
3.2 ALL OVER.

DO NOT SCALE

THIRD ANGLE PROJECTION

DIMENSIONS IN MILIMETERS

DRAWING STANDARD AS1100

DESIGNED	Riley Lodge	DATE	18/05/2017
DRAWN	Riley Lodge	DATE	20/05/2017
CHECKED		DATE	
APPROVED		DATE	
MATERIAL			

PROJECT Upper Body Exoskeleton

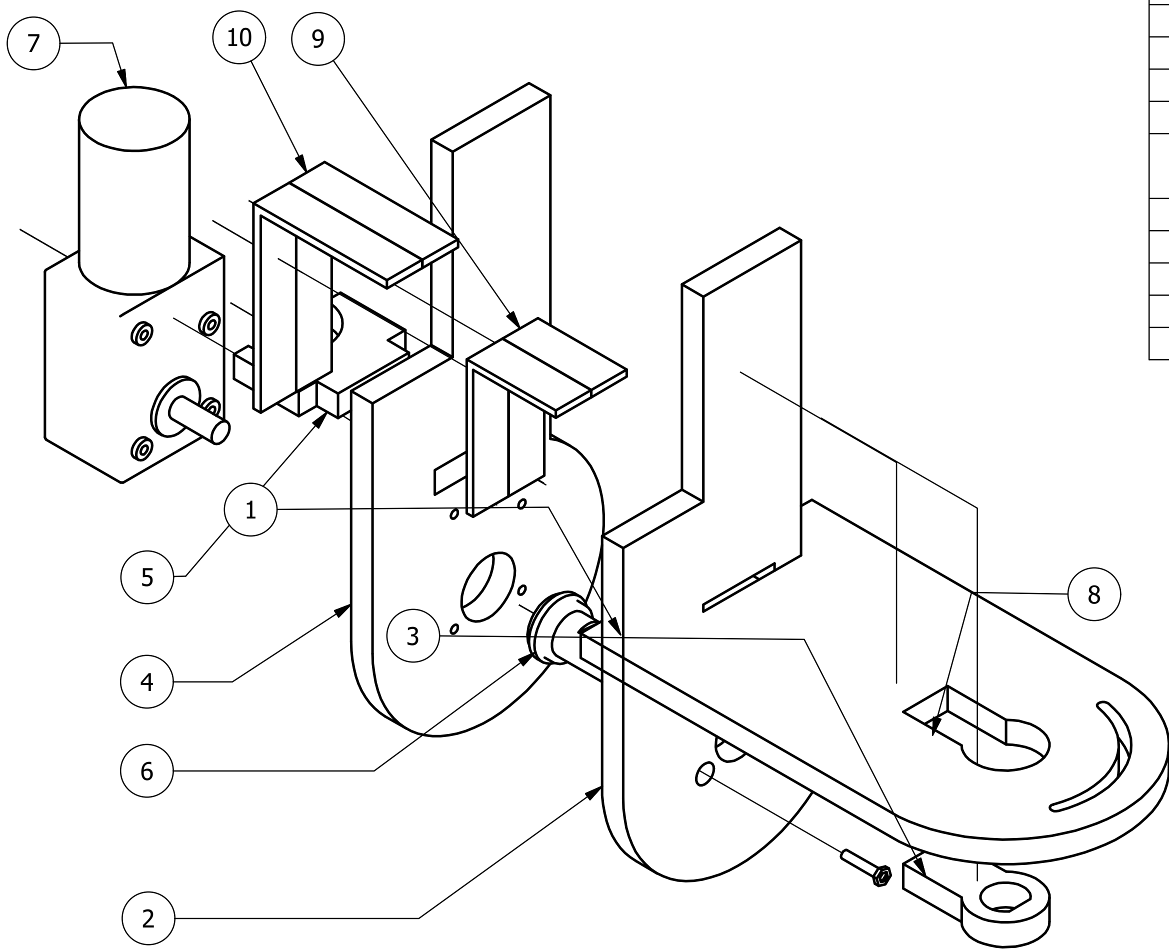
TITLE Upper Arm Sub Assembly

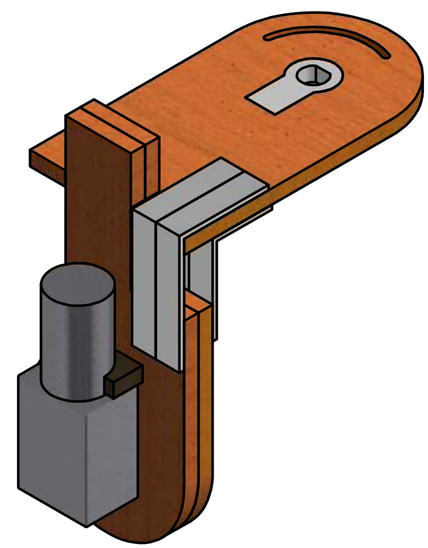
PART NUMBER WID-01-03

REVISION 1

QTY 1 | MASS N/A | SCALE 1:1 | SHEET 1 of 1 | A3

PARTS LIST			
ITEM	PART NUMBER	DESCRIPTION	QTY
1	01-04-01	Shoulder Main Board 1	1
2	01-04-02	Shoulder main board 2	1
3	01-04-05	Shoulder connector	1
4	01-04-03	Shoulder main board 3	1
5	01-04-04	Back motor holder	1
6	20x26x12mm Needle roller bearing		1
7	Back Motor		1
8	M4 20mm bolt		4
9	Zenit 50_50_20		2
10	Zenit 100_75_20		2
11	01-02-04	Elbow Pin	1





THE UNIVERSITY of ADELAIDE

UNLESS STATED OTHERWISE
GENERAL TOLERANCE:
LINEAR: ± 0.3
ANGULAR: ± 1˚
REMOVE BURRS & SHARP EDGES
3.2 ALL OVER.

DO NOT SCALE

THIRD ANGLE PROJECTION

DIMENSIONS IN MILIMETERS

DRAWING STANDARD AS1100

DESIGNED	Theodore Kong	DATE	27/04/2017
DRAWN	Riley Lodge	DATE	20/05/2017
CHECKED		DATE	
APPROVED		DATE	
MATERIAL			

PROJECT Upper body exoskeleton

TITLE Shoulder Sub Assembly

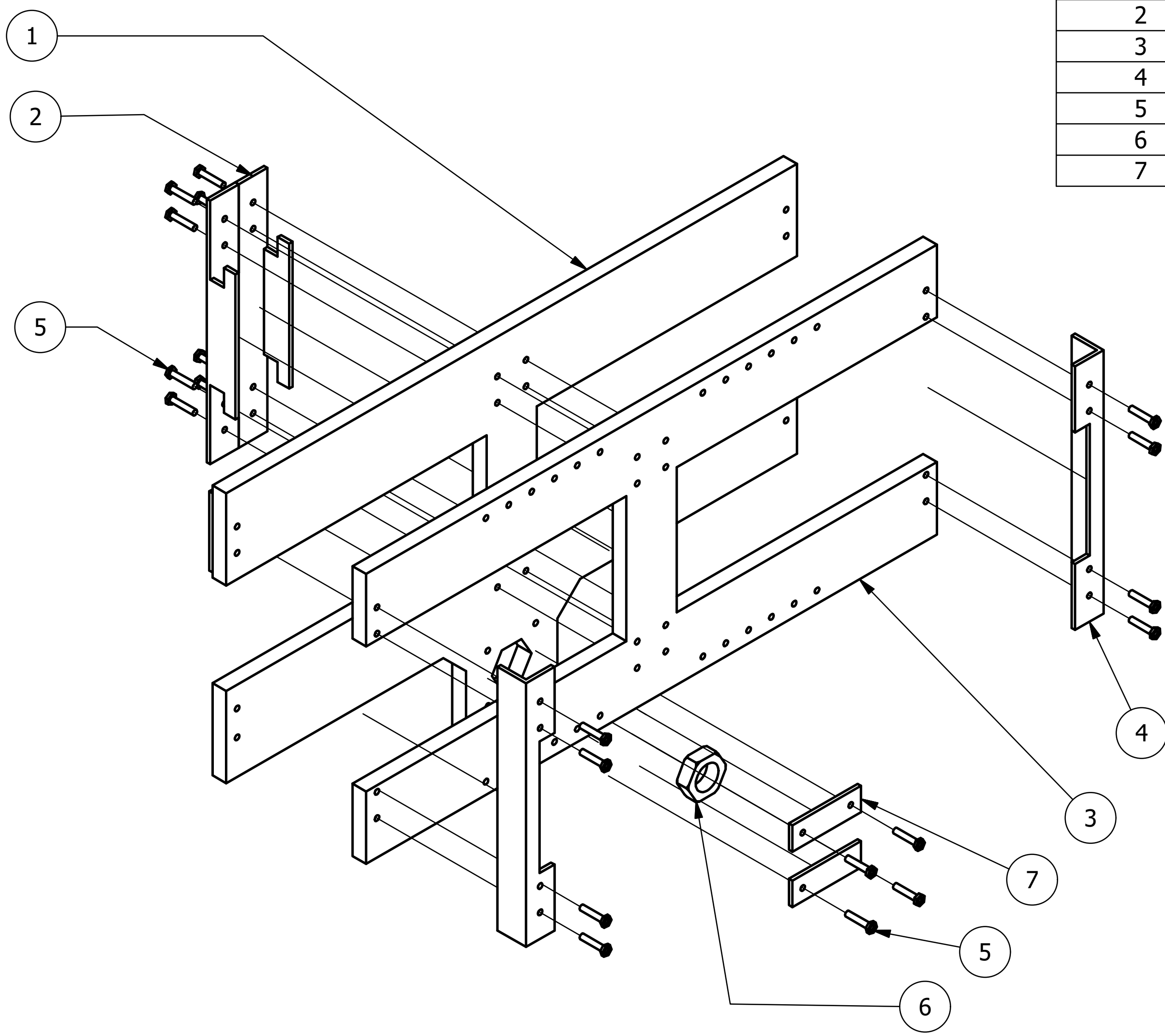
PART NUMBER WID-01-04

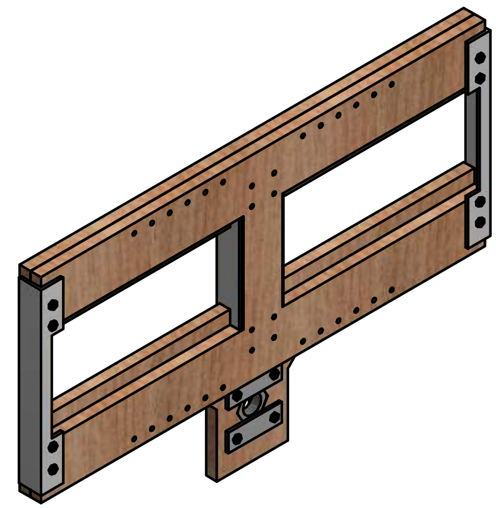
REVISION 1

QTY 1 | MASS N/A | SCALE 1:1 | SHEET 1 of 1 | A3

PARTS LIST

ITEM	PART NUMBER	DESCRIPTION	QTY
1	01- 05-02	T-Back Layer 2	1
2	01- 05-03	Aluminium angle 1	2
3	01-05-01	T-back layer 1	1
4	01- 05-04	Aluminium angle 2	2
5	M4 20mm bolt		20
6	M20 lock nut		1
7	01- 05-05	Bolt support	4





THE UNIVERSITY of ADELAIDE

UNLESS STATED OTHERWISE
GENERAL TOLERANCE:
LINEAR: ± 0.3
ANGULAR: ± 1°
REMOVE BURRS & SHARP EDGES
3.2 ALL OVER.

DO NOT SCALE

THIRD ANGLE PROJECTION

DIMENSIONS IN MILIMETERS

DRAWING STANDARD AS1100

DESIGNED	Theodore Kong	DATE	21/05/2017
DRAWN	Riley Lodge	DATE	20/05/2017
CHECKED		DATE	
APPROVED		DATE	
MATERIAL			

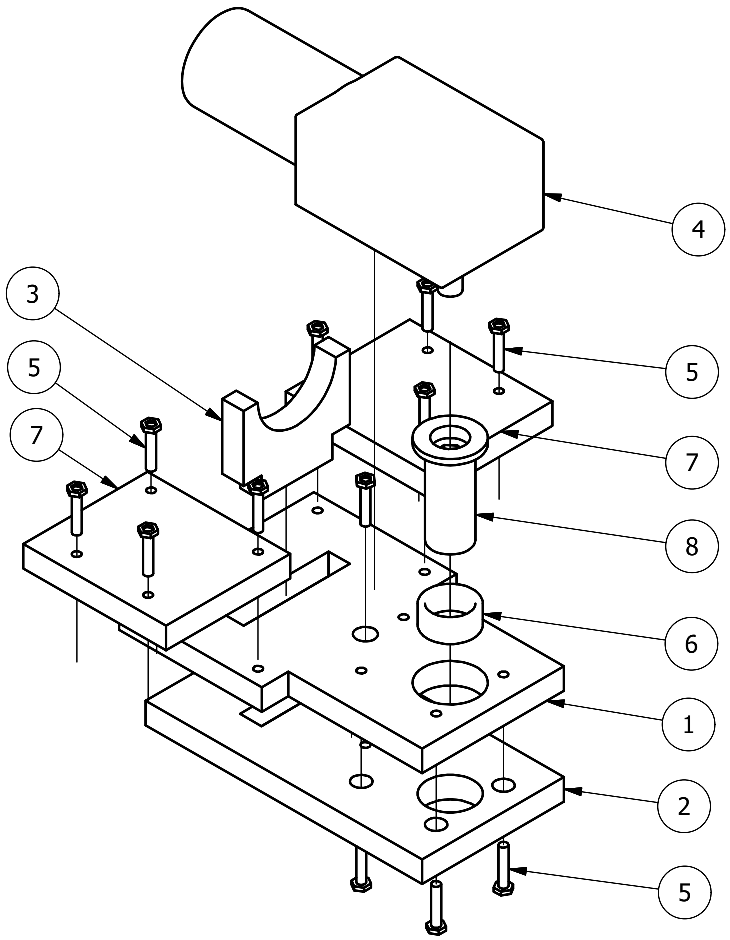
PROJECT Upper body exoskeleton

TITLE Upper back sub assembly

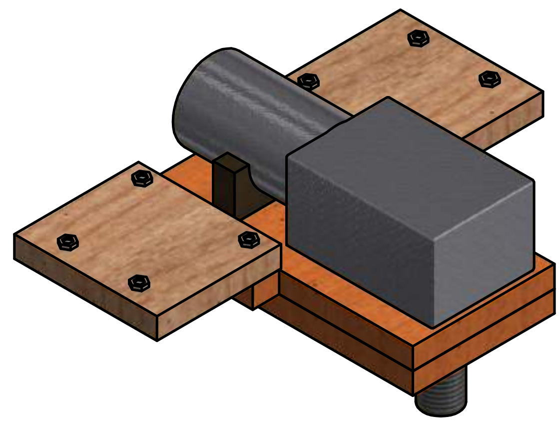
PART NUMBER WID-01-05

REVISION 1

QTY 1 | MASS N/A | SCALE 1:1 | SHEET 1 of 1 | A3



PARTS LIST			
ITEM	PART NUMBER	DESCRIPTION	QTY
1	01-06-01	Back motor board top	1
2	01-06-02	Back motor board bottom	1
3	01-04-04	Back motor holder	1
4	Back Motor		1
5	M4 20mm bolt		13
6	20x26x12mm Needle roller bearing		1
7	01-06-03	Back motor board wing	2
8	01-02-04	Elbow Pin	1



THE UNIVERSITY of ADELAIDE	DO NOT SCALE	DESIGNED Theodore Kong — DATE 20/05/2017	PROJECT Upper body exoskeleton
	THIRD ANGLE PROJECTION	DRAWN Riley Lodge — DATE 20/05/2017	TITLE Back motor holder sub assembly
UNLESS STATED OTHERWISE GENERAL TOLERANCE: LINEAR: ± 0.3 ANGULAR: ± 1˚ REMOVE BURRS & SHARP EDGES 3.2 ALL OVER.	DIMENSIONS IN MILIMETERS	CHECKED — DATE	PART NUMBER WID-01-06 — REVISION 1
	DRAWING STANDARD AS1100	APPROVED — DATE	QTY 1 — MASS N/A — SCALE 1:1 — SHEET 1 of 1 — A3
		MATERIAL	