Comparing The Simulated Impedance Control Of A One Degree Of Freedom Robotic Arm With An Antagonistic Cable Joint To A Physical Model

Third-Year Individual Project - Final Report

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Abstract

The implementation of Impedance Control systems in modern robotic manipulators is essential for mechatronic development, as it is utilised in most applications where robots interacts with their environment and the force position relation is of concern. The algorithm controls the force of the motors driving the cables and therefore the machine, after a motion or deviation from an initial starting position is measured. The predicted models are first validated by simulations and then demonstrated experimentally with a prototype. The prototype arm will be split into two 3D printed parts, forearm, and bicep, whilst being suspended above the ground via a laboratory stand for a foundation, using two antagonistic revolute joint motors to pull the cable. The cable will be wrapped around a pulley that will act as a revolute joint around the elbow of the arm. The research behind this project is to emulate closely and fluidly that of a human's bicep muscle to create an insight into human prosthetic as well as the possibility of an exoskeleton for an arm.

Declaration of originality

I hereby confirm that this dissertation is my own original work unless referenced clearly to the contrary, and that no portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Intellectual property statement

1 Introduction

1.1 Background

When building robots that interact with their surrounding environments, they are required to exploit contact forces safely whilst being proficient. The use of impedance control systems in the modern world of mechatronic engineering is considered as the leading approach in robotics to avoid large impact forces while operating in unknown environments. When robots are placed into these environments it is necessary, for operation, that the robot is supplied with the appropriate tools to adapt its movement in real time to adjust to new forces and objects in this environment [1].

Impedance Control allows one to modify the apparent inertia, stiffness and damping of a robot as seen by the environment. A robot operating with pure position control, would be demanding when in contact with a very stiff environment, this is because the interaction forces would be difficult to control. The impedance control algorithm uses closed loop feedback, where the apparent inertia, stiffness, damping and force are fed back into the system to control the acceleration of the end effector, which is why impedance control is preferred in this area of robotics. [2].

The understanding of movement and manipulation in robotics whilst finding the optimum and most efficient path for movement is essential in a multitude of fields. As an example, robots are used in the development of artificial limbs that could rehabilitate people with functional disabilities. The development of these robots requires a paramount understanding of not only the human body's normal controls and command movements, but the best method of implementation in a prosthesis or an orthosis. Therefore, the modern industrial robotics world is focusing the forefront of its attention on the fundamental problems of manipulation by machine [3]. More information on Impedance control can be found [4] [5].

1.2 Motivation

The work presented here is to portray the benefits of implementing impedance control in industrial robotics, as well as the applications to human biomechanics for prosthetic and orthosis, whilst using an alternative method of actuation for an arm. The findings in this specific research task would be best applied to orthosis which is a device designed to improve biomechanical function or proper joint alignment, instead of substituting a limb, as prosthetic would do. The machine built in this report would be better suited to envelope a person's arm like an exoskeleton, where the antagonistic actuated wires/ropes could run along the patient's arm to assist the bicep in lifting objects. In a prosthetic it would be better to use a normal revolute joint motor machine as it would take up less physical space [6].

Inside of the world of biomechanics the assistance of impedance control is immense, as the algorithm easily surpasses position control, when working with humans. It is crucial for the machine to react to a patient's movements when they have upper-extremity deficits that often present with tremors, sensitivities and spasticity that can be painful when a movement threshold is met or exceeded; position control would not react to a patient's reluctance to move in the same direction as the robot and could end up hurting the patient [7]. Hence, the development of impedance control is essential in the evolving world of orthosis and is currently popularly used in the field of lower limb prostheses and exoskeleton development [8].

Additionally, the prototype fabricated will be used to validate the potential usage of a newly developed integrated physics engine that has not been reviewed or researched. The BETA Coppeliasim software integrates the MujoCo physics engine to provide competent tools that support soft bodies, to better envision and measure the forces and reactions of the ropes that actuate the arm [9].

If evaluated positively, the proposed simulation resource would be substantial in furthering future research projects that integrate rope or wire actuation in larger systems, when using Coppeliasim.

1.3 Aim and Objectives

The specific intended learning outcomes of this project are to design a one Degree-of-Freedom (DOF) robotic arm, that operates via two antagonistic string actuated motors attached to a pulley system, to imitate a revolute joint around the elbow of the robot. This design should be thoroughly simulated in Coppeliasim_Edu_V4_3_0_rev12 and will be replicated in the physical prototype. Upon validation, the impedance control algorithm should be transferred across to the realised model. With these learning milestones set in place, six research of objectives can be outlined:

1. Study rotational impedance control to develop a comprehensive understanding of its theory, to fully implement the control system in a real application.
2. Research the BETA integration of Coppeliasim & MujoCo to simulate wire ropes digitally.
3. Develop a preliminary testing simulation for the oscillatory response of a spring and research the physics enforced on the rope and wire tools in CoppeliaSim.
4. Adapt the simple simulation and design an antagonistic rope and spring actuated pulley system to replicate a revolute joint.
5. Build a prototype to experiment and validate the digital models via implementing all previous control systems into the prototype for demonstration.
6. Compare the systems and evaluate the potential usage of the integrated physics engine for future mechatronic research projects and technological advancements.

2 Literature Review

2.1 Commercialisation

With prosthesis and orthosis there are notable economic benefits, alongside the psychiatric benefits. Primarily, it would increase employment in a section of the population who could not previously entertain jobs that required lifting or continuous movement of their limbs.

The commercialisation of prosthetic limbs and orthotic exoskeletons has increased with the constant development and innovation of this technology. There is a steady increase of supply and demand for these products by those who require additional body support; the prosthetics and orthotics market were valued at £4958.95 million in the year 2018 and is expected to grow with a compound annual growth rate of 4.8%. This is a resulting combination from its fastest growing market Asia-Pacific and its largest market North America projecting the market to reach £6502.28 million in 2028.[10]

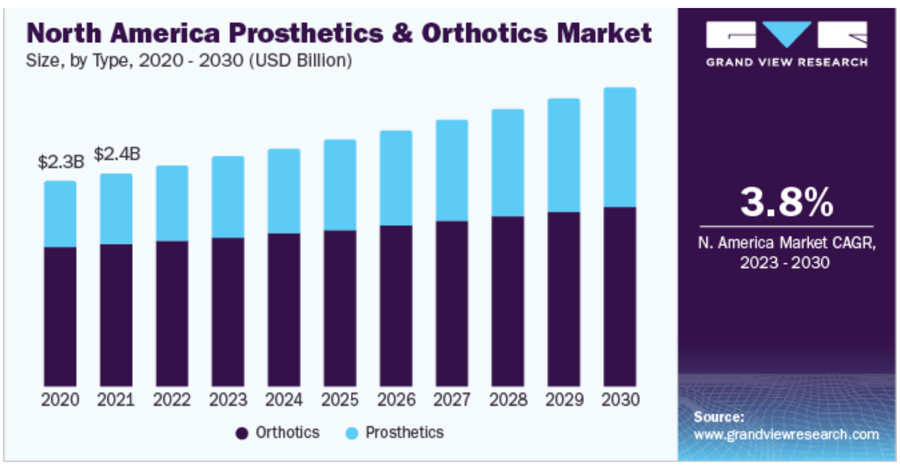


Figure 1: Shows the projected rise of the Prosthetics and Orthotics Market in its largest market over the next 10 years [11]

The prosthetic market is becoming more affluent because of the increase of amputations due to road accidents and diabetes. Similarly, the growth of the orthotic market is increasing due to higher incidences of sport related injuries and the growing prevalence of osteosarcoma. These factors therefore mean the global market is predicted to escalate as displayed in Figure 1. [11].

2.2 Sustainability

Due to the vast majority of products being made out of plastics, the market suffers from the main sustainability problems of recycling the plastic and limiting, if not preventing, environmental damage.

As plastic does not break down naturally, plastic companies cause the pollution of natural systems such as rivers, oceans, and other marine environments causing a direct increase in greenhouse gas emissions from plastic disposal [12].

The market does have initiatives, with companies working to combat these pressing issues such as Project Circleg; An organisation decreasing the world's plastic pollution by producing low cost lower-limb prosthetics from recycled plastics [13].

Additionally, prosthetics and orthotics can be donated to others that match the products profile, once a patient no longer needs it. With the options of redistributing and recycling the products, the future of the market and its sustainability will be able to grow without damaging the planet.

2.3 Future

Both modern commercial and research products rely on incorporated microprocessors to aid the prosthetics and orthotics by implementing a finite state machine impedance controller for movement. The two categories are active products and passive products. Active products inject energy into the system aiming to control movement and is often used in research for machines and AI's. Passive products are more commercially focused, aiding the movement of the user without injecting additional energy into the system [14].

The future of the market is integrating the powered active prosthetics and orthotics with more complex controllers with intent recognition in uncontrolled environments. However, the commercial availability has been hindered by the complexities in developing an active product.

This research project aims to help advance this technology, evaluating the potential of new features in software and its ability to predict soft body motion. Hence, furthering the development of active mechatronic orthotic technology.

3 Methodology

The methodology will go through the following sections of the diagram seen in Figure 2. Each section will then be assessed on performance, evaluating the progress of the project's individual elements, making note of successes. The five sections that will be assessed for this project include;

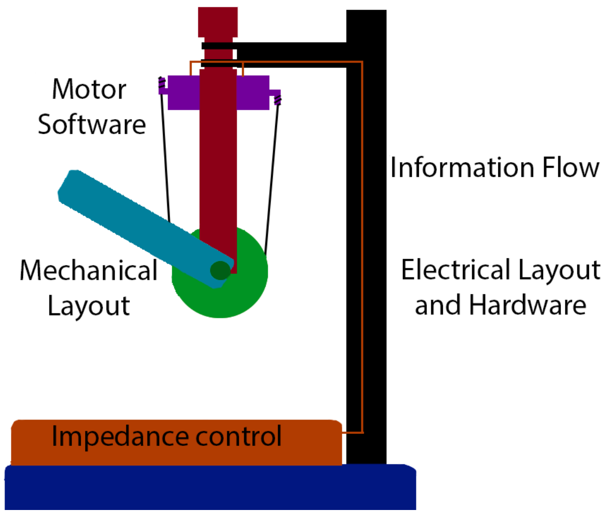


Figure 2: Visualises the initial one DOF robotic arm design and each section of the project that needs to be completed and evaluated.

1. Information Flow – Ensuring all components can communicate with each other and that there is a constant, steady flow of information in the system.
2. Impedance Control – Ensuring the Mircrocontroller has been implemented with an impedance controller, and that it is working as intended.
3. Mechanical Layout – Ensuring that the passive mechanical components of the arm, such as the frame and actuation wires, are structured correctly to enable smooth motion.
4. Electrical Layout and Hardware – Ensuring all electrical components and hardware are correctly and safely wired, and that the arm's motors are operational.
5. Motor Software – Ensuring that the motor's code works as intended and can implement a method of control.

These five sections will be used to assess both the physical and simulated robotic arms to demonstrate the accomplishments of this research project.

3.1 Information Flow

To achieve impedance control in the physical prototype of the one DOF arm, the following information between each component must be correctly implemented as described below. For the antagonistic motor control, two motors connected to a micro-controller are used. The mircrocontroller will contain onboard code for the impedance control system.

Once an applied force is manually induced into the system, the motion of the end effector creates a chain reaction through a pulley system that will turn two motors on the arm. The potentiometer in the motors will measure the error of angular displacement. If this value is positive, the mircrocontroller will actuate one motor to counter act the downwards movement on the end effector (pulling it up); if the value is negative, the other motor will be actuated to counteract the upwards movement of the end effector (pulling it back down). The interaction between motors creates actuation in the system.

Due to the oscillatory behaviour of the system, each motor will take turns in reducing and damping the harmonic end effector movement. The impedance controller will control the speed of the motors and modify their apparent inertia to slowly decrease the speed until the end effector returns to its original position. Shown in Figure 3.

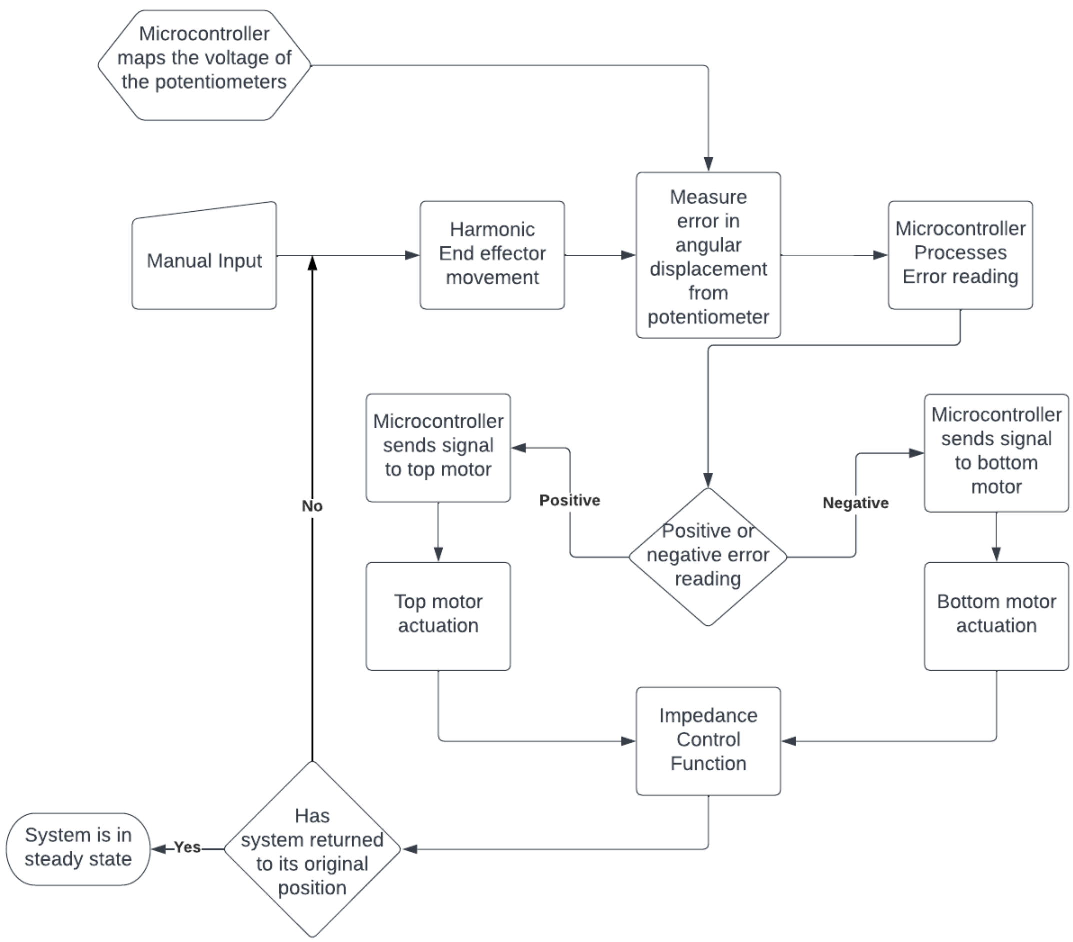


Figure 3: This diagram maps the path of the information that flows in the system and how the components communicate with each other.

3.2 Impedance Control

The definition of impedance control is a measure of how much a structure resists motion when subjected to a harmonic force. The opposite of impedance is admittance, which is the ratio of velocity to force. As an example, pushing a simple pendulum with a specific frequency that has a low admittance, would require greater force to reach the same velocity as a pendulum with high admittance. As such, a pendulum with a high admittance, would only require a small amount of force to swing the mass very high into the air.

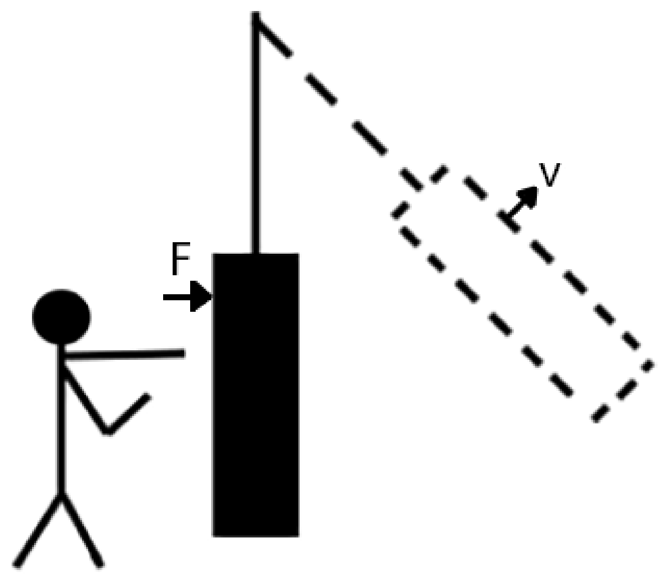


Figure 4: Shows the effects of high admittance, where the pendulum is being pushed by the man with a small amount of force, inducing a fast velocity.

Assume that Z is the impedance, F is the force and v is the velocity. Two equations can derived describing impedance ($Z = Fv$) and admittance ($v = Z^{-1}F$) [15].

The essence of impedance control in this project is to feedback variables derived from angular displacement. The potentiometer on the servo motors will be able to measure the amount of degrees they have turned from their original position, from the initial force applied to the end effector. This, therefore, gives the system its initial condition for error in angular displacement,

$$\widetilde{q} = q - q_d \tag{1}$$

where q is the measured angular displacement and q_d is the desired angular displacement.

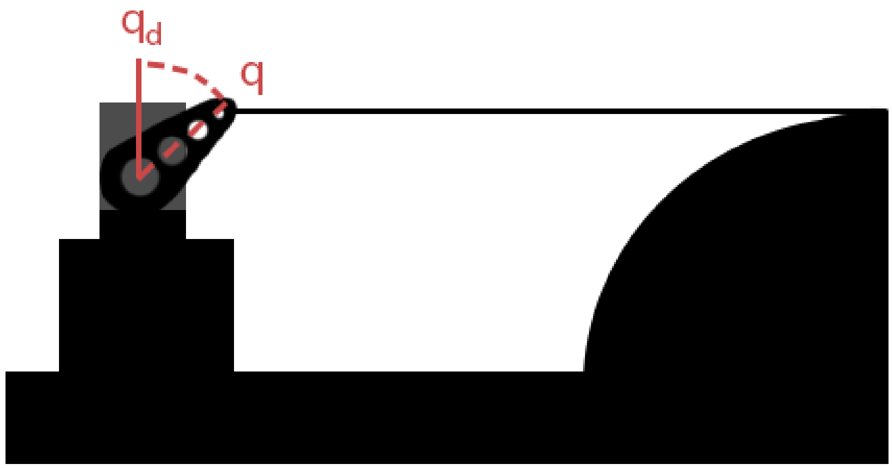


Figure 5: Shows the measured angular displacement q from the desired angular displacement q_d on a servo motor

The forces involved in any mass-spring-damper system conforms to the general solution of found from Newtons second law ($F = ma$), Hooke's law ($F = kX$), and the damping principle, where the faster an object moves the more force is required ($F = -cv$). Using the same model as in Figure 4, pushing a heavier bag with the same force would cause the bag to accelerate (a) proportionally to the mass (m) of the bag (Figure 6a). If the bag was infinitely massive there would be no motion, instead the bag will deform and behave like a spring. Pushing the bag would displace it's surface proportionally to the stiffness (k) of the bag, until the force of the spring and the force of the push are in equilibrium (Figure 6b). If the bag was placed underwater the water would resist the push creating a damping force (c), which would be proportional to the speed of the push (Figure 6c).

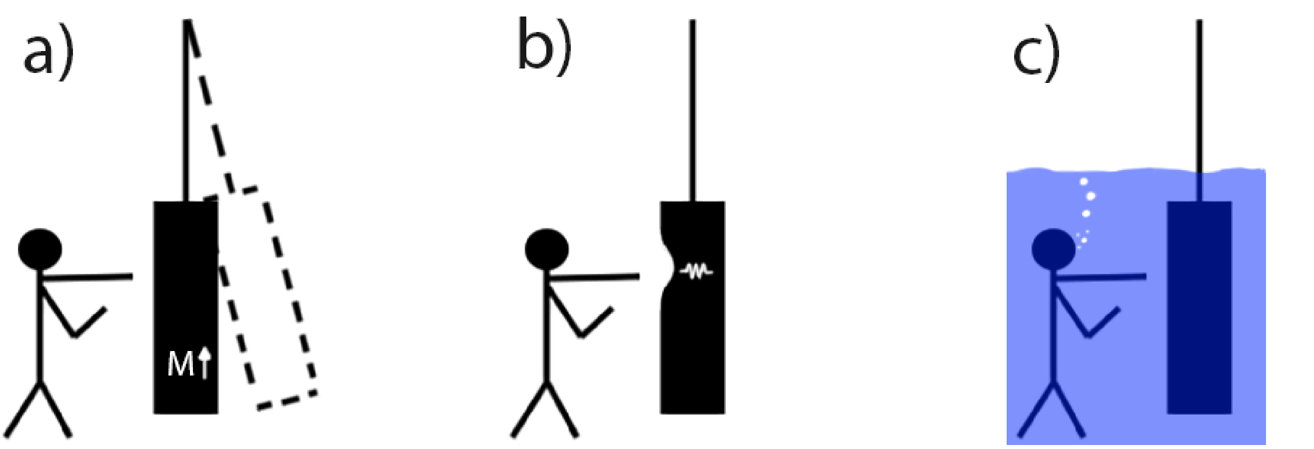


Figure 6: Portrays the effects on the pendulum from the force applied by the man according to Newtons second law, Hooke's law and the damping principle respectively.

Combining these equations gives

$$M_d\ddot{\widetilde{X}} + B_d\dot{\widetilde{X}} + K_d\widetilde{X} = -F, \tag{2}$$

where F is the force applied to the system, M_d is the desired mass of the body, B_d is the desired damping coefficient, K_d is the desired spring constant and $\ddot{\widetilde{X}}$,$\dot{\widetilde{X}}$and $\widetilde{X}$ are the errors in linear acceleration, linear speed and linear displacement respectively.

This general solution (2) can be used to describe a robot as a mass-spring-damper system expressing the relationship between force and velocity (the impedance). This can be expressed in the Laplace domain

$$Z = M_d s^2 + B_d s + K_d. \tag{3}$$

Once linear displacement has been measured, the linear velocity can be found using the derivative of the displacement and the acceleration can be found using the derivative of the velocity [14]. This impedance model is adapted to find the robots torque and joint angular displacement, and rearranged to find the joint angular acceleration,

$$M_d\ddot{\widetilde{q}} + B_d\dot{\widetilde{q}} + K_d\widetilde{q} = -\tau \tag{4}$$

$$\Rightarrow \ddot{\widetilde{q}} = M_d^{-1}(-\tau - B_d\dot{\widetilde{q}} - K_d\widetilde{q}) \tag{5}$$

where τ is the load torque applied to the system and $\ddot{\widetilde{q}}$, $\dot{\widetilde{q}}$ and $\widetilde{q}$ are the errors in angular acceleration, angular speed and angular displacement respectively. To find the angular acceleration the appropriate approximation is used

$$\ddot{\widetilde{q}} \approx \frac{\dot{\widetilde{q}}_k - \dot{\widetilde{q}}_{k-1}}{T} \tag{6}$$

where $\dot{\widetilde{q}}_{k-1}$ is the previous interval of error in angular velocity $\dot{\widetilde{q}}_k$ and assuming the time step $T > 0$; Rearranging this approximation presents an approximate value for angular velocity,

$$\dot{\widetilde{q}} \approx \dot{\widetilde{q}}_{k-1} + T\ddot{\widetilde{q}} \tag{7}$$

where Eq. (5) can be substituted into the approximation (7) to give a complete model to approximate angular velocity of the servo motors with impedance control,

$$\dot{\widetilde{q}} \approx \dot{\widetilde{q}}_{k-1} + T\left(M_d^{-1}(-\tau - B_d\dot{\widetilde{q}} - K_d\widetilde{q})\right). \tag{8}$$

However, the complete model seen in approximation (8) is an implicit approximation where the output

$\dot{\tilde{q}}$, is also an argument in the approximation. Therefore, the original approximation (6) must be re-purposed to find the error in angular velocity,

$$\dot{\tilde{q}} \approx \frac{\tilde{q}_k - \tilde{q}_{k-1}}{T} \tag{9}$$

and be substituted back into the model (8) as the argument.

To complete the model, the missing variable of load torque, on the pulley system needs to be analysed and substituted into the approximation (8). The value of the load torque (τ) in the pulley drive system can be found with the following equation,

$$\tau = \frac{F \bullet D}{2}$$

$$\Rightarrow \tau = \frac{(mgd) \bullet D}{2} \tag{10}$$

where m is the total mass of the end effector arm (forearm), d is the length from the end effector arm's centre of mass to the revolute joint, D is the diameter of the pulley wheel and g is the constant of gravitational acceleration (9.807) [16][17]. This gives the one DOF arm's pulley a total torque where the torque is,

$$\tau = \frac{(0.119 \bullet g \bullet 0.072) \centerdot 0.1}{2} = 4.201 * 10^{-3} Nm.$$

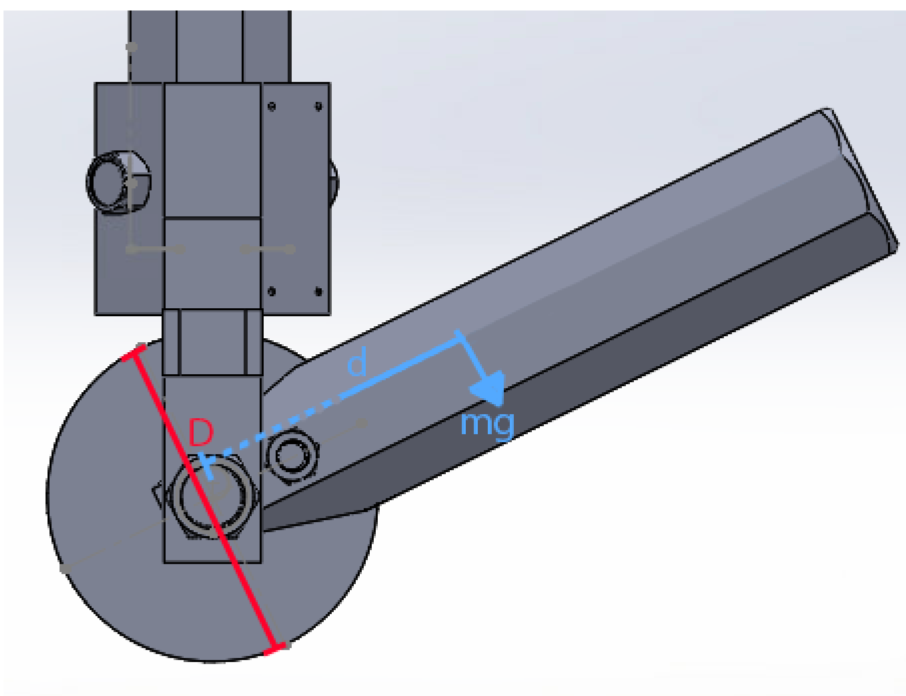


Figure 7: Visualises the torque free body diagram in Solidworks

With the complete model and the understanding that the Pulse Width Modulation (PWM) is proportional to voltage, which is proportional to angular velocity of the motors ($PWM \propto V \propto \dot{q}$) , it can be shown that

$$\dot{q} = \lambda \cdot PWM, \tag{11}$$

where λ is an arbitrary value of proportionality.

Therefore, to control the one DOF robotic arm with impedance control, a closed loop control system will be implemented. This will feed the errors of angular acceleration, velocity, and displacement back into the approximation (8) to control the PWM hence the speed of the motors. This controlled velocity will act as a counter measurement to the initial input displacement to bring the end effector back to its original angular position, leaving the system in steady state.

The desired values of Mass (M_d), Damping coefficient (B_d), and spring constant (K_d) will imitate the effects of the proportional control, integral control and derivative control variables, seen in proportional-integral-derivative control, respectively. The complete control system is shown in Figure 8.

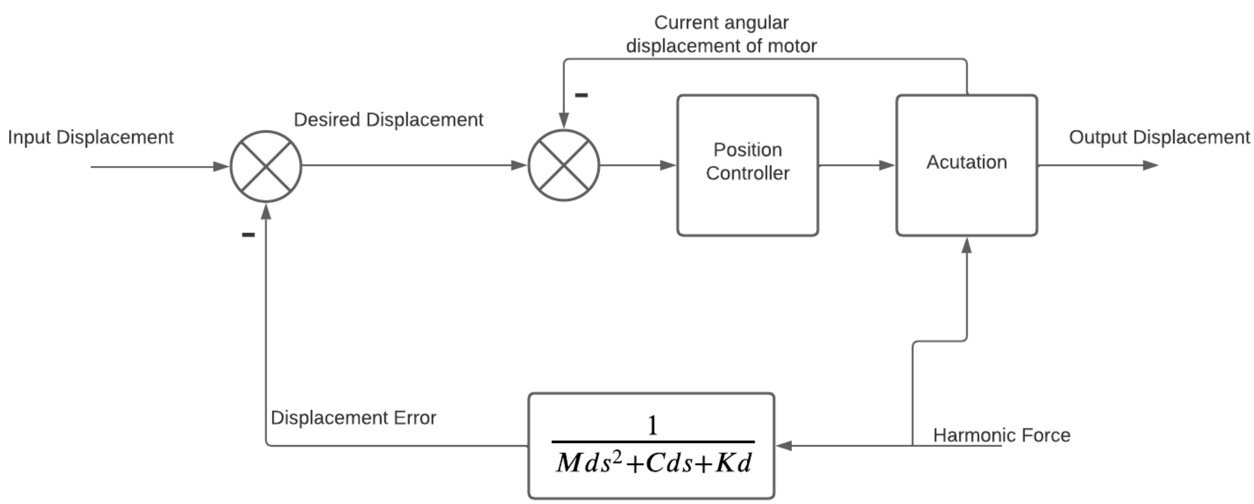


Figure 8: Visualises the complete transfer function model of the system.

3.3 Mechanical Layout

The 3D printed arm itself is fabricated with computer assisted design (CAD), in Solidworks 2020 Education Edition, so that the entire robotic arm could be 3D printed, excluding the electronic components. This makes the whole prototype as inexpensive as possible. The first challenge in the project is working out how to break down the whole arm and reconstruct it from its fragmented pieces. The solution to this problem was to split the arm into four major pieces, the “Upper Arm”, the “Elbow Joint”, the “Fore Arm” and the “Pulley Flywheel”. These pieces were connected by drilling holes through the frames and inserting a pin with two nuts, at either end, to secure its location as a connecting piece. All parts and sections of the arm were printed, including all the pins and the bolts, for the assembly of the arm.

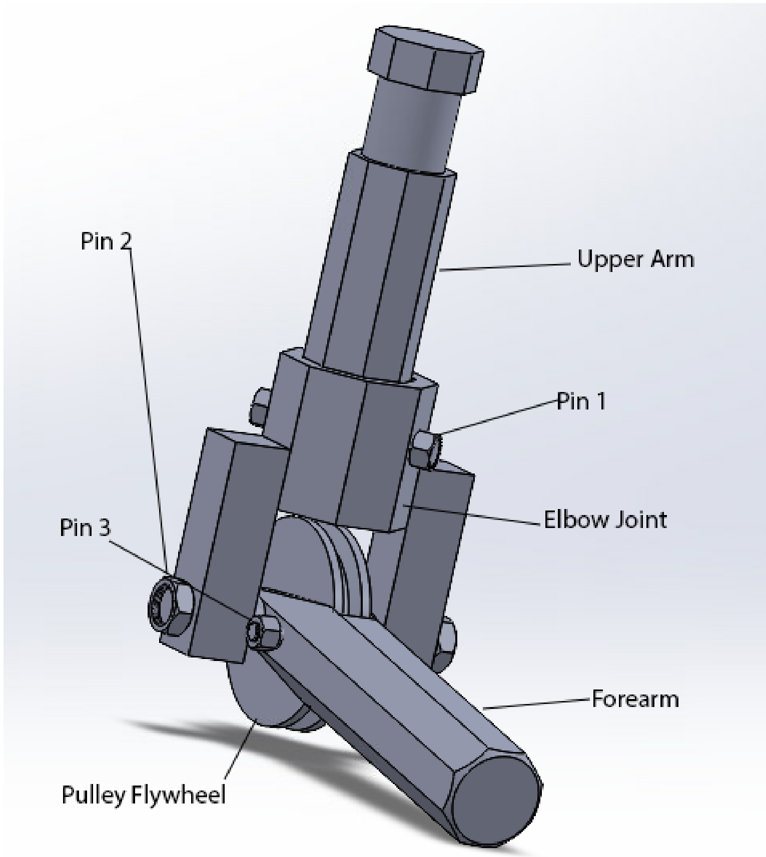


Figure 9: Shows the 3D Computer Assisted Design of the one DOF robotic arm in Solidworks

The cylindrical face on the top of the Upper Arm, shown in Figure 9, will be grasped by the Clamp on the Science Stand, which is being used as a foundation to suspend the arm in the air. The metal servo motors are placed on the Upper Arm between the elbow joint and the cylindrical surface on both the front and back to create an antagonistic relationship. The motors will have pegs on their servo arm that will have the fishing wire threaded through, and wrapped around, to create a secure base for the wire anchor points. The motors will be connected by Nylon Fishing Wire (8.0) that loops around the elbow pulley multiple times. This will create enough friction for the motors to turn the pulley and, therefore, turn the end effector. The wire will connect to the top and bottom of the upper-arm to two stainless steel extension springs (25 mm x 5 mm) for an oscillatory response from an applied force.

Three pins are used in the construction. The first goes through the Upper Arm and the Elbow Joint, assisted by having the Upper Arm slot into the Elbow Joint with a hollowed top, to then drive the pin through both bodies to connect them. The next pin connects the Pulley Flywheel, Elbow Joint and Fore Arm; this is the largest pin and the crucial pivot piece for the whole arm. The last pin is a small pin that connects the Pulley Flywheel and the Fore Arm so they behave as one whole object.

These pins also dictate the cross-sectional area shape of the arm. The original plan was to have a square cross-sectional area. However due to the physical space required for a nut and pin, it means that once the wire WAS attached from the motor vertically down towards the Pulley, the nut impeded the wire mechanism and affecting the functionality of the arm. To solve this problem an octagonal cross-sectional area is chosen for the design to allow for an additional surface that would allow a nut and pin to penetrate through the body while being offset to the fishing wire.

During the CAD stage, it was found that the stress on the arms of the elbow joint was high once a load was applied to the end effector (Figure 10). To resolve this, the arms are not only made thicker to handle the stress, but the connection to the upper base is made with a bigger surface area of connecting material, for more support.

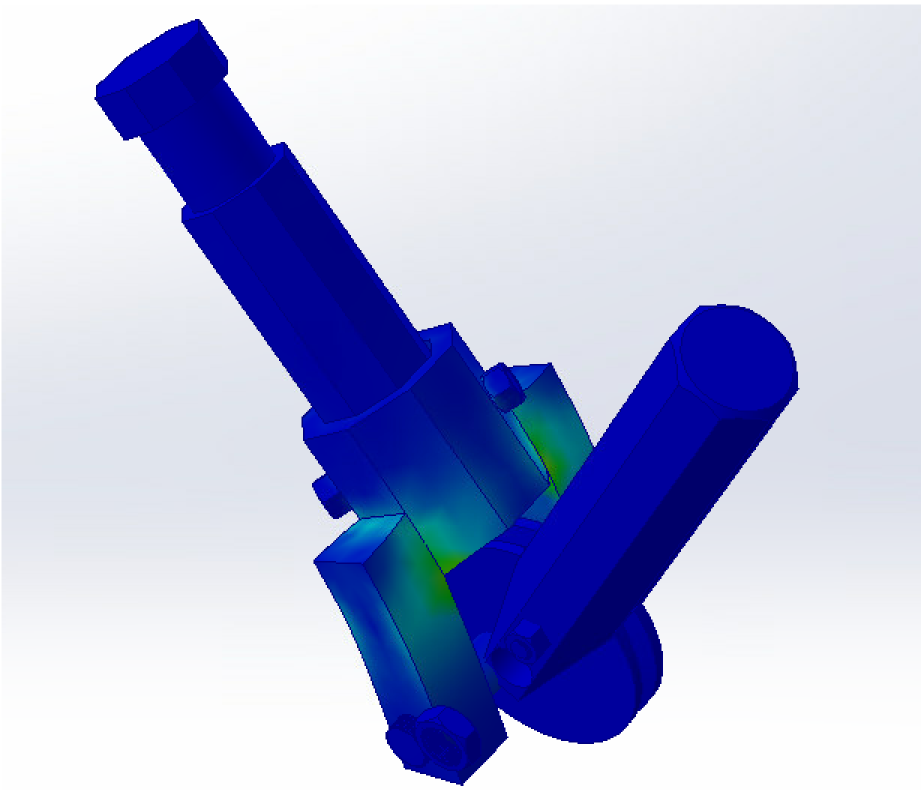


Figure 10: Shows the 3D stress analysis in solid works when a load is applied.

After the initial 3D print, it was decided that the best method of attaching the motors is to slot them into two cages on the Upper Arm of the structure. They are secured using tape as shown in Figure 11. Additionally, there were some problems that were highlighted with the initial design.

A problem occurred due to the increase in size of the arm as the constant design changes in the digital construction stage. These changes enabled more features and fluidity to the robot at the cost of size and weight. The Science stand, intended as a foundation for the machine had become unstable with the increased size of the arm. To solve this an additional support (clamp) is attached between the bottom of one of the Elbow Joint arms to provide stability during actuation. The same peg and bolts mechanism is implemented as the other attachments.

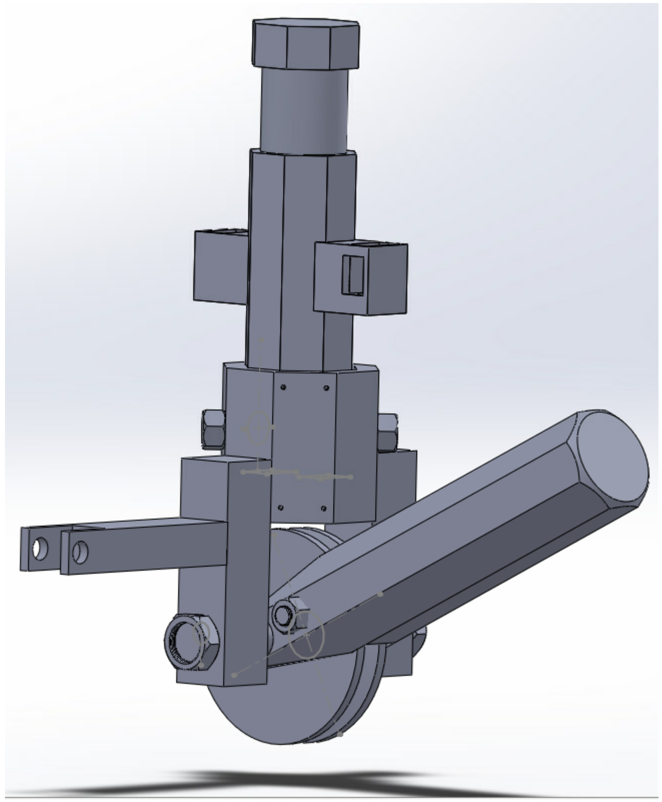


Figure 11: Shows the final 3D CAD print in solid works after initial testing to include its modifications.

3.4 Electrical Layout and Hardware

For the electrical layout and design of the robot, two MG90S Metal Gear Servo motors are used in tandem with the STM32 Nucleo-64 MCU development board micro-controller shown in Figure 12. Due to the adoption of the MG90S metal gear servo motors in the system, a different calculation is used to find the angle of displacement. The MG90S servo motors do not include any encoders to find the angle they are holding, instead, the servo motors track its current position by utilising an internal potentiometer. The potentiometer analog out signal can be read and mapped to angles between $0°$ and $180°$. [18]

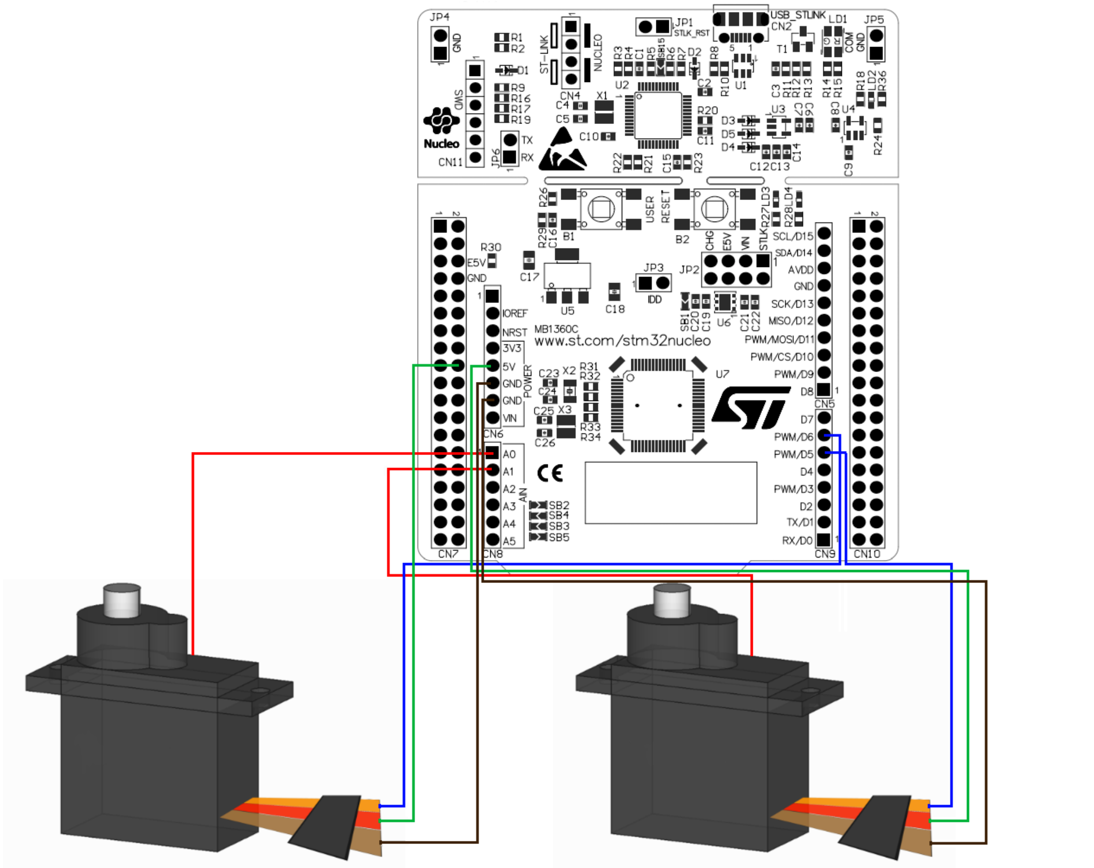


Figure 12: Wiring Diagram of the electrical system with the STM32 Nucleo-64 MCU development board and two MG90S metal gear servo motors [19][20]

Metal servo motors are being used as the lowest cost of actuation. Idealistically, a torque actuated motor would be better suited for the prototype, as the unknown calculated variable load torque could be instantly measured, however, these motors are an order of magnitude more expensive and out of budget.

The use of higher quality motors, such as continuous rotation servo motors or encoded motors, would be highly beneficial as the readings of their angular displacement would be more precise and accurate. Though for this prototype only $180°$ range of motion is all that is required, and so, the closed loop control, cost and efficiency of the servo motors are superior [21].

It is notable that if the prototype model would be scaled up and DC motors were being used for actuation in harmony with a H-bridge, then a unipolar PWM strategy would be most efficient as the motors will be operating at a close to zero state. This system would favour a steady voltage at 50% output in order to attain a fixed-in-place robot arm, instead of a close to zero voltage, which could appear during bipolar PWM and cause an open circuit.

3.5 Motor Software

The STM32 Nucleo-64 MCU development board micro-controller is coded in Arduino 1.8.19 (Legacy version is used to reduce errors and bugs) to make use of the servo.h library [22]. This library creates a Servo variable which can be attached using the "servo.attach()" instruction. This instruction has three parameters inside the brackets; the pin the servo motor PWM is assigned to, the minimum pulse width in milliseconds corresponding to 0°, and the maximum pulse width in milliseconds corresponding to 180°[23]. The initial command for the software is to define the servo motors. The next progression of the code is to set up the calibration technique to map out the voltage values of the internal potentiometer inside the MG90S servo motors. A "calibration()" function is added, that writes the motor's minimum and maximum values, reading the analog output value of the pins and receiving the potentiometer output signal. To ensure the wire is not stretched, the motors undertake antagonistic motion.

A loop is then provided to map currently read analogue values to the newly defined range. This is done in Arduino with the map(x, fromLow, toLow, fromHigh, toHigh) command [24].

Now the angular displacement (q) can be measured, the angular speed ($\dot{q}$) needs to be calculated using the approximation (9) with a time step T of 1000 ms and saved as a variable. The actuation function is now calculating the value of the angular speed and substitutes this value back into the implicit approximation (8), where $M = 0.119$ kilograms, $B = 0.01$, $K = 0.045$ as the system holds two springs in series with a spring constant of 0.09, and $\tau = 4.201 * 10^{-3} Nm$ which was calculated in Eq. (10). It was found that $\lambda = 20$ as the speed of the servo motors was mapped to a PWM value between 0-30. The maximum speed of the motors was 180°$/0.3s$ [19], therefore

$$\frac{(180/0.3)}{\lambda} = 30$$

$$\Rightarrow \lambda = 20. \tag{12}$$

The MoveTo function is then used to set the speed of the servo motors. The function takes the desired position and speed as input parameters, before running a block of code to differentiate which direction the motor needs to turn (positive or negative angular displacement). The servo motor will then iterate one degree of movement with a delay that matches the desired speed parameter. This function allows the motor to turn a specified distance, over a desired time, to emulate speed control [25]. All Algorithms are shown in the Appendices.

All of these functions are then combined into two final calculations to create impedance control for two motors. The full program is shown in Algorithm 1, where the desired angles for each motor are 135° for the top motor and 45° for the bottom motor. This enables the end effector to be suspended at a 45° angle.

Algorithm 1 Impedance Control Loop

Define Servos and Variables
while (1)

$q1 = (AnalogRead(Pin1)) - (DesiredAngle1)$;
$q2 = (AnalogRead(Pin2)) - (DesiredAngle2)$;
$Speed1 = (q1 - Lastq1)/Time$
$Speed2 = (q2 - Lastq2)/Time$

$qSpeed1 = (LastSpeed1 + (Time * ((\tau - (Speed1 * B) - (K * q1))/M)))/\lambda$;
$qSpeed2 = (LastSpeed2 + (Time * ((\tau - (Speed2 * B) - (K * q2)/M))))/\lambda$;
$MoveTo1(q1, qSpeed1)$;
$MoveTo2(q2, qSpeed2)$;
$Lastq1 = q1$;
$Lastq2 = q2$;
$LastSpeed1 = Speed1$;
$LastSpeed2 = Speed2$;

end while

4 Simulation

4.1 Simulation initialisation and design

Coppeliasim_Edu_V4_3_0_rev12 is the software used to create the digital simulation of the one DOF robotic arm [26]. In this BETA version of Coppeliasim the MujoCo physics engine has additional elastic features. These new features are essential to create the elastic physics of the fishing wire and pulley system. Despite the developers of this software stating that "the more complicated wire situations as you describe (wire wrapped around a pulley) are not currently supported via CoppeliaSim unfortunately. Only point-to-point wires are supported." [27], an intuitive solution to the problem was exercised.

Upon further investigation it was found that the two possible features that could be used are the wire tool and the rope tool. Both methods create an object between two test points that could be attached to different objects in the simulation.

The wire tool creates an intangible line between the two test points and pulls the two objects in contact with the test points towards each other along this line. There are two dynamics options for the wire tool; overlap constraint, which instantly pulls the two test points towards each other with immense force, and tendon constraint; which uses this same force to pull the test points together up to a set distance set by the programmer. This tool had no real application in the intended model as an intangible wire wrapped around a pulley is not feasible without friction.

The rope tool created numerous small spherical objects between the two test points. The amount, weight, size and the spacing of the objects could be varied by the user. This would have been ideal for the simulation as it created a tangible wire between the two test points that could interact with its environment, hence a physical interaction with the pulley. Unfortunately, the arrangement of the spherical objects are immovable and rooted in a fixed-point in space, once loaded in by the engine. As a result, the rope does not move in correspondence to the test points. There is no current method or technique of wrapping the rope around objects in this version of CoppeliaSim.

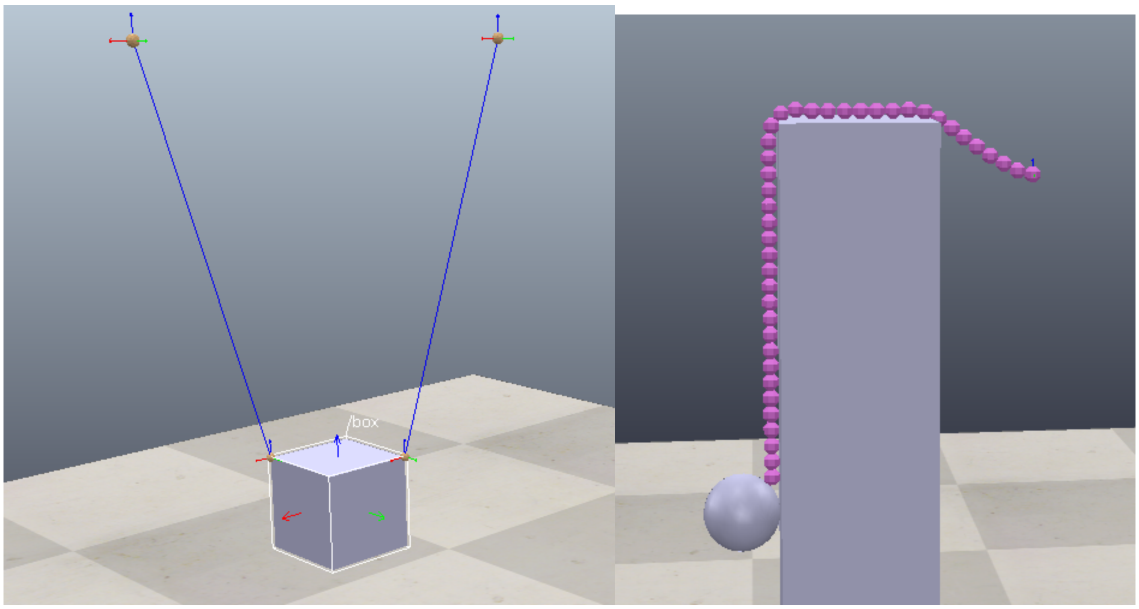


Figure 13: Shows the wire and rope MujoCo features respectively. The wires suspending a cube in mid air by hanging from fixed test points in space under the tendon constraint. The rope shows that the spheres that spawned in to form the rope are affected by gravity but cannot be moved by any future forces.

The only possible method of implementing this simulation into the Coppeliasim software is to use an integration of both tools. By creating small objects and grouping them with test points and then connecting them together via the wire tool, the physics of a rope is emulated. This creates a rope that is partially solid and partially intangible. This would be an estimate but, it would still mimic the behaviour of the prototype. To increase the accuracy of this model the resolution of the rope would have to be increased by making smaller objects, as to create a majority in the rope that acts as a dynamic interactive surface. However this is not only time exhaustive and tedious but also computationally taxing on the computer running the software.

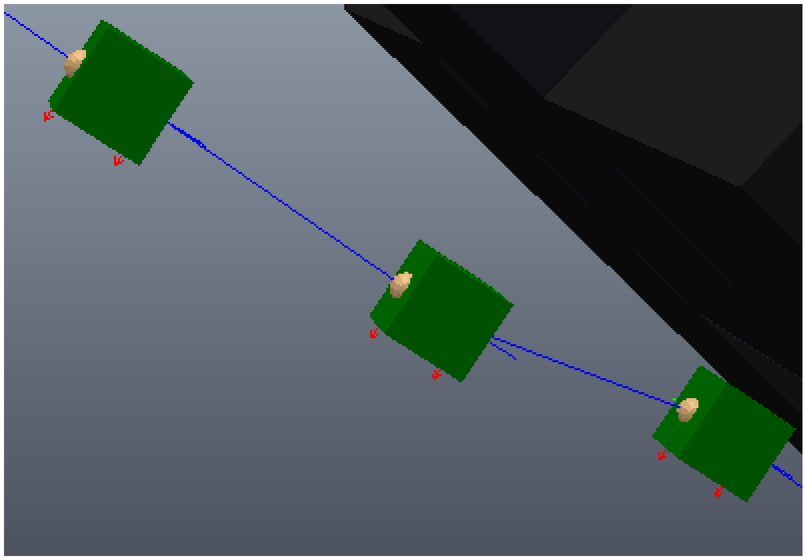


Figure 14: Shows the theorised rope by integrating ideas from both techniques.

To test the theory, a simple test model is made to see if the friction force is applied to a free revolute joint of no motion, to embody a pulley system. This is done by changing the weights of the cyan and green box below the wheel would spin to favor the heavier box in the chain and is shown in Figure 15.

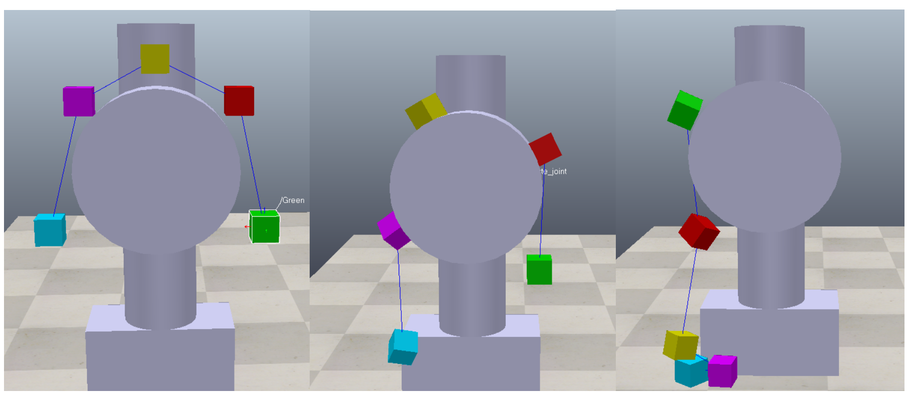


Figure 15: Shows the example set up, with a free spinning Flywheel and a chain of cubes and the full release of the chain as the flywheel rotates as predicted.

Combining the long chain of wired-up cubes creates a rope structure that could interact with a pulley system correctly, and showed promising developments. This rope was then attached to a stand with two revolute joints that were set up as motors to replicate the real life prototype.

After rigorous testing in the simulation, it was discovered that the smaller objects tend to glitch and phase through other objects when subjected to numerous opposing large forces from the wires. These glitches, when in abundance, create a chain reaction of spasms along the rope which would destroy the physics of the rope and would in turn break the simulation. Alternatively the objects would bounce so vigorously that they would break their tendon constraint and the wires would then be longer than the pulley object, which would allow the wire to phase through the pulley object. The rope would hang and no longer interact with the system.

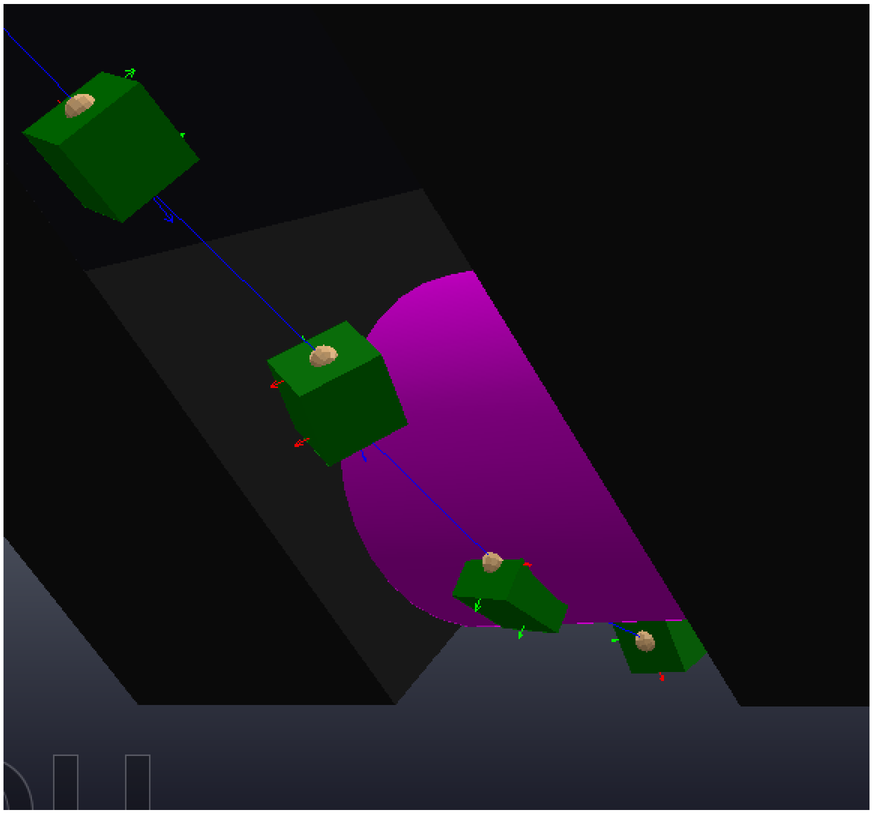


Figure 16: Gives an example of the cubes surface and the pulleys surface phasing through each other.

The best method of reducing glitches, and hence crashes, is to reduce the amount of high variance interactions between the objects. This was done through a mixture of solutions; the first method was to make the cubes bigger, so that the engine would have larger objects and more surface area to interact and lock onto. This spread out the reaction force that is presented from the pulley object, so the small cubes would not bounce around as violently as before.

The second method is locking the cubes into place, by grouping themselves with rotating cylinder objects so that their surfaces would never phase through one another. To do so the cubes need to be evenly spread around the cylinder with the correct ratio between intangible wire and solid object in the rope. For this even spacing, an equation for even distribution around a circle is used, so that the system can be scaled correctly if required. Upon scaling, a more refined rope is required and hence more cubes. The equation is given by the position of the kth object (P_k),

$$P_k = (R + \frac{h}{2})e^{\jmath\theta} = ((R + \frac{h}{2})(cos\theta + \jmath sin\theta), \tag{13}$$

where R is the radius of the circle, h is the length, width and height of the cubes, and θ is given by the equation,

$$\theta = k\frac{2\pi}{n} \tag{14}$$

where k are the required number of objects to be distributed $k \in \{0, 1, 2 \ldots, n-1\}$. This formula sets the centre of a circle as the origin point of an imaginary axis, and distributes the object's positions uniformly [28].

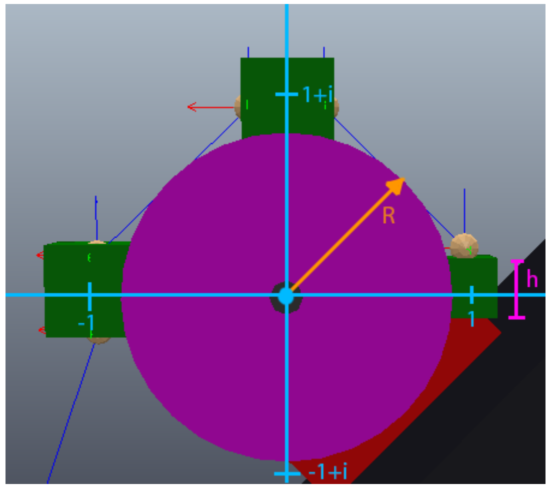


Figure 17: Shows the uniform distribution around the cylinder using the imaginary axis and Eq. (13) and (14).

The final step of the design process was to implement a spring joint to simulate the springs attached to the fishing wire in the real prototype. This was done by setting a prismatic joint's dynamic properties as a spring and matching up to the spring constant $K = 0.090/2 = 0.045$.

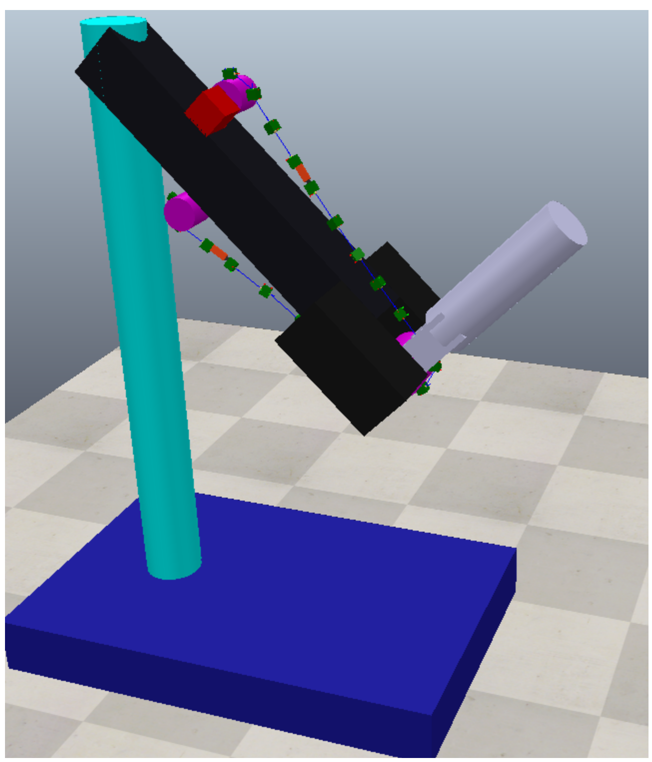


Figure 18: Shows the final simulation design, with the springs implemented into the rope, running to hold the end effector at $45°$ to the X-Y plane.

4.2 Simulation software code

The code to actuate the motors in Coppeliasim closely resembles the Arduino code for the prototype, seen in Algorithm 4. However, with the simulation, no approximations have to be made outside of the main function to find angular velocity ($\dot{\tilde{q}}$) using Eq. (10), as the values can be obtained with functions inside the engine via Lua. Additionally the time step T was decreased to 1 ms as the time step of the simulation was greatly reduced to 10 ms. Both motors use a child script that implements the same code. The code is represented as pseudo-code and is the same as the physical model shown in Algorithm 1.

5 Results and Discussion

The final appraisal of the project yielded positive results and provided strong evidence that all five sections of validation (from Figure 2) were completed and working as intended:

1. Information Flow – All components in both models can communicate with each other and there is a constant, steady flow of information in the system.

2. Impedance Control – Both controllers can be implemented with an impedance controller, although it is only demonstrated in the integrated simulation environment.

3. Mechanical Layout – All passive mechanical components of both machines are structured correctly and enable the arm to move smoothly.

4. Electrical Layout and Hardware – All electrical components and hardware are correctly and safely wired, however, due to the cost and time restrictions of the project, the physical model could not execute impedance control because of the lack of back drive in the servo motors [29]. The motors are too strong to reposition with an input force once a voltage is supplied, and a large force would surpass the motor's breaking torque, meaning that the motors would turn off and would no longer be actuated.

5. Motor Software – In both models, the code for the motors work as intended. The simulation can implement impedance control, while the physical model implements position control, due to the aforementioned problems with the servo motors.

5.1 Prototype Robot Arm

The constructed arm was coded to perform position control, by adapting the previous impedance controller to move to a specific position, accurately and precisely. This new code implements a

Proportional Derivative (PD) controller of the form,

$$\dot{\tilde{q}} + \beta\tilde{q} = 0$$

$$\Rightarrow \dot{\tilde{q}} = -\beta\tilde{q}, \tag{15}$$

where β is an arbitrary value of proportionality, chosen to match the spring constant $K = 0.045$ [30]. This speed was then used in Eq. (11) to match the real speed of the motor arm. Then, using different combinations of angles for q_1 and q_2, to consistently create the desired angle (q_d), the arm was moved in increments of $5°$ using the angle and speed position control. Each position of the end-effector was recorded and compared to the intended angle and recorded ten times to determine repeatability.

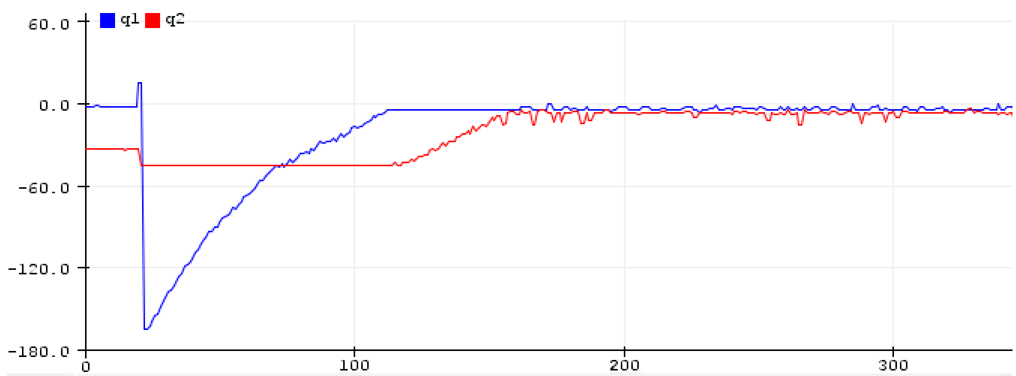


Figure 19: Shows the exponential decay graphs of the position controller in both motors for the end effector to hold an angle of $50°$

Table 1: Angular Position of the End Effector using Position Control

q_d	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	Mean	Sample Variance
$25°$	$25°$	$25°$	$25°$	$25°$	$25°$	$24°$	$25°$	$25°$	$25°$	$25°$	$24.90°$	$0.1000°$
$30°$	$30°$	$30°$	$30°$	$31°$	$30°$	$30°$	$30°$	$30°$	$30°$	$30°$	$30.25°$	$0.1000°$
$35°$	$35°$	$35°$	$35°$	$35°$	$34°$	$36°$	$35°$	$35°$	$35°$	$35°$	$35.00°$	$0.2222°$
$40°$	$40°$	$40°$	$41°$	$40°$	$40°$	$40°$	$41°$	$40°$	$40°$	$40°$	$40.20°$	$0.1778°$
$45°$	$46°$	$45°$	$45°$	$46°$	$46°$	$45°$	$45°$	$45°$	$45°$	$46°$	$45.40°$	$0.2667°$
$50°$	$51°$	$50°$	$50°$	$50°$	$51°$	$50°$	$49°$	$51°$	$50°$	$50°$	$50.20°$	$0.4000°$
$55°$	$55°$	$56°$	$55°$	$55°$	$54°$	$56°$	$55°$	$55°$	$55°$	$55°$	$55.10°$	$0.3222°$
$60°$	$60°$	$60°$	$60°$	$60°$	$60°$	$60°$	$60°$	$60°$	$60°$	$60°$	$60.00°$	$0.0000°$

The results of the test presented in Table 1 show that the arm can perform a high level of position control, with a high level of precision and repeatability, with a maximum variance of $0.4000°$. Although, the motors of the arm do not allow for $90°$ of motion. The range of the end effector is limited when moving to a desired position beyond the minimum and maximum angles of $25°$and $60°$ respectively. The motors are not strong enough to pull and stretch the wire and allow for the full range of motion.

The springs could still be attached to the wires and maintain their use as passive components to protect the motors from large input forces. Although, the springs restrict the range of motion of the arm further, after factoring in the elongation of the spring when extended. The angular precision test was repeated again with the springs, where the one DOF robot arm operated in an attenuated range of motion, seen Table 2.

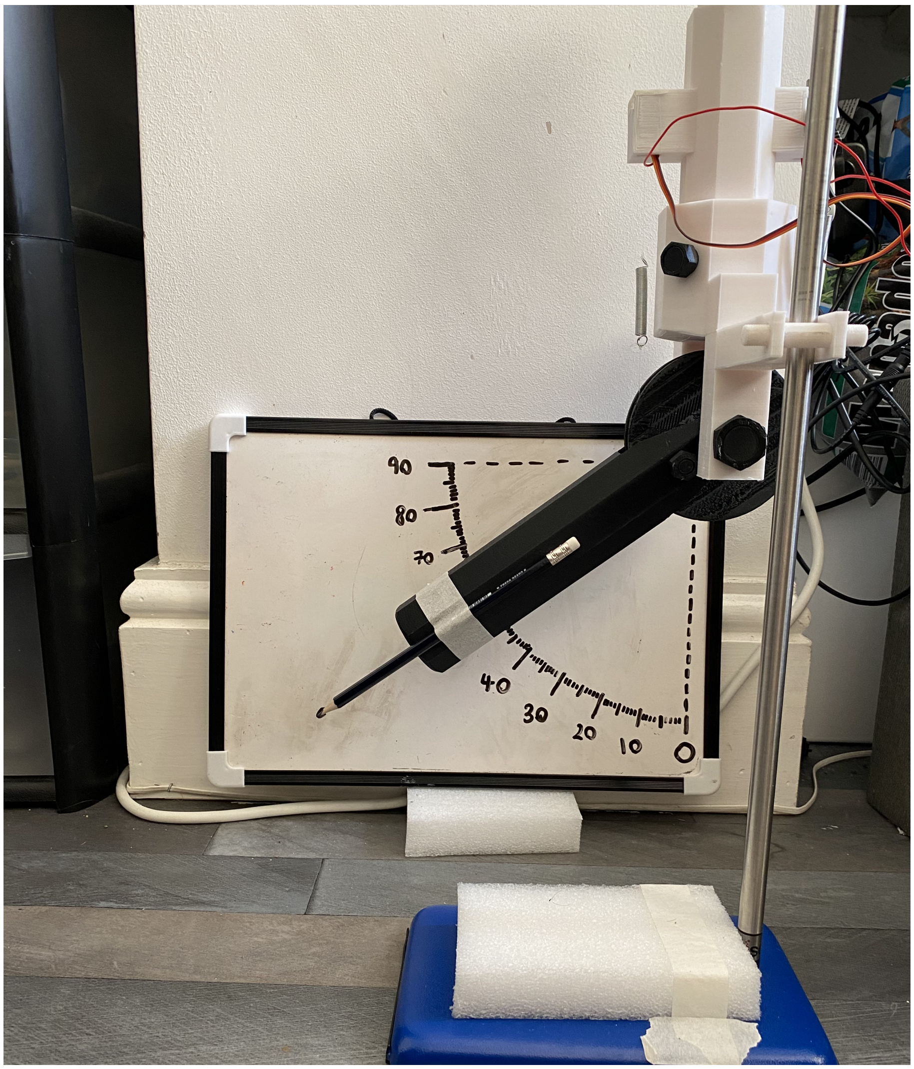


Figure 20: Is the prototypes full set up with the springs attached, the arm implemented position control, and a pencil was fixed to the centre of the end effector for clarification when recording angles.

To fix the attenuated range, the spring could be made shorter, or a damper could be put in place to restrict the expansion of the spring under tension. The spring would then not extend and the arm will be able to perform the original range of actuation. Regardless of the range, the results shown in Table 2

Table 2: Angular Position of the End Effector using Position Control With Springs

q_d	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	Mean	Sample Variance
35°	35°	35°	35°	35°	35°	35°	35°	35°	35°	35°	35.00°	0.0000°
40°	40°	41°	41°	40°	40°	40°	40°	40°	40°	40°	40.20°	0.1778°
45°	45°	45°	46°	45°	45°	44°	45°	44°	45°	45°	44.90°	0.3222°
50°	50°	49°	51°	51°	50°	50°	50°	51°	50°	50°	50.20°	0.4000°
55°	55°	53°	54°	55°	55°	55°	55°	55°	55°	55°	54.70°	0.4556°
60°	60°	59°	60°	60°	60°	60°	60°	60°	60°	60°	59.90°	0.1000°
65°	65°	65°	66°	66°	65°	65°	66°	65°	65°	65°	65.30°	0.2333°

further solidify the precision that the one DOF robotic arm can perform with a maximum variance of $0.4556°$.

These two tests show the capabilities of the model, while restricted, to portray its potential if upgraded to perform impedance control. The system has the capacity to perform high level position control which would be transferable in accordance with an impedance controller.

If this model was to be developed further to create an impedance controller, an additional potentiometer would have to be placed to measure the revolute joint of the elbow. This would not impede the movement of the motors and it would allow for the system to read the angular displacement of the end effector, relaying a new speed to the motors to perform impedance control. Additionally, although the accuracy of reading angles of the motors through the potentiometer was high, an encoder would greatly improve performance and accuracy.

5.2 Simulated Robot Arm

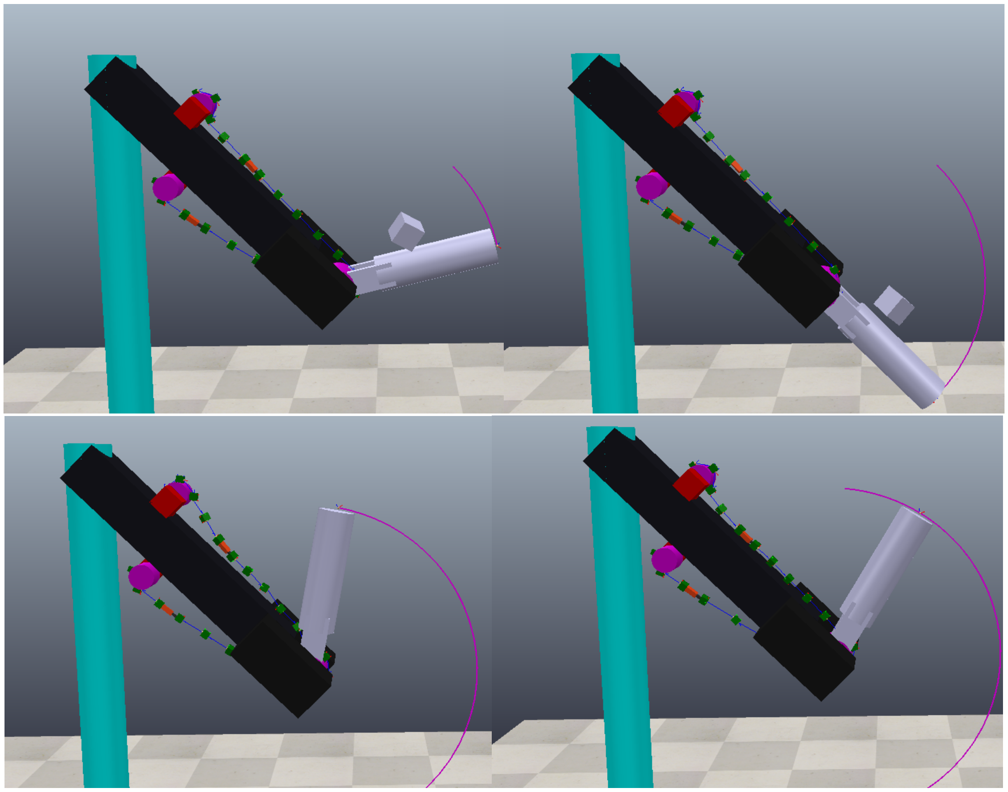


Figure 21: Visualises the simulated arm in action, after a small 1kg cube was dropped onto the arm as a input displacement, the purple arc shows the movement of the end effector after impact.

The result of the Coppeliasim software experiment presented positive results with the impedance controller working as intended, however, the rope structure induced large volatile forces onto the system due to the unpredictable elasticity of the wire tools. When the linked dummies reach their individual tendon restraints, a large force is applied on the objects along the path of link towards the paired dummy object. Due to the dynamic nature of the system, these tendon constraints are constantly strained and tested, until multiple linked pairs harmonise and inflict a large angular displacement onto the end effector, before being corrected by the controller. This can be observed in Figure 22 as the feedback controller response maintains an angle of $65° \pm 5°$ with sharp deviations spikes.

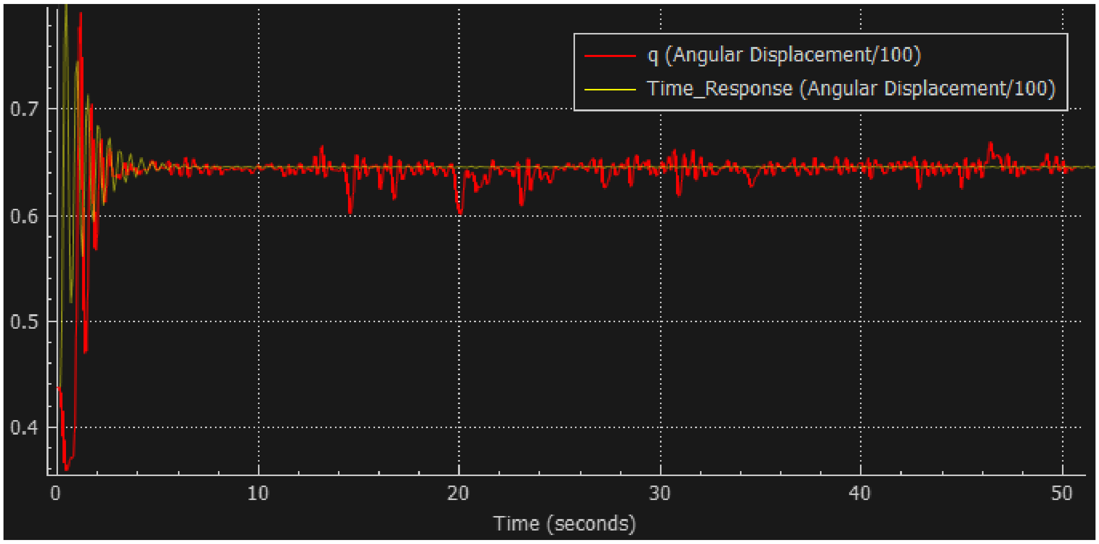


Figure 22: Shows the angular displacement ($q/100$) over time of the natural response of the system alongside the time response of the system.

The impedance control test was repeated with a falling 1 kg mass that served as an input displacement, shown in Figure 22. From the graph it can be observed that the angular displacement corrects itself to 65 degrees, before returning to its steady state using the feedback impedance controller. Thus, indicating the impedance control works on the Coppeliasim software using the experimental rope structure.

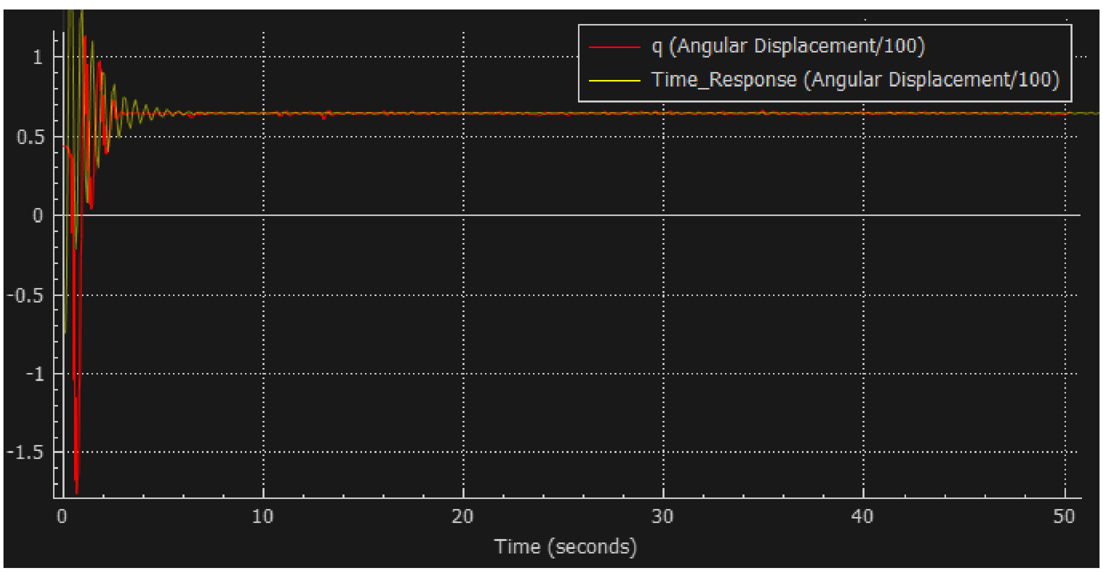


Figure 23: Shows the angular displacement ($q/100$) over time of the response of the system with an input displacement from a 1kg cube alongside the time response of the system..

To further show the deviation caused from these spontaneous spikes, Figure 23 displays the same robotic arm being simulated three times with the same input conditions with different desired values for angular displacements (q_d). This created three different waveforms that closely follow of averages of 40°, 50°and 60°.

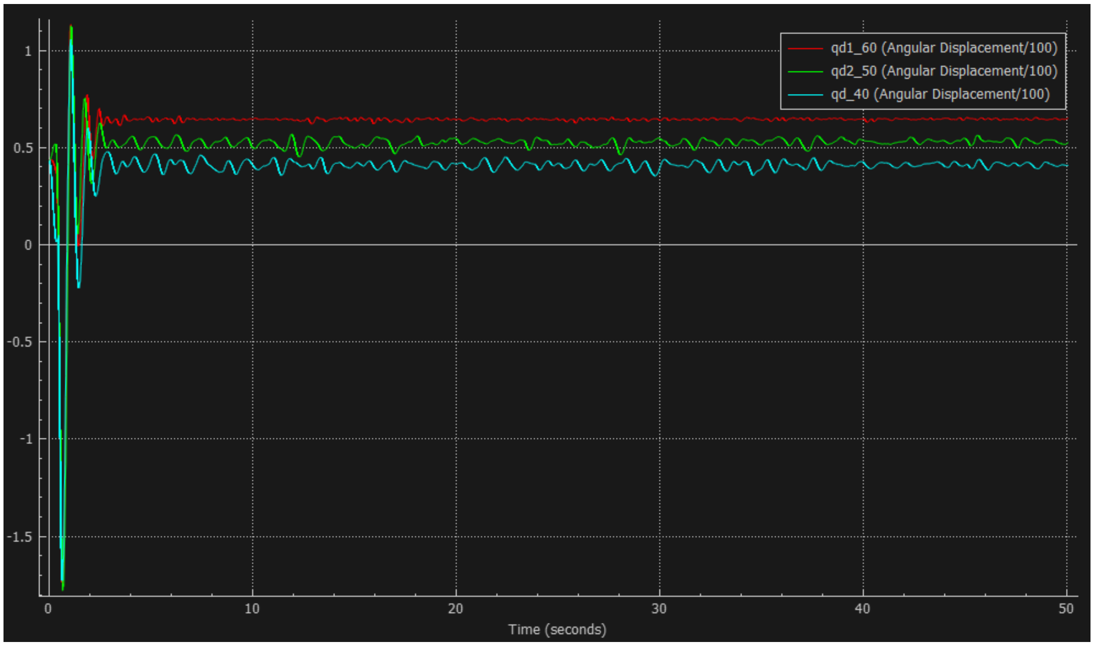


Figure 24: Shows the angular displacement ($q/100$) over time of the response of three systems with an input displacement from a 1kg cube, with three different desired angles: 60 (red), 50 (green), and 40 (cyan).

It can be observed that shallower angles have larger spikes due to wire not being as taught as when compared to 60°. The system is more dynamic in this position and therefore, the motors oscillate more when subjected to larger forces, as the resultant gravitational force is greater when the angles q_1 and q_2 are parallel to the X-Y plane (0°). These oscillations create more reaction forces with the tendon constraints, causing the controller to become less accurate.

To improve the simulation, to have it functioning optimally, more analysis would have to be performed on the feedback controller to locate and correct the source of the system that creates these abnormal deviations in the angular displacement. This way the controller could adapt to the tendon constraints to include their forces in the impedance equation. However, as this is new software, it is highly likely that CoppeliaSim will introduce a full rope tool that will be able to wrap around and interact with other objects in future editions, or edit their current tools to provide more possibilities to the user.

In this experiment, this research has shown substantial evidence of validating the potential of CoppeliaSim integrating with MujoCo, with soft body interactions. These simulations will greatly advance mechatronic and orthotic development in the future, giving researchers and companies conceptual insights for new technology and machines, without further expenses. Models that include wire actuation can be simulated, edited and verified before any physical adaptation is constructed.

6 Conclusions and Future Work

6.1 Conclusions

In conclusion, the intended learning outcomes for this project were attained; a one Degree-of-Freedom robotic arm with two antagonistic string actuated motors was designed and constructed, alongside an impedance control simulation in CoppeliaSim.

To summarise, all aims and objectives for this research project were completed. Rotational impedance control was researched to a high comprehensive level, before being implemented into two real applications. The BETA integrated simulation environment, between CoppeliaSim and MujoCo was thoroughly researched and a unique soft body, wire actuated model was fabricated on the software. The simulation was slowly adapted and built upon, from creating a simple spring model to manifesting an antagonistic rope and spring actuated pulley machine. A physical prototype was then built to validate the impedance controller from the simulation, but, this model could only implement position control due to the constraints of the servo motors. Additionally, this research project has sufficiently evaluated the potential usage of the integrated physics engine of CoppeliaSim and MujoCo, granting researchers a new resource for developing string and wire actuated systems and machines.

6.2 Future Work

The clear progression for the physical project would be to add one additional sensor component, so that impedance control could be transferred from the simulation, and implemented into the physical prototype with ease. Alternatively, the potential future research possibilities presented from the integrated simulation environment are boundless. The ability to model machines and systems with soft bodies, such as strings and wire actuation, digitally before being applied to real world models is an outstanding apparatus for all mechatronic academics and developers. This was previously not possible. It is notable, that Coppeliasim_V4_4_0 is now online and the BETA software used for this project has already been updated, to include the MujoCo physics engine, and the software is continuing to update.

References

[1] "Variable Impedance Control and Learning—A Review",Frontiers, Fares J. Abu-Dakka & Matteo Saveriano, Volume7, 2020 [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2020.590681/full

[2] "Robot Modeling and Control" Spong, Mark W. author.; Hutchinson, Seth, author.; Vidyasagar, M. (Mathukumalli), 1947- author. 2020; Second edition.

[3] "Impedance Control: An Approach to Manipulation, Part 1 -Theory", Neville Hogan, Massachusetts Institute of Technology.

[4] "Impedance Control: An Approach to Manipulation, Part 2 -Implementation", Neville Hogan, Massachusetts Institute of Technology.

[5] "Impedance Control: An Approach to Manipulation, Part 3 -Application", Neville Hogan, Massachusetts Institute of Technology.

[6] "WHAT'S THE DIFFERENCE BETWEEN ORTHOTICS AND PROSTHETICS?",Touchstone Rehabilitation, September 1, 2021, [Online]. Available: https://www.touchstonerehabilitation.com/blog/whats-the-difference-between-orthotics-and-prosthetics

[7] "Position control vs impedance control", Harmonic Bionics, Video [Online]. Available: https://www.youtube.com/watch?v=KJ8s1BUHoks&ab_channel=HarmonicBionics

[8] "Impedance Control of a Transfemoral Prosthesis using Continuously Varying Ankle Impedances and Multiple Equilibria", Namita Anil Kumar, Woolim Hong, Pilwon Hur, [Online]. Available: https://arxiv.org/abs/1909.09299

[9] "Physics engine differences", CoppeliaSim, n.d[Online]. Available: https://www.coppeliarobotics.com/helpFiles/en/physicsEngineDifferences.htm

[10] "PROSTHETICS AND ORTHOTICS MARKET - GROWTH, TRENDS, AND FORECASTS (2023 - 2028)", Mordor Intelligence, n.d [Online]. Available: https://www.mordorintelligence.com/industry-reports/prosthetics-and-orthotics

[11] "Prosthetics And Orthotics Market Size, Share & Trend Analysis Report By Type ((Orthotics (Upper Limb, Lower Limb, Spinal), Prosthetics (Upper Extremity, Lower Extremity)), By Region, And Segment Forecasts, 2023 - 2030", Grand View Research [Online]. Available: https://www.grandviewresearch.com/industry-analysis/prosthetics-orthotics-market

[12] "Plastics: The challenges and possible solutions", Principles for Responsible Investment, n.d [Online]. Available: https://www.unpri.org/plastics/plastics-the-challenges-and-possible-solutions/4773.article

[13] "AFFORDABLE PROSTHETICS MADE FROM RECYCLED PLASTIC WASTE", Material District, January 11, 2019 [Online]. Available: https://materialdistrict.com/article/prosthetics-recycled-plastic/

[14] Comparison of Control Strategies in Commercial and Research Knee Prostheses. IEEE Trans Biomed Eng. 2020 Jan;67(1):277-290. doi: 10.1109/TBME.2019.2912466. Epub 2019 Apr 22. PMID: 31021749. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/31021749/\

[15] "Impedance Control", Annika, Robotics Explained [Online]. Available: https://robotics-explained.com/impedancecontrol

[16] "Motor Sizing Basics Part 1: How to Calculate Load Torque", Johann Tang, January 14, 2020 [Online]. Available: https://blog.orientalmotor.com/motor-sizing-basics-part-1-load-torque#:~:text=To%20calculate%20load%20torque%2C%20multiply,x%200.05%20m%20%3D%201%20Nm.

[17] "Examining motor torque for belt and pulley systems", Temitayo Oketola, October 18, 2021 [Online]. Available: https://insights.globalspec.com/article/17505/examining-motor-torque-for-belt-and-pulley-systems

[18] "How to Control Servo Motors with Arduino – Complete Guide", Dejan[Online]. Available: https://howtomechatronics.com/how-it-works/how-servo-motors-work-how-to-control-servos-using-arduino/

[19] "MG90S Micro Servo", Makersportal , n.d. [Online]. Available: https://makersportal.com/shop/mg90s-micro-servo

[20] "UM2324 User manual" STM32 Nucleo-64 boards (MB1360) - User manual [Online]. Available: https://www.st.com/resource/en/user_manual/um2324-stm32-nucleo64-boards-mb1360-stmicroelectronics.pdf

[21] "Advantages and Disadvantages of a Servo Motor", Racine County Eye Staff, October 14th, 2021, Updated October 20th, 2021 [Online]. Available: https://racinecountyeye.com/2021/10/14/advantages-and-disadvantages-of-a-servo-motor/

[22] "Reference > Libraries > Servo", Arduino.cc, n.d [Online]. Available: https://www.arduino.cc/reference/en/libraries/servo/

[23] "Reference > Libraries > Servo", Arduino.cc , n.d[Online]. Available: https://reference.arduino.cc/reference/en/libraries/servo/attach/

[24] "map()/", Arduino.cc [Online]. Available: https://cdn.arduino.cc/reference/en/language/functions/math/map/

[25] "How to Control Speed of Servo Motor - Arduino Project", Circuit Magic [Online]. Available: https://www.youtube.com/watch?v=xyOQ4J4BroE&ab_channel=CircuitMagic

[26] “A Complete CoppeliaSim Tutorial (V-REP)”, Leopoldo Armesto [Online]. Available: https://www.youtube.com/playlist?list=PLjzuoBhdtaXOoqkJUqhYQletLLnJP8vjZ

[27] “One-Degree-Of-Freedom Robotic arm with wire actuation in MujoCo”, November 21, 2022 [Online]. Available: https://forum.coppeliarobotics.com/viewtopic.php?t=9976

[28] M. M. Marinho and B. V. Adorno, "Adaptive Constrained Kinematic Control Using Partial or Complete Task-Space Measurements," in IEEE Transactions on Robotics, vol. 38, no. 6, pp. 3498-3513, Dec. 2022, doi: 10.1109/TRO.2022.3181047

[29] “What is back driving and why is it important?”, Danielle Collins, March 7, 2017 [Online]. Available: https://www.linearmotiontips.com/what-is-back-driving-and-why-is-it-important/

[30] “Advanced Controls > Advanced Controls Introduction > Introduction to PID”, First Robotics Competition, n.d [Online]. Available: https://docs.wpilib.org/en/stable/docs/software/advanced-controls/introduction/introduction-to-pid.html

Appendices

Algorithm 2 Initialisation

```
#include <servo.h>
Servo servo1;
Servo servo2;
void setup(){
servo1.attach((pin),600,2300);
servo2.attach((pin),600,2300);
}
void calibration () {
servo1.write(0);
servo2.write(180);
delay(2000);
servoValue0Deg1=analogRead(AnalogPin1);
servoValue180Deg2=analogRead(AnalogPin2);
servo1.write(180);
servo2.write(0);
delay(2000);
servoValue180Deg1=analogRead(AnalogPin1);
servoValue0Deg2=analogRead(AnalogPin2);
}
```

Algorithm 3 Loop to find angular displacement

```
int qd1 = 135;
int qd2 = 45;
While (1){
q1 = ((map(analogRead(servoAnlogOut1),servoValue0Deg1,
servoValue180Deg1,0,180) - qd1);
q2 = ((map(analogRead(servoAnlogOut2),servoValue0Deg2,
servoValue180Deg2,0,180) - qd2);
}
```

Algorithm 4 MoveTo function

```
void MoveTo1(int position, int speed){
mapSpeed1= map(speed,0,30,30,0);
if (position > pos){
for (pos = pos1; pos <= position; pos += 1){
servo1.write(pos);
pos1=pos;
delay(mapSpeed1);}
}
else{
for (pos = pos1;pos >= position; pos -= 1){
servo1.write(pos);
pos1=pos;
delay(mapSpeed1); }
}
Speed1 = ((map(analogRead(servoAnalogOut1),servoValue0Deg1,
servoValue180Deg1,0,180)-LastAngle1)/(30.0f/mapSpeed1));
}
void MoveTo2(int position, int speed){...
}
```

Algorithm 5 Full Program with Impedance Control

```
#include <servo.h>
Servo servo1;
Servo servo2;
int qd1 = 135;
int qd2 = 45;
float M = 0.119;
float B = 0.01;
float K = 0.045;
float T = -0.004201
setup();
calibration();
While (1){
q1 = ((map(analogRead(servoAnlogOut1),servoValue0Deg1,
servoValue180Deg1,0,180) - qd1);
q2 = ((map(analogRead(servoAnlogOut2),servoValue0Deg2,
servoValue180Deg2,0,180) - qd2);
qSpeed1 = (LastSpeed1 + (1*((T-(Speed1*B)-(K*q1))/M)))/6;
qSpeed2 = (LastSpeed2 + (1* ((T-(Speed2*B)-(K*q2)/M))))/6;
moveTo1(q1,qSpeed1);
moveTo2(q2,qSpeed2);
delay(1000);
}
```

Algorithm 6 Coppeliasim_Edu_V4_3_0_rev12 LUA code

```
function sysCall_init(){
j1 =sim.getObject('.');
q=0;
qd=(0*math.pi/180);
qdot=1;
K = 0.045;
B = 0.01;
M = 0.119;
T = –0.004021;
Lspeed = 0;
}
function sysCall_acutation(){
sim.setJointTargetVelocity(j1,qdot);
Lspeed = sim.getJointVelocity(j1);
q = (sim.getJointPosition(j1)-qd);
wait(10);
qdot = Lspeed + (0.01*(T-(sim.getJointVelocity(j1)*B)-(K*q))/M);
}
```

Developing a robotic bicep with string-based actuators and integrating impedance control

Third Year Individual Project – Alexander Morley

Final

For the project I plan to characterise and create a singular degree of freedom robotic arm, that would move a forearm by extending and contracting a cable via a motor. In the first three weeks of the first semester, I plan to research the biomechanics of the muscle and extensively calculate the dimensions of the device before I start construction. I intend on attaching the bicep robot to a stand with a counterweight so it can operate above the ground. The building process should be finished before the end of the first semester, at which time I would start coding the machine with a micro-controller to be able to contract and extend to any degree of freedom between 180° (fully extended or a straight arm) and 45° (fully contracted). After this, I plan on developing and researching a method of implementing impedance control. The robot should be able to detect it's being moved and try to resist the applied force or move back to its original position with a very mild oscillation effect. The torque applied to the robot will be calculated with a one degree of freedom torque sensor attached to the bicep cable. There will be three settings of the impedance control which will include; 'Stiff' which will make the robotic arm very hard to move away from its original position; 'Soft' which will make the robotic arm very easy to move away from its original position, however it will return to its starting point after some time; and 'Neutral' which the robotic arm will be easy to move, although it will try to return to its original position as fast as possible. All these modes are expected to have very mild oscillation effect and should be able to adapt to all degrees of freedom about the elbow joint. At the end of the project, I intend to present my work with a presentation, showing the robotic arm contracting and extending in a controlled fashion, stopping the robot at an angle chosen by a professor, before presenting the three settings of impedance control. With this project I intend to deeper my learning with control systems as well as robotics Characterisation. This individual project, I believe is not only challenging but also attainable, whilst broadening my own knowledge and skills to become a better engineer.

The envisaged work will deliver a one degree of freedom robotic arm that would stand no taller than 30 cm and when fully extended shall be no longer than 20 cm. The depth of the robot will be determined by the width of the motor, torque sensor and micro-controller. The device's parts will be 3D printed with acetyl and assembled in 3 parts, the forearm, the bicep and the stand. The robot should be able to contract and extend the cable, attached to the forearm, which should move the arm and its position should be managed with the impedance control, based on its settings and the applied torque. The robot's cost will be slightly more than £100. The motor, torque sensor and micro-controller should all be under £30, and the cable will be no more than £10. All the 3D printing material can be bought for under £20.

My motivation for this project is rooted in my interest in sports and human athletes. I believe that making a robotic arm with the use of tendon-like actuators will further my understanding of biomechanics and let me take steps into developing prosthetic limbs and artificial muscles later in my career. By first learning about impedance control systems, I will be able to access more complicated control algorithms and robotic designs for any complex projects in the future.

The GANTT charts below show the weekly progression of my project in its entirety over the academic year, including all the necessary work I aim to complete before each Project Review Meeting (PRM) Deliverable. I have separated the bars into three colors indicating the type of work during this time; Blue is written documentation work such as reports; Red is programming and computer-based work, while green is physical construction or purchasing of components. During the first semester most of the time is spent getting as much planning and preparatory work done as possible. The reason for this is because I have less courses during my first semester so I should use this time to effectively complete as much of my project as I can before the second semester starts and I'm over encumbered in work. Tasks 1 through 7 have all been completed and consist of initial research and GANTT chart planning. This was all for my first PRM deliverable.

Going into the second phase of the project I am anticipated to do most of the coding research as well as develop a digital simulation/model of the arm once it's been constructed. After completing the simulation, I will buy components and print any 3D structures necessary, so it's all delivered shortly after the second PRM deliverable.

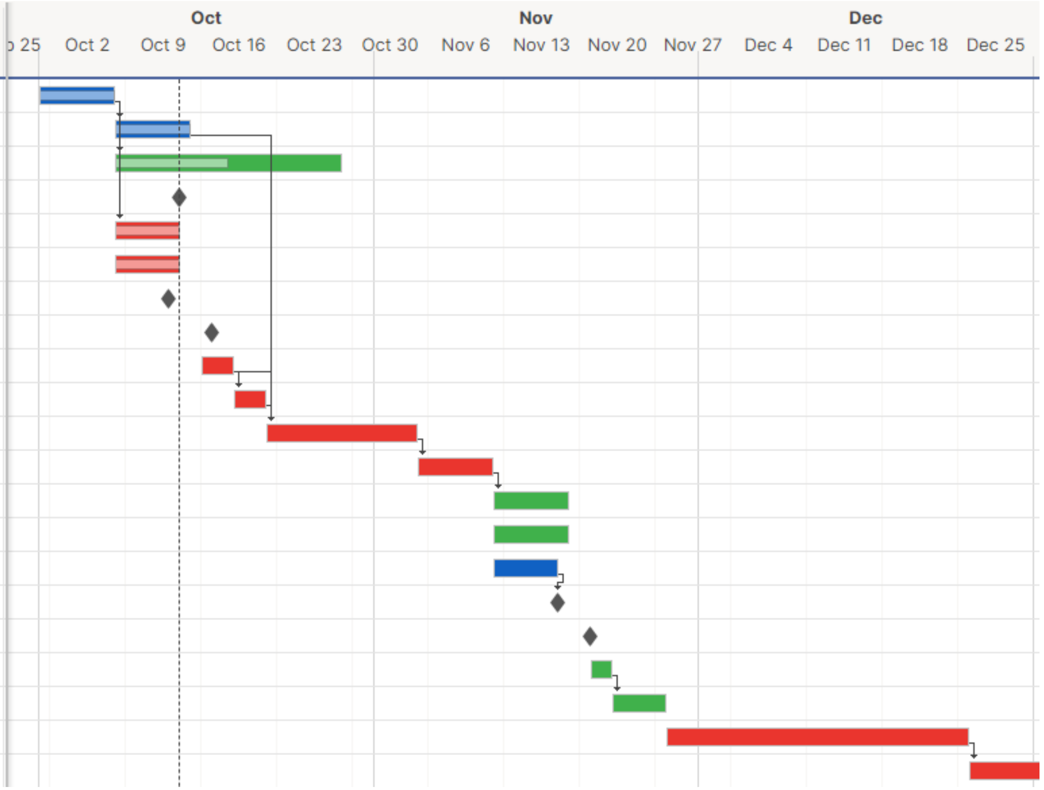
After this section the GANTT chart planning isn't as reliable as the plan is highly susceptible to change. Not only does it depend on the time it takes for the components to be constructed/delivered, but it also depends on how smoothly the project has been progressing. I have assumed here that there would be no stalling time during the second PRM and that the project would be running as intended. Once the parts arrive, I will begin construction of the arm and start initial testing of code.

During the December period I will have exams so I have been generous with the time I will spend programming, however in the second semester I plan to have already constructed the arm and started implementing impedance control before the start of January. After this point I will start preparing for my final report with the Project Methodology Report.

After the third PRM I will implement the two other impedance control settings (stiff and soft) which should only consist of fine tuning my control algorithm, leaving me a lot of time to dedicate to my other courses and create a draft for the final PRM deliverable. I should be very ahead of schedule by this point, to finalize my report and start practicing my presentation.

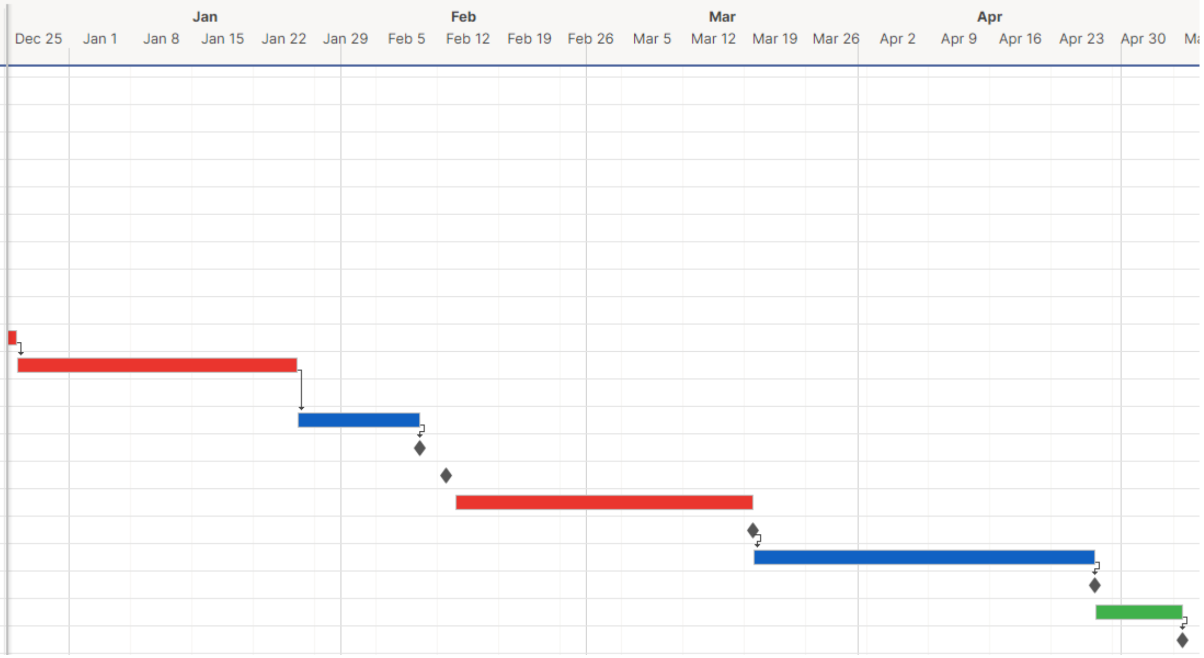
Semester 1

	Task Name	Duration	Start	Finish	Predecesso...
1	Initial Research	e7d	10/01/22	10/08/22	
2	Impedance Control	e7d	10/08/22	10/15/22	1
3	Component Researc	e21d	10/08/22	10/29/22	1
4	Preliminary Project I	0	10/14/22	10/14/22	
5	Gantt Chart	e6d	10/08/22	10/14/22	1
6	Risk Assessment	e6d	10/08/22	10/14/22	
7	Health and Saftey	0	10/13/22	10/13/22	
8	PRM 1	0	10/17/22	10/17/22	
9	Coppelasim Resear	e3d	10/16/22	10/19/22	
10	Mujoco Research	e3d	10/19/22	10/22/22	9
11	Digital Model	e14d	10/22/22	11/05/22	10, 2, 9
12	3D CAD Design	e7d	11/05/22	11/12/22	11
13	3D printing	e7d	11/12/22	11/19/22	12
14	Buy Components	e7d	11/12/22	11/19/22	
15	Draft Introduction	e6d	11/12/22	11/18/22	
16	Draft Intoduction	0	11/18/22	11/18/22	15
17	PRM 2	0	11/21/22	11/21/22	
18	Prototype Assembly	e2d	11/21/22	11/23/22	
19	Initial Configuration	e5d	11/23/22	11/28/22	18
20	Program Movement	e28d	11/28/22	12/26/22	
21	Initial Impedance Cc	e32d	12/26/22	01/27/23	20



Semester 2

	Task Name	Duration	Start	Finish	Predecessors
11	Digital Model	e14d	10/22/22	11/05/22	10, 2, 9
12	3D CAD Design	e7d	11/05/22	11/12/22	11
13	3D printing	e7d	11/12/22	11/19/22	12
14	Buy Components	e7d	11/12/22	11/19/22	
15	Draft Introduction	e6d	11/12/22	11/18/22	
16	Draft Intoduction	0	11/18/22	11/18/22	15
17	PRM 2	0	11/21/22	11/21/22	
18	Prototype Assembly	e2d	11/21/22	11/23/22	
19	Initial Configuration	e5d	11/23/22	11/28/22	18
20	Program Movement	e28d	11/28/22	12/26/22	
21	Initial Impedance Cc	e32d	12/26/22	01/27/23	20
22	Impedance: Neutral				
23	Project Methodolog	e14d	01/27/23	02/10/23	21
24	Project Methodothol	0	02/10/23	02/10/23	23
25	PRM 3	0	02/13/23	02/13/23	
26	Impedance:Stiff/Sofl	e34d	02/14/23	03/20/23	
27	PRM 4	0	03/20/23	03/20/23	
28	Final Report	e39d	03/20/23	04/28/23	27
29	Final Report Submis	0	04/28/23	04/28/23	28
30	Practice Demo/Pres	e10d	04/28/23	05/08/23	
31	Final Demo/Present	0	05/08/23	05/08/23	30



The University of Manchester

General Risk Assessment Form

Date: 14/10/2022	Assessed by: Alexander Morley	Checked / Validated* by: (3)	Location: University of Manchester Engineering Building A Home Location	Assessment ref no (5)	Review date: (6)
Task / premises: GENERIC ACTIVITY RISK ASSESSMENT FOR INDIVIDUAL PROJECT INSIDE MENG TEACHING SPACES AND WORKING AT HOME **-** This risk assessment covers general use of the MEng teaching spaces used by the Department of Electrical & Electronic Engineering within MECD Engineering Building B and Sackville Street Building, and working at home. - Activity specific risk assessments must be written for activities which are not covered in this risk assessment - Those following this risk assessment should also follow the FSE_EngB_Generic Teaching Laboratories Risk Assessment					

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
Preparing for the MEng Teaching Space	Students not familiar with emergency evacuation, 1st aid and general information about practical class	Staff, students Students not aware of the controls in place may put themselves or others in unnecessary danger	1. Lead Academic to provide induction prior to work commencing. 2. Lead Academic must ensure the MEng students are competent to work in the space including delivering the following information a. The most appropriate evacuation routes from the space b. Location of assembly point outside the building c. Clarify to the students if the fire alarm testing will occur during the class d. If student feels unwell or require first aid they must alert staff as soon as possible e. Location of 1st aid notices in the building f. Location of 1st aid boxes and eyewash g. Location of welfare facilities h. Appropriate dress code (PPE, no shorts or short skirts, hair tied up) i. No eating or drinking j. Must follow instructions at all time, no horseplay	Low	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
	Students new to lab environment	Staff, students Students not aware of the controls in place may put themselves or others in unnecessary danger	1. **Students are not allowed to work lone work in the lab and must always be in the space with at least 1 other person.** 2. They must never attempt the work if not sure and always ask for help. 3. Academic lead must ensure MEng students are trained and competent to support the class. 4. Students must be provided with appropriate PPE according to the specific risk assessment 5. Students should be told of basic lab hygiene and good laboratory practices E.g. No eating & drinking, correct gloves removal technique, wash hands before leaving lab etc. 6. After class, students must tidy up, collect all their belongings and leave the lab in good condition 7. **All students have completed a Department H&S induction** 8. **All students have completed the FSE Health and Safety Course on blackboard** 9. **All students have completed the MECD Health and Safety Courses on blackboard**	Low	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
General working in the teaching laboratory	Slips, Trips and falls	Staff, students Strains and impact injuries	1. Floors and walkways kept clear of items, e.g. boxes, packaging, equipment etc 2. Furniture is arranged such that movement of people and equipment are not restricted. 3. No running in the spaces 4. Drawers and cabinets kept closed. 5. Walkways to be kept clear of trailing cables, bags to be stored under desk or in the lockers provided. 6. Ensure floor remains dry and mop up any spilt liquids. 7. Reasonable standards of housekeeping maintained. 8. Report damaged flooring to Academic supervisor who will report appropriately 9. Adequate lighting provided. 10. At least one member of staff to be present at all times during timetabled laboratory sessions	Low	A
	Building Security Suspicious people in and around campus	User and others in building Difficulty in contacting help/assistance	1. Ensure Swipe card is used to access building and must not allow anyone to tailgate 2. If you see any suspicious activities in and around the premises, get yourself to a safe place and call Campus Security immediately on 0161 3069966 3. Must not enter into any area unauthorised for lone working or out-of-hours 4. When entering and exiting the building, keep to well-lit area and be extra vigilant of surrounding 5. **Students encouraged to download the SafeZone app to quickly get in touch with Security team to call for assistance, whether it's for a first aid incident or in an emergency.** 6. **Students to used SafeZone app to check-in which alerts security if you don't check-out.**	Med	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
	Out of hours and lone working	User Difficulty in contacting help/assistance	1. **No working out of hours allowed and only work within the MEng spaces can take place between 9am-5pm Monday to Friday** 2. **Students are not allowed to work alone work in the MEng teaching spaces and must always be in the space with at least 1 other person.** 3. **At least once a day, 1 project supervisor will do a spot check on the MEng spaces** 4. **Students will have access to their project supervisor 9am-5pm via teams** 5. **Students will have access to local support within the YSB if required.** 6. **Students will log themselves into the space using an online spreadsheet** 7. Carry a always charged up mobile phone on person. 8. Be aware of security contact telephone numbers, evacuation and first aid information indicated above.	Med	A
Regular computer use	Poor posture, repetitive movements, long periods looking at DSE (display screen equipment)	Staff, students, visitors Back strain (due to poor posture). Repetitive Strain Injury (RSI) to upper limbs. Eye strain.	1. Please refer to the DSE policy, guidance and poster for more information on how to set up your workstation properly 2. Complete DSE self-assessment for guidance on how to set up workstation properly 3. Set up workstation to a comfortable position with good lighting and natural light where possible 4. Take regular breaks away from the screen, at least some activity at your workstation every 20mins and a 5 minute break from workstation every hour. 5. Regularly stretch your arms, back, neck, wrists and hands to avoid repetitive strain injuries. Refer to workstation exercises here 6. Set up a desktop working space where possible and try to avoid working on a laptop without a docking station	Low	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
Use of equipment	Electricity	User and others in the area Can cause fire, burns or electric shock	1. User is trained and supervised until fully competent. 2. Visual inspection of equipment for obvious defects 3. Defective plugs, cables equipment etc reported for repair/replacement and taken out of use. 4. Check for PAT sticker is valid 5. Use equipment as per manufactures guide. 6. Sufficient power sockets provided to reduce need for extension cables. 7. Make sure wires and cables never make contact with liquid. 8. If faulty stop use immediately and report it to a lab technician. 9. Switch off and make safe after use.	Med	A
Use of hand tools (like sharp / pointed tools, Scalpel blade)	Sharp cutting edges	Users /Others in proximity / Visitors Risk of cuts and puncture injuries	1. User is trained and supervised until fully competent. 2. Only use the tool for the intended use. 3. Pre-use check for any faults and remove from use if any found. 4. Avoid use of 'open bladed' tools, e.g. use scissors instead of scalpels if possible. 5. Make safe after each use, e.g. razor blades to be put in sharps bin after use, knives to be replaced into protective cover. 6. Place in safe storage immediately after each use. Never leave cutting tools unattended. 7. Do not place cutting tools too close to the edge of workstation to avoid falling off onto legs and feet 8. Consider the use of cut resistant gloves 9. Use safe cutting technique e.g. cut away from the body and away from the hands and fingers	Med	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
Use of equipment with mechanical hazards	User wearing loose clothing or long hair	User /Others in proximity / Visitors Risk of entanglement	1. Training and supervision on the machinery until fully competent. 2. Avoid loose clothing and loose jewellery. 3. Long hair must be tied back. 4. Users must wear lab coat, safety glasses BS EN 166 and cut resistant gloves BS EN 388. 5. A conveniently positioned mushroom shaped emergency stop button or is present to quickly stop the machine in an emergency. 6. Machinery turned off when not in use.	Med	A
Moving /lifting large/heavy items (including furniture, PCs, stationary)	Moving heavy, large or cumbersome loads/object	Staff, students, visitors, cleaners Crush injuries, strains and sprains, bruising	1. Contact Technical Services Manager or University porterage for moves of large and or heavy furniture. Do not attempt lifting heavy items unless trained and experienced 2. For lighter items (generally below 10kg although dependant on individual capabilities), perform kinetic lifting with feet apart, load held close to body and in front of operator. 3. Perform good loading technique: check weight, centre of gravity, sharp edges, use stable position, bend knees not back, have a firm grip on load, keep load close to body, avoid twisting or stretching, avoid lifts above shoulders / below knees, move smoothly, avoid jerky movements 4. Do not store large, heavy or cumbersome items at height (eg on high shelves or on top of cabinets/bookcases etc).	Med	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
Manual soldering Creation of joints between wires or components using molten solder. The application requires the use of a hot (~370-420oC iron) usually mains powered.	Heat	User / Visitors / Occupants of neighbouring areas Minor burns to skin, fire	1. No soldering equipment should be left unattended while switched on and for a minute after switching off to allow to cool. 2. Anyone approaching soldering equipment should assume it is hot. 3. 0.11mm nitrile gloves can be worn to protect hands from spitting solder 4. Solder away from combustible and flammable material 5. When not in use, soldering irons must be stored in the stands provided. 6. Cold water or burn gel should be applied immediately to all soldering iron burns and first aider called to assist.	Low	A
	Colophony (e.g. rosin) based solders that cause asthma All other solders	All users in lab Risk of asthma from Colophony Risk of irritant to respiratory system	1. The use of rosin-based solders and fluxes should be limited and require registration with occupational health by emailing the lab screen questionnaire to millocchealth@manchester.ac.uk (ask the Safety Advisor for a copy) 2. The use of local fume extraction is required when using rosin-based fluxes; or when using alternative fluxes for more than a few minutes a day, according to HSE guidance 3. If using extraction, do not begin task unless you have confirmed that the equipment is working. Ensure Allianz inspection is up to date and that the extraction is used as close to the fume source as possible 4. Label bottles clearly and decontaminate work area regularly 5. Keep away from food and drink areas and wash hand before leaving the lab 6. Add solders and fluxes to labcup	Med	A
	Solder pastes and fluxes	All users in lab Risk of allergic contact dermatitis	1. The use of solders and fluxes that cause allergic contact dermatitis should be limited and require registration with occupational health by emailing the lab screen questionnaire to millocchealth@manchester.ac.uk (ask the Safety Advisor for a copy) 2. 0.11mm nitrile gloves should be worn to protect skin from contact 3. Label bottles clearly and decontaminate work area regularly 4. Keep away from food and drink areas and wash hand before leaving the lab 5. Add solders and fluxes to labcup	Med	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
	Lead based solder	All users in lab Lead poisoning, increased risk for pregnant / breastfeeding mothers.	1. Lead at work guidance states below 500oC the lead fume is controlled, soldering irons do not reach this temperature (max 420oC) 2. Keep away from food and drink areas and wash hands after use 3. Add solders and fluxes to labcup	Med	A
Test and measurement	Electrical	Users /Others in proximity / Visitors Electric shock User / Others in proximity / Visitors	1. User is trained and supervised until fully competent 2. Specific risk assessment required for: a. >50 volts AC / >60 volts DC b. intentional connection to human tissue c. low impedance situation, e.g. wet conditions	Low	A
	Heat	Minor burns, fire	1. User is trained and supervised until fully competent 2. Keep area tidy and free from combustible or flammable materials 3. Exercise caution on first power-up. Limit supply current to just above expected level. 4. Specific risk assessment required for circuits containing intentional heating elements and/or operating at >85oC 5. Consider signage to warn others of heat hazard above 85oC	Low	A
	Component ejection	User / Others in proximity / Visitors Minor burns, eye injury	1. User is trained and supervised until fully competent 2. Wear safety glasses 3. Exercise caution on first power-up. Check for reverse connection of electrolytic capacitors before energising the circuit. 4. Limit supply current to just above the expected level 5. Avoid close visual inspection of an unproven circuit during the first few minutes of operation	Low	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
Solvent-based cleaning	Chemicals with heath affects and flammable	Users /Others in proximity / Visitors Health damage and fire risk	1. Without a chemical risk assessment specific to the room and activity, no liquid chemicals are to be used in MEng spaces. 2. Complete chemical risk assessment and follow controls identified such as PPE (labcoat, correct gloves, safety glasses), extraction, training, supervision, storage and disposal procedures. 3. Perform correct glove removal to ensure you don't touch the outer part of the glove 4. Use the minimum quantity necessary (always below 500ml, above which required flammable storage) and ensure containers are sealed when not in use and stored safely. 5. Ensure good workspace ventilation. 6. In case of spillage, remove all sources of ignition. Absorb with absorbent materials from the lab's hazardous spill kit. Safely collect spills into suitable container for chemical waste disposal.	Med	A

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

Action plan (14)				
Ref No	**Further action required**	**Action by whom**	**Action by when**	**Done**
1	All equipment is inspected, and PAT tested annually. Any maintenance is to be carried out by trained staff only. (REF 1).	Users/ALPI/ISA	Continuous	
2	Train users and monitor until fully competent, maintain a training record for lab equipment	ALPI/Research supervisor	continuous	

Result : T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk