Developing an affordable open-source robotic platform for precisely manipulating ultrasonic transducers for laboratory experimental FUS studies

Xingzao Shi, Student Member, University College London and Dr Seyyed Reza Haqshenas, Professor Of Therapeutic Ultrasonics, University College London

DECLARATION

"I, Xingzao Shi, confirm that the work presented in this report was my own. Where information has been derived from other sources, I confirm that this has been indicated in the report."

Abstract

This report will provide in-depth documentation on the development of a robotic platform designed to manipulate focused ultrasound (FUS) transducer for therapeutic applications. It will begin with an introduction to FUS technology, highlighting the challenges associated with its manipulation in laboratory settings.

Subsequently, design specifications aimed at addressing these challenges will be outlined. A comprehensive background research and literature review follows, with a focus on selecting the optimal robotic mechanism for the manipulator.

Moving forward, the development process of the robot was documented, including the various prototypes and designs, as well as the integration of electronics and sensors. Additionally, assembly blueprints and step-by-step instructions for building the robot from scratch will be provided. Testing will be conducted at each stage of development, with detailed documentation of the results obtained.

Finally, the report will conclude by discussing potential avenues for future improvements and provide a comprehensive list of references for further reading.

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I – Introduction

A) Background

Focused Ultrasound (FUS) was an emerging medical technology that uses ultrasound waves to treat various medical conditions. FUS works on the principle of focusing ultrasound waves onto a specific target area in the body. This was done by using multiple ultrasonic transducers and firing them so that all the individual waves focus on one point through interference and superposition. At the focal point, the high energy frequencies can cause thermal ablation and heating destroying the cells in the local area or it can trigger cavitation, imploding the target zone. [1] The focused nature means that the effect was only localized at the focal region without affecting surrounding healthy tissue. FUS was usually implemented with MRI guidance to locate and assess the treatment at the target location. Currently, it is used as a non-invasive or minimally invasive technique for therapeutic purposes in different medical fields, including oncology, urology, and neurology.

- Oncology: FUS was commonly used in the treatment of various types of cancer, including prostate cancer and uterine fibroids. In prostate cancer treatment, FUS can be used to precisely target and thermally ablate cancerous tissue within the prostate gland while minimizing damage to nearby structures. It was considered a less invasive alternative to surgery or radiation therapy.
- Urology: FUS can also be used in urology to treat conditions like kidney stones. The high intensity of the focused ultrasound creates shockwaves and shatters the kidney stones.
- Neurology: Neurological disorders such as Parkinson’s and essential tremors can be treated with FUS where the region of the patient’s brain responsible for the condition can be targeted.
- Drug delivery: The challenge of precise drug delivery can be solved by FUS. The drug was injected intravenously into the patient in temperature-sensitive gel carriers. Then, FUS can be used to raise the temperature of the target location melting the carriers and releasing the drug at the target location.

Benefits of FUS include reduced risk of infection, minimal scarring, shorter recovery times, and potentially fewer side effects compared to traditional surgical procedures. However, the effectiveness of FUS can vary depending on the specific condition being treated, the size and location of the target tissue, and individual patient factors.

B) Motivation

In therapeutic ultrasound, ultrasonic energy was focused on the target tissue to induce bioeffects. To treat the entire volume, the ultrasonic beam was steered either electronically, mechanically, or electromechanically (in hybrid equipment). Electrical steering utilises an array of multiple transducers firing out of phase to direct and move the focal point of the ultrasounds through interference. This was a very versatile but expensive option. On the other hand, mechanical steering can be carried out by utilising a robotic platform whereby the transducer was attached to a robot and the focal point was moved by controlling the robot.

However, current robot platforms for ultrasonic transducer manipulation are heavily commercialised and very expensive. Often, complex proprietary software was used to control them, and it was very difficult to modify the design for bespoke applications. Solutions such as the MGIUS-R3 cost upwards of 100,000 pounds [2] and although being very capable, the price makes it out of reach for most researchers. This was a problem, and a cost-effective DIY robotic platform needs to be developed to allow more researchers to be able to precisely control the position and orientation of ultrasound transducers. The project will be open-sourced to allow other researchers to access the required designs for 3D printing and add improvements to the design.

The robot needs to be affordable yet reliable and capable. It must also be possible for a fellow researcher with basic mechatronics knowledge and experience to fabricate. The following design specifications are based on the general requirements of researchers in focused ultrasound.

- Cost – The cost of the robot was to be kept under five hundred pounds for all materials and parts.
- Simplicity of design and construction – All components should be easily sourced online, and all custom parts should be 3D printed with .stl files available for download. The assembly should be clear and easy to follow using nuts and bolts rather than welds or wood joining work.
- Load carrying capabilities – The robot should be able to successfully manipulate an ultrasonic transducer weighing up to five hundred grams.
- Workspace – The robot should have a field of reach of around 300mm from the base to the tip of the ultrasonic transducer.
- Ease of use – The robot needs to have an intuitive and simple form of control with a user-friendly display interface. The codes for this should be open-sourced for further development and improvements.
- Precision – The precision of the robot should be in the tolerance of millimetres in terms of positioning and sensing.
- Durability – The robot needs to be durable for repeated operation within its intended use.

II – Manipulator Selection

A) Robot Mechanisms

From the motivation and parameters, a design for a robotic manipulator for the ultrasonic transducer was required. Initially, to start the designing process, a class of manipulator mechanisms needs to be selected. For this purpose, thorough research into different types of manipulators was conducted.

1) Serial Manipulators

A serial robot consisting of a series of interconnected links joined by moving joints in a sequential chain-like structure. [3] Each joint can either be prismatic adding a linear motion variable, or revolute adding a new rotational axis and degree of freedom. Either allows motion between their adjacent links, enabling the robot to manipulate objects in its workspace. Serial robots have a rigid base and an end-effector, which is the part of the robot that interacts with the environment or performs specific tasks. In this case, the end effector would be the ultrasonic transducer.

Figure 1: Serial robot manipulator [4]

An example of a serial robot is an articulated robot commonly seen in industrial applications such as vehicle assembly lines. These robots often have multiple revolute joints and thus multiple degrees of freedom allowing them to achieve a wide range of motions such as reaching, picking, placing, and manipulating objects within their workspace.

Serial robots excel in precision, accuracy, and repeatability in performing tasks. They can be programmed to follow specific trajectories and manipulate objects with high dexterity. However, due to their sequential structure, they may have limitations in terms of speed and payload capacity as high moments and torques occur around the joints.

To achieve motion, an articulated robot can include either revolute, linear or spherical joints.

- A revolute joint moves around an axis achieving rotational motion. It provides a single degree of freedom, allowing rotation along one axis while constraining motion along the other axes.
- A linear or prismatic joint can move in a translational motion along a single axis this can be in the form of a sliding mechanism or piston actuating the joint making it longer or shorter.

- A spherical joint can move in multiple degrees of freedom around a single point. It was the combination of three revolute joints with an axis that intersects at a common point.

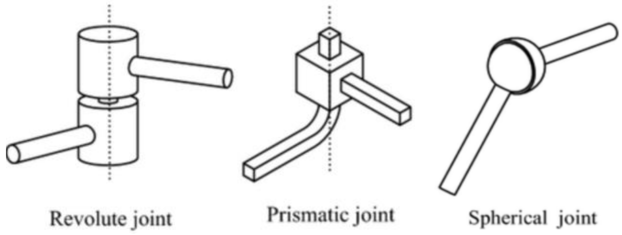


Figure 2: Mechanism types [5]

2) Parallel Manipulators

A parallel robot utilises multiple independent kinematic chains and links to connect the base of the robot to the end effector. [6] Each kinematic chain was independently actuated, allowing the robot to move the end effector in a coordinated manner. The design of a parallel robot allows for simultaneous control of multiple degrees of freedom from a single joint. An example of a parallel manipulator was a delta robot with three kinematic chains. This design provides excellent speed, accuracy, and agility, making delta robots well-suited for tasks that require rapid and precise positioning such as pick and place operations.

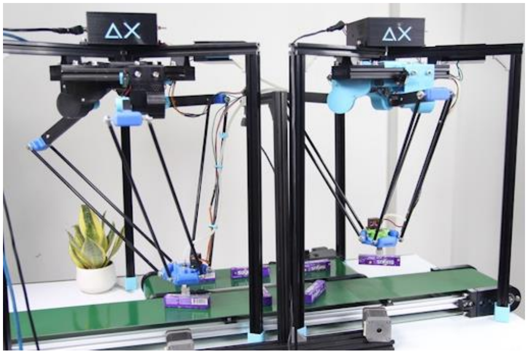


Figure 3: Parallel manipulator [7]

One characteristic feature of parallel robots is that they distribute the forces and loads among multiple limbs, allowing for better stability and load-carrying capacity. This attribute makes them suitable for applications that require high stiffness and heavy payload handling, such as flight simulators, machining, and heavy-duty industrial tasks. Parallel robots are also known for their exceptional accuracy, as their design reduces the effects of individual joint and link tolerances, resulting in precise and repeatable motion. They are often used in applications that demand high accuracy, such as surgical robots and 3D printing.

However, parallel robots can be more complex to design, and control compared to serial robots due to the interdependencies between the limbs and the need for coordinated motion. In addition, their workspace was also more limited compared to serial robots, as the range of motion was constrained by the mechanical structure. Furthermore, parallel manipulators are very sensitive to small errors in control signals or component defects as a small error was magnified by the mechanism having a large knock-on effect on the position of the end effector.

3) Hybrid Manipulators

A hybrid manipulator incorporates elements of both serial and parallel robots to combine their features and leverage their respective advantages and overcome limitations. [8] For example, a hybrid robot might use a serial robot arm for precise manipulation tasks and incorporate a parallel mechanism for increased stiffness and load-carrying capacity. This helps to improve their versatility, adaptability, and efficiency in performing complex tasks.

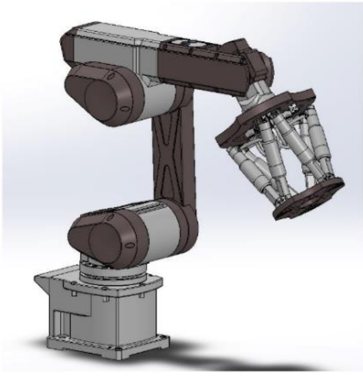


Figure 4: Hybrid manipulator [9]

An example of a hybrid manipulator was a serial-parallel robot. This type of hybrid robot has a serial robotic arm for reaching long distances and performing complex tasks, along with a parallel mechanism before the end effector for increased stability, load-carrying capacity, or high-speed operations. The combination of serial and parallel components allows for improved performance in terms of precision, speed, and versatility.

However, hybrid manipulators are the most complex to design, code and manufacture. And their nature of combining serial and parallel components makes them the most expensive option. Furthermore, hybrid mechanisms have increased failure points which make them less reliable and require more maintenance.

4) Cartesian Manipulators

Cartesian manipulators are very simple in design and can have a very large workspace. As a result, they are primarily used for transferring heavy objects from one place to another. [10] The gantries are mutually perpendicular to each other and mobilised using stepper motors and belts for precision control. This was the cheapest method to manipulate objects including pick and place operations and CNC (Computer Numerical Control) machine tooling.

Figure 5: Cartesian manipulator [11]

Cartesian robots are known for their higher payload-carrying potential, cost-efficiency and ease of programming. Additional modules can also be added to the already existing mechanism to increase the motion capabilities of the robot. More advantages of this robot category are that it showcases higher skill in precision and accuracy, plus it consumes smaller factory space to operate compared to other robotic counterparts.

Despite their advantages, Cartesian robots may have limitations in terms of flexibility and manoeuvrability compared to robots with articulated or parallel kinematics. The linear motion along orthogonal axes may not be optimal for tasks that require complex or curved trajectories.

5) Tendon-driven Manipulators

Tendon-driven robots or continuum robots a robotic mechanism inspired by flexible and continuous structures found in natural organisms like octopuses and elephant trunks. They are designed to mimic their flexibility, dexterity, and adaptability, making them well-suited for tasks that require navigating through complex and constrained environments. [12] Continuum robots are often composed of soft materials or have flexible segments allowing them to bend and twist. This flexibility allows for a wide range of motion and helps robots reach spaces that might be inaccessible to traditional rigid robots. These traits make tendon-driven robots ideal for applications such as minimally invasive surgeries and search and rescue operations.

The continuous and soft nature of continuum robots presents both challenges and advantages. They are generally more adaptable to different environments but may require advanced control algorithms to accurately manipulate them.

Figure 6: Continuum robot [13]

B) Selection Process

Out of the five mechanisms, one needs to be chosen for implementation. This was done with careful consideration of the design specifications.

The simplicity of design and construction was of utmost importance for others without a manufacturing background to replicate. As a result, the mechanism needs to be simple preferably using as few moving parts as possible. The optimal candidates for this would be cartesian robots with three axes of motion needed for the gantry or continuum robot with its driving motors only responsible for pulling on strings to actuate a tendon. The complexity and high number of parts required for parallel and hybrid robots are unsuitable for this factor. Serial robots can also be considered as a potential candidate although being more intricate than the others.

The workspace and capability of the design also need to be considered. In ultrasonic transducer manipulation, it was crucial to be able to control the orientation of the transducer. This eliminates purely cartesian systems because only the position of the transducer can be controlled and not the orientation. As a result, the mechanism was unsuitable for applications where the sides of subjects need to be treated by FUS.

Thus, serial and/ or continuum robots are both well suited for this project where simplicity of design and capability are dictating factors. Both are equally viable for the required applications and have a similar range of workspace. However, since continuum robots are still under development, further research into the field can be beneficial not only for FUS research but also towards the advancement of continuum robotics in general. Therefore, continuum robots are chosen as the mechanism for manipulating FUS transducers.

C) Terminology

- Degrees of freedom – A degree of freedom refers to the ability of motion for a robot. this can be translational in the x-y-z axis or rotational about an axis. Each degree of motion removes a motion constraint and a robot with six degrees of freedom can move to any position and orientation in 3D space.
- End effector – The end effector sits at the end of the robot and is the component responsible for interacting with the task. For example, the bucket was the end effector of an excavator machine.
- Robot workspace – The workspace of a robot defines the region around the robot that the end effector can potentially reach. A robot's workspace was dependent on its link lengths and joint configurations.
- Robot links and joints – Robot links are the rigid members connecting the joints. They are solid components with no motion capabilities. The joints are the movable components of the robot that cause relative motion between adjacent links.

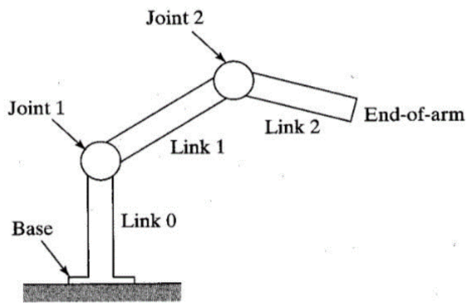


Figure 7: Serial robot features [14]

D) Literature Review On Continuum Robots

Currently, continuum robots are still in their infancy stage with incomplete mathematical modelling and developing prototypes. The aim was to develop a controllable mechanism to have the properties of that of continuous, soft organisms such as octopuses. This was different from that of traditional robots which use rigid joints without flexibility. Continuum robots are controlled by actuators which can be positioned away from the mechanism rather than being on the mechanism as joints. Currently, as of August 2023, there have been numerous studies and experiments carried out to explore the discipline.

1) COAST

The coaxially aligned steerable (COAST) guidewire robot was developed by the Georgia Institute of Technology in 2021. [15] It was developed as a manipulable catheter for performing cardiovascular surgeries in arteries as manual guidance was the only solution at the time. This was a slow and risky process where the surgeon required extensive skill and experience to navigate the catheter to the target zone using fluoroscopic images. This exposed the surgeon to high levels of radiation making the practice unsustainable.

The COAST robot uses a flexible, nitinol inner and outer tube which can be independently actuated. The inner tube was connected to the outer tube via a joining insert at one end. Actuating the inner tube relative to the other tube thus causes a change in the trajectory of the catheter. The tendon was also fitted with pressure sensors so that the surgeon could determine whether excessive force was being applied to the walls of the arteries.

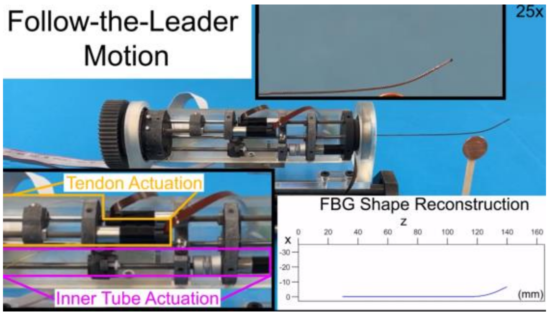


Figure 8: COAST manipulator

An algorithm was also developed to calculate the trajectory which the robot needed to take from entry to the target zone using images from fluoroscopic images. This was successfully done with the hardware having a reported mean error of 2.87 mm deviation from the computed path.

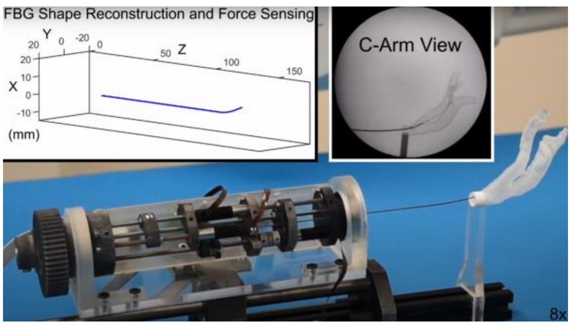
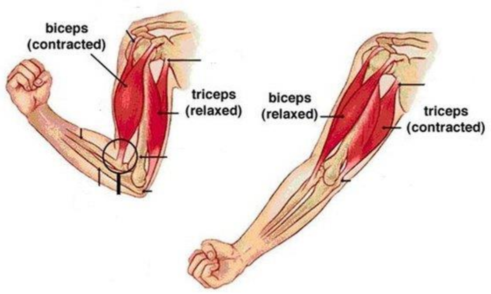


Figure 9: COAST manipulator

2) REDSLAB

The Imperial College London REDSLAB developed an open-source continuum manipulator for surgical robotics research. [16] The tendon was a flexible 3D-printed TPU rod actuated by strings. The robot was actuated by four strings which are controlled by a servo pulley mechanism such that rotating the servo arm causes the pulley to also rotate. This pulls on the string in one direction while giving slack to the string directly opposite allowing the robot to bend mimicking that of antagonistic pairs in muscles.



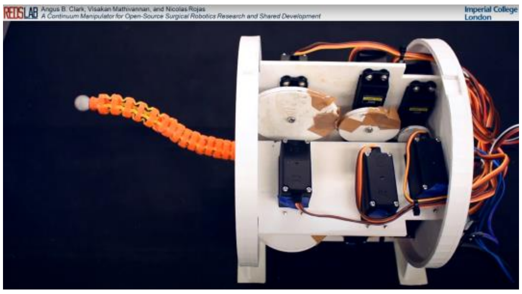


Figure 10,11: Antagonistic continuum robot

Three sections were made each actuated by 2 sets of pulleys giving the robot 6 degrees of freedom using 6 servo mechanisms. It was also possible to see that the first joint located closest to the base has 3 wires passing through to independently control the next 2 sections.

Figure 12: Flexible tendon

The entire robot was controlled by an Arduino UNO which can be programmed to follow a path and has a good field of workspace around the tendon to position the end effector.

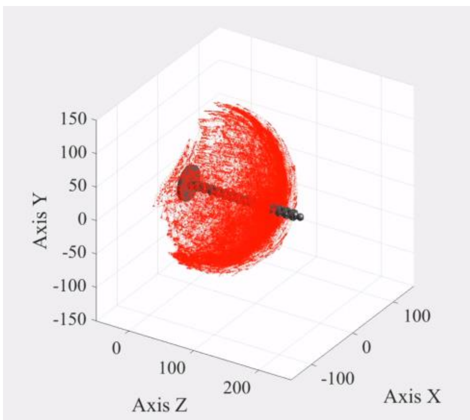


Figure 13: Robot workspace

III – Iterative Design Process

A) Prototype One

1) Prototype Aim

The first prototype aims to evaluate the feasibility of a tendon-driven robot and to create a physical model to inspire new possible designs. The prototype acts as a base for the other iterations to improve upon. As a result, it needs to demonstrate all the basic mechanisms for a tendon-driven device and be quick and simple to fabricate at a low cost. For this purpose, a segmented, sting-pulled tendon was proposed. The prototype will have a flexible, incompressible backbone to support and hold each one of the ligaments. The ligaments themselves need to allow the strings to pass through and have a method of being attached to the backbone. In terms of degrees of freedom, four DoFs were chosen allowing the tendon to be driven in any direction on two joints.

2) A Note On Nuts And Bolts

In the following sections, many components are designed to be fixed with nuts and bolts. Everything in the build was designed to be secured using M3 bolts meaning a bolt with a 3mm diameter shaft. This kit from Amazon will include all the fixings necessary for the build (link in the cost of robot section of the report).

Figure 14: Nuts and bolts [17]

However, the instructions will not include the length of the bolts. This was because the length of bolts only needed to be long enough to pass through the subjects and leave room at the end for a nut. As a result, the exact lengths of the bolts aren't very important as long as they can pass through and secure the robot.

3) CAD Model

The following design was developed in Fusion 360 [18] whereby the tendon can be manipulated by two sets of four strings on eight ligaments. The strings extend out of the case of the device and are actuated by hand pulling on individual springs. One set of the four strings will pass through the base onto the fourth ligament whereas another set will pass on the inner pass from the base to the furthest ligament. This gives a joint at the base and another one at the fourth ligament achieving the four degrees of freedom. A rubber tube was chosen as the central backbone as a spare part lying around the workshop. Alternatively, any semi-rigid PVC tubing or even hot glue rods can also be used to achieve the same effect. The ligaments are made of laser-cut acrylic and have an outer diameter of 700mm allowing for easier manipulation as the further away from the centre the strings are attached, the more precise the tendon becomes. Individual ligaments are spaced 35mm apart to achieve an overall reach of 320mm which meets the requirements in the brief. A base ligament was also introduced to allow the rest of the tendon to be fastened to the base.

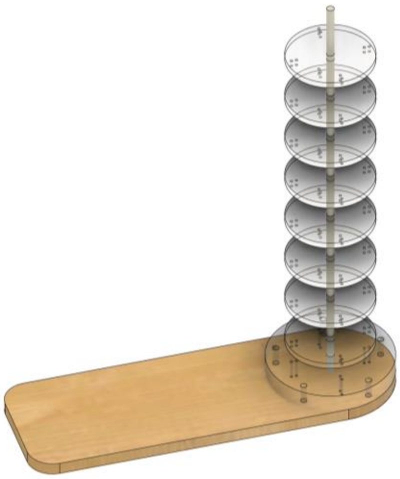
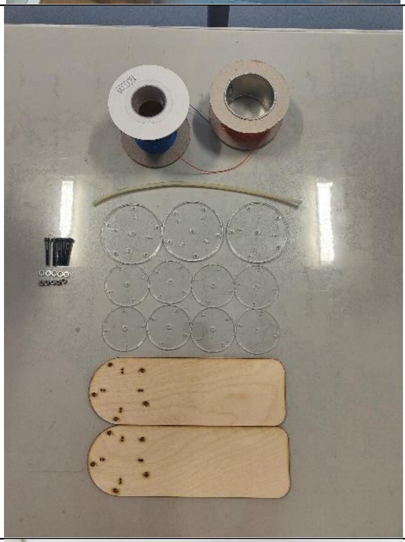


Figure 15: CAD model of prototype one

4) Manufacture And Assembly

The base was laser cut out of wood and 2 sets were made to increase the strength of the base adding to 10mm. The ligaments are also manufactured from 5mm thickness acrylic.	
All the parts required for the prototype are shown here including five M3 X 45 bolts and accompanying nuts and washers. For the strings, electrical wires were used as it was the only available option at the time but a braided fishing line would be ideal for the purpose.	
The tendon was assembled by gluing the ligaments at set distances marked 35mm apart using a hot glue gun. A 45mm gap was left at one end to accommodate the thickness of the wooden base.	

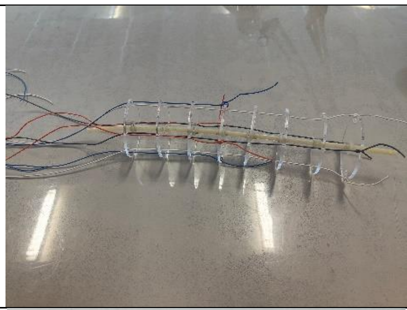
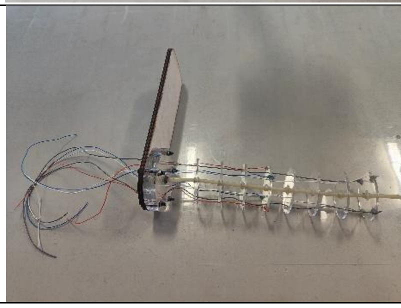
The wires were connected to the tendons with one set of four attaching to the fourth ligament and another passing within the inner drill-outs to the end ligament. The wires were then tied and securely fastened with a reasonable length protruding out of the base allowing the tendon to be pulled and driven by hand.	
The base was assembled by bolting the wooden base and acrylic tendon base together with nuts and bolts.	
Finally, the base was hot glued to the tendon with the wires passing through and the prototype was complete.	

Table 1: Manufacture and assembly of prototype one

5) Testing

For testing purposes, the base was fastened to a table with a clamp so that the strings could be manipulated. By pulling on the outer wire connected to the end of the ligament, the tendon can be made to go in that chosen direction curling up. By pulling on its adjacent wire, the tendon can be manipulated to move towards the latter direction depending on the applied force.

Figure 16,17: Tendon manipulation with end string

A similar effect can be seen when the inner wire was pulled, although this only affects the first four ligaments and does not impact the end four ligaments.

Figure 18: Tendon manipulation with inner string

When both the inner and outer wires are pulled simultaneously, the tendon can be manipulated in much more interesting ways, for example. Pulling on the same side makes no difference whereas opposing sides cause the tendon to bend back on itself. Finally, pulling adjacent wires results in a twisting motion in the joint.

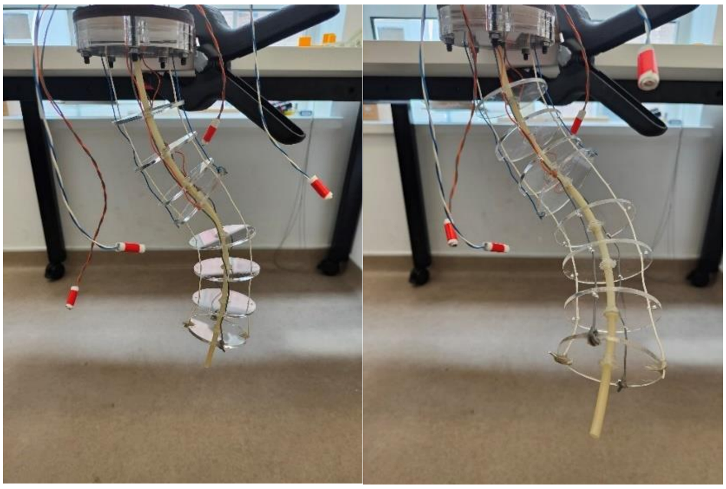


Figure 19,20: Tendon Manipulation with multiple strings

Many more combinations are possible to manipulate the tendon's shape and orientation.

6) Prototype Evaluation

The prototype can be deemed a success in demonstrating the feasibility of a tendon-driven robot. It successfully shows that the position of the end effector can be manipulated and placed within space by individually actuating each of the strings. However, the tendon was very unstable in the upright position and tends to collapse so it could only be reliably used in the upside-down orientation. Furthermore, the backbone was not strong enough to support the robot in a sideways setup. Finally, as a first prototype, there was no way of controlling the tendon electronically and everything was done manually which was unintuitive and difficult.

B) Prototype Two

1) Prototype Aim

The second prototype aims to motorise the tendon as well as making it much stronger to be used in the upright and sideways orientation. For this purpose, an Arduino was introduced to act as the control interface for the robot. To keep the cost down, only two degrees of freedom are designed so only a single set of four strings needs to be actuated and this can be easily scaled up if the prototype proves successful. The Arduino will control two sets of servo motors since only one of the strings in an axis was pulled at any time to achieve motion so by connecting two strings to one servo, the full range of motion can be achieved.

Figure 21: SG-90 micro-stepper [19]

To strengthen the tendon, a new mechanism was proposed to use springs for the backbone. This was because springs offer a resistance to motion which would help the tendon to stay in its original position no matter the orientation as well as when a load such as the ultrasonic transducer was applied. This was at the expense of the tendon requiring higher actuation forces since now the servo will also have to overcome the resistance of the springs.

2) CAD Model

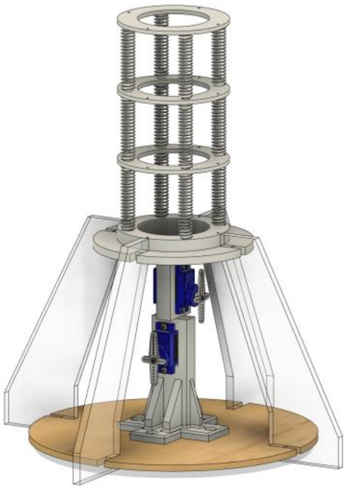


Figure 22: CAD model of prototype two

The above model was designed for the second prototype. The new tendons are reinforced with four springs between each ligament positioned equidistant from the string pass-throughs. Three sets of springs are used with four ligaments spaced 40mm apart to achieve a total workspace of 160mm. The springs have an inner diameter of 5mm so four circular extrusions protruding 5mm out of each ligament were modelled to indicate where the springs need to be placed in assembly as well as reinforcing the joint by adding more surface area for the gluing process. The base ligament also includes attachment points to allow it to join the base section. A two-part design was utilised to allow the tendon to be swappable with other, future designs.

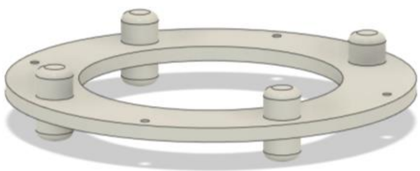
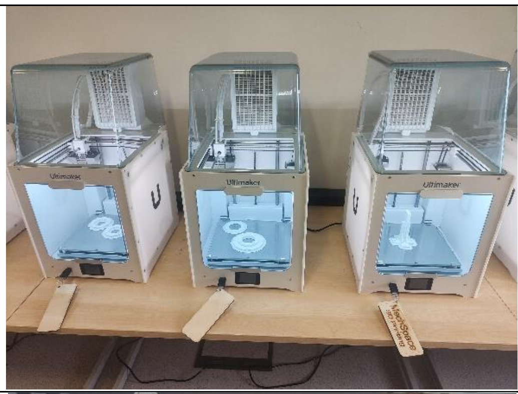
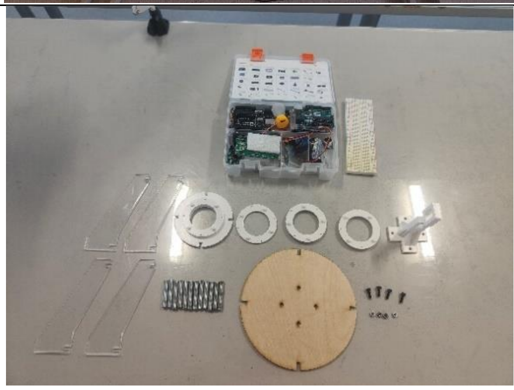


Figure 23: Ligament CAD

The base section comprises of a stand to mount the two stepper motors as well as attachment holes to bolt it to a wooden base. The housing positions the steppers in such a way that the servos' adapters are parallel and directly underneath the exit for the string of the tendon. To join the sections together, four acrylic fins were used to connect the base of the robot to the top allowing the robot to be in an upright position.

3) Manufacture And Assembly

All the required components were 3D printed on the Ultimaker 2+ connect printer but any printer with a sufficient bed size could also be used. Cheaper alternatives like the Ender 3 series are a great more cost-effective solution. The material used was white PLA which was standard with all 3D printers. The acrylic supports and the wooden base was also laser cut out of 5mm sheets.	
All the required parts for the build are gathered including four M3 X 12 bolts and M3 nuts, twelve 7mm by 42mm springs and an Arduino with two stepper motors and jumper cables. The microcontroller was an Arduino UNO which has more than sufficient ports for the project and the SG-90 micro-stepper motor was chosen as it came with the kit purchased (link below in cost section). The servo's orientation can be controlled by manually rotating a potentiometer.	
The springs were glued onto the ligaments using epoxy resin or Araldite for increased strength and durability to hot glue since the forces in the joints are much stronger in this prototype.	

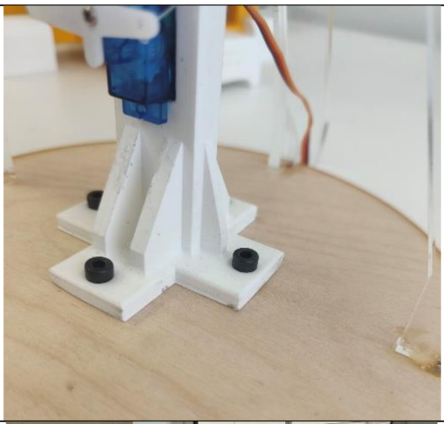
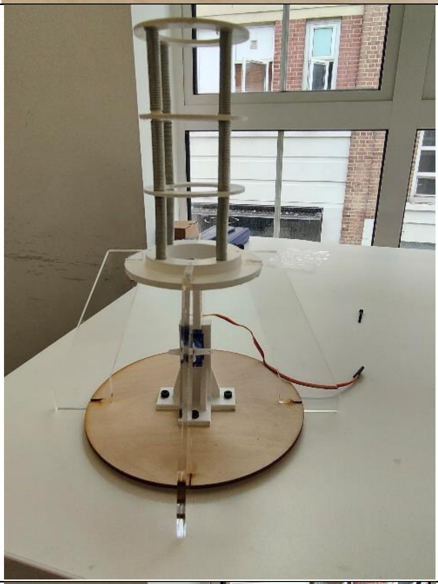
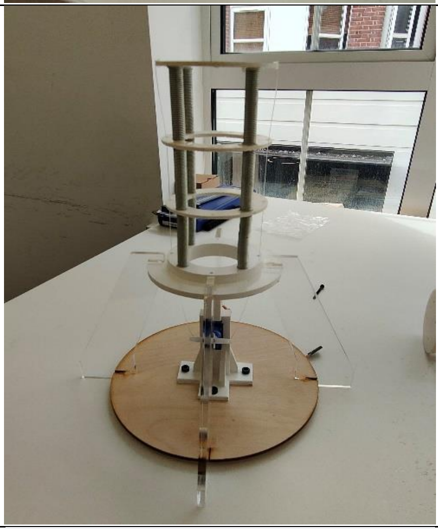
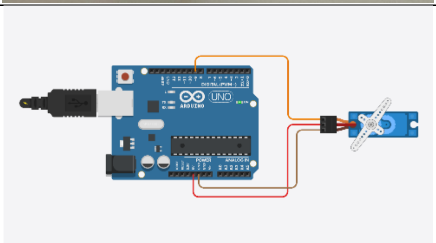
The servo housing was fastened onto the base plate with nuts and bolts and servos were inserted. Here, only one servo was present to test if the design works.	
The acrylic support fins are attached to connect the robot base to the tendons.	
Strings are strung from either end of the servo to the end of the tendon and tied at ends once in tension.	
The Arduino circuit was wired in the following manner and the system was programmed in the Arduino IDE program completing the build (code can be found in Appendix 1).	

Table 2: Manufacture and assembly of prototype two

4) Testing

Upon testing, the stepper motors did not generate enough torque to pull the strings and manipulate the robot. Thus, an attempt was made to manually drive the tendon by hand pulling on the strings.

Figure 24,25: Collapse of tendon spring joints

Here, the tendon was very difficult to manipulate, and a very large amount of force was required to move it. Then once the tendon starts actuating, two sets of springs very quickly undergone collapse rendering the mechanism unsuitable for use. The cause for this was due to the springs being extension springs which meant it was not possible to become compressed making it act like a rigid joint under compression. As a result, a large force was needed to overcome this leading to collapse. Due to this, the second servo motor was not connected to the robot. Furthermore, it was noticed that since the strings were attached at an angle to the base, abrasion would cause an issue as the string was dragged along the edges of the base.

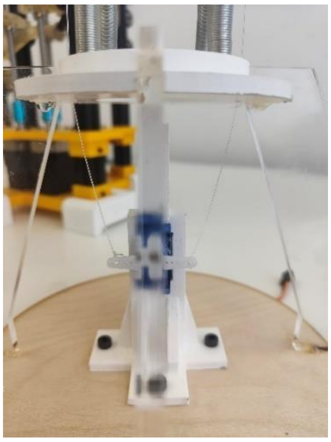


Figure 26: Strings attached at angle causing abrasion

5) Prototype Evaluation

The prototype was not successful in achieving electronically controlled manipulation of the tendon but it did provide a lot of insight for future iterations. Features which should be kept include the two-part design for the tendon and driving mechanism allowing for modulization and testing different designs without redesigning the others saving time and cost. A stronger drive mechanism was required and should pull the strings directly underneath and not at an angle to prevent abrasion to the strings increasing the design's lifespan. In terms of tendon design, springs offer a solution to the issue of the tendon collapsing under load but these need to be changed to compression springs to allow the spring to both expand and contract.

C) Prototype Three

1) Prototype Aim

For the third prototype, a two-part design system was implemented with separate prototypes for both the driving mechanism and the tendon. This allows for the optimisation of both systems without having an impact on each other. Sensors were also implemented to provide the user with essential information about the transducer.

2) Sensors

To fully and safely utilise the ultrasonic transducer, certain variables such as orientation and distance between the transducer and subject need to be identified. Orientation was important as the transducer needed to adapt to the curvature of the animal and thus it was important to know the orientation of the ultrasonic transducer. A distance sensor was needed to identify the distance between the transducer and the subject. A method of telling whether the transducer was in contact with the subject was also crucial as the cone needs to be directly in contact with the subject with no air gaps for the ultrasound to fully propagate.

2.1) Orientation

The orientation of the transducer within 3D space can be determined with a gyroscope. Digital gyroscopes measure angular velocity and acceleration and then through processing, the raw values can be computed to become orientational tilt in the X, Y and Z axis. The chosen gyroscope was an MPU 6050 which was a three-axis gyroscope capable of measuring tilt and acceleration in all three axes.

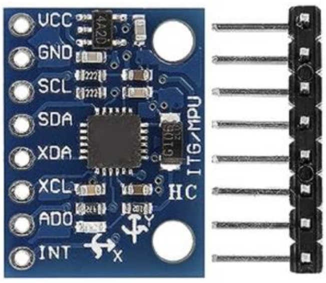


Figure 27: MPU6050 gyroscope [20]

It was also fully compatible with Arduino and cheap costing around three pounds per unit. The circuit plugs need to be soldered onto the sensor and the rest of the circuit was wired as follows:

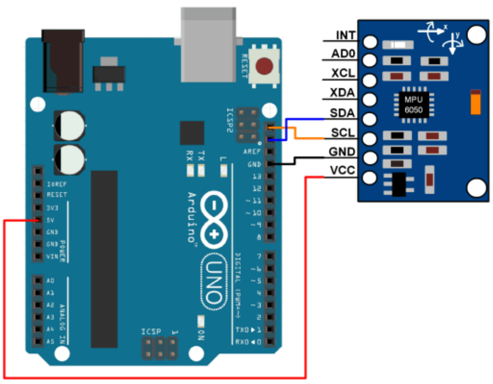


Figure 28: Arduino wiring diagram for MPU6050 [21]

2.2) Distance

The distance sensor must have a high resolution so the user can get a precise understanding of the distance between the target and the transducer to not crash it into the subject harming it. The latency of the sensor must also be very quick to assess the instantaneous distance without a time delay. It must also be small and light enough to fit onto the robot without weighing it down. Two separate, similarly priced, sensors were considered including an ultrasonic and infrared sensor.

- Ultrasonic sensor – The HC-SR04 was a very common distance sensor which uses a sender and receiver to determine the time delay between the sent and received ultrasound signal and thus calculate the object's range based on the speed of sound through air. It has a maximum range of 400cm and a minimum range of 2cm with a resolution of 1 cm. [22]

Figure 29: HC-SR04 ultrasound distance sensor [23]

- Infrared sensor – The VL53L0X was a time-of-flight sensor which measures distance based on the speed of infrared radiation. It contains a module which sends pulses of infrared light and a receiver detecting and determining the time taken for the pulse to be reflected. It has a range of two meters and no blind distance like the ultrasonic sensor. It also has a higher resolution of 1mm. [24]

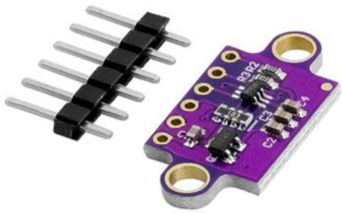


Figure 30: VL53L0X infrared distance sensor [25]

From the comparison, the VL53l0x was chosen as the distance sensor since it has the higher resolution of 1mm which gives the user a much greater level of accuracy regarding the distance to the subject. It was also smaller and lighter making it perfect for the project. The pins are once again soldered on and the rest of the circuit was wired as follows:

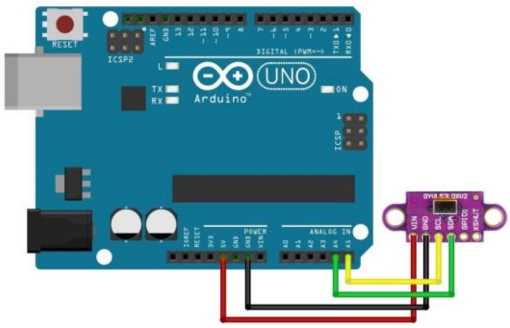


Figure 31: Arduino wiring diagram for VL53L0X [26]

2.3) Pressure

The pressure exerted can be determined by a force-sensitive resistor, the sensor uses piezo electrics which change resistance based on how much force was applied to it.

Figure 32: Pressure contact sensor [27]

Then a voltage divider circuit can be set up with an Arduino to convert the resistance to voltage and the force can be calculated based on the properties of the sensor given by the manufacturer. It was very light and small making it ideal for the application. The wiring for the circuit was as follows using a 10kOhm resistor:

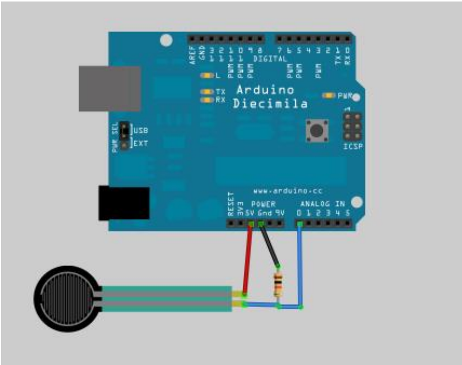


Figure 33: Arduino wiring for pressure contact sensor [28]

2.4) Display

To present all the information to the user, a compact LCD screen was used. The LCD chosen was a standard 16-pin interface which displays data controlled by an Arduino. The LCD was wired as follows with a potentiometer and 10kohm resistor:

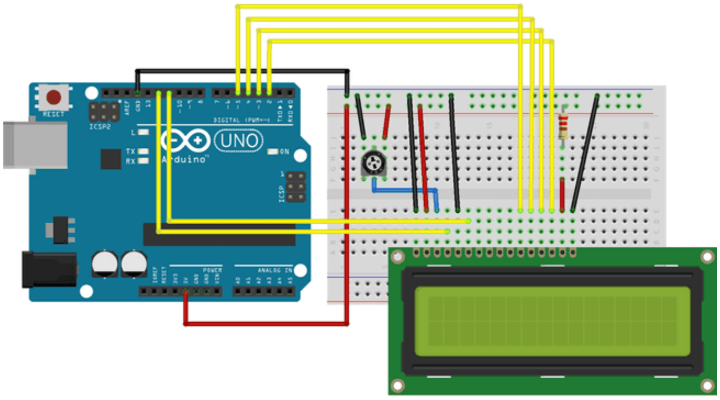


Figure 34: Arduino wiring diagram for 16x2 LCD display [29]

From this, the X and Y-axis tilt, distance and pressure are displayed on the LCD. The Z-axis data was not displayed as the tendon does not twist so it was constant.

2.5) Assembly

The wiring for all three sensors and LCD was connected to an Arduino Uno using the circuits provided. Since three 5V and ground supplies are needed but only one port was provided on the Arduino, the 5V supply and ground are connected in parallel to all three sensors on a breadboard shown below. The LCD was connected to the 3.3-volt outlet. The code for all the sensors and LCDs can be found in Appendix 2.

3) Driving Mechanism

Initially, a stronger servo was considered to replace the weaker servos. These would be in the same orientation as prototype two but have longer, custom-made arms to reach under the tendon string attachment points. However, it became evident that the arms would be subjected to very high loads and would most likely require to be machined out of metal putting it out of budget and accessibility for the project. In addition, all the forces are concentrated in the servo motor which can cause long-term damage and overheating issues. Furthermore, the nature of the design means that as the arm was rotated to pull the strings, it would trace an arc which would wear out the string and exert less force requiring further correction. All these factors ultimately lead to the rejection of this mechanism.

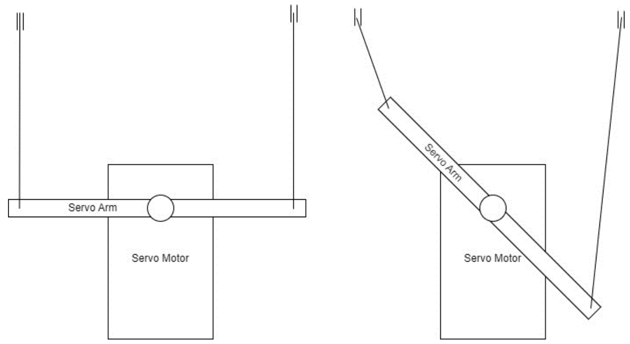


Figure 35: diagram showcasing the drawbacks of using servo motors and arms

The next design came from a cartesian rail system found in 3D printers and CNC machines. The mechanism uses stepper motors connected to a threaded rod via a coupling. A slider with a screw adaptor was then fitted onto the threaded rod and fitted to a sliding rail with bearings. As the motor spins, the rod connected by the coupler also spins. The screw adaptor acts to translate the rotational motion into linear motion which moves the slider up and down the rail.

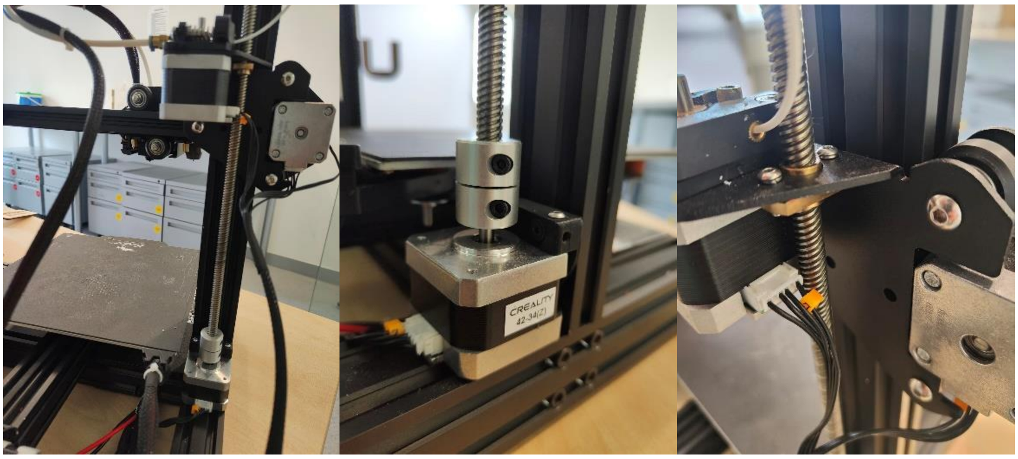


Figure 36,37,38: Cartesian rail system found on 3D printers

This was ideal for the design as it allowed for much more precision and control. The screw adaptor also acts to magnify the rotational force generated by the stepper motor to the linear force meaning more force can be exerted to pull the tendons. As a result, stronger springs and longer tendons can be incorporated whilst withstanding the weight of the transducer. The nature of the mechanism allows it to be placed directly under the tendon and always pull the strings vertically down eliminating wear through abrasion. Moreover, all the forces are also offloaded onto the slider instead of the stepper which means that the position was held so that the motor was not subjected to the resistance of the compression springs prolonging lifespan and reducing the risk of overheating leading to longer operation times during use. These factors are very promising, and a new design was made based on this mechanism. Four stepper motors were proposed each with the sliders having an attachment point to pull the strings. The stepper motors will be controlled by an Arduino microcontroller with an intuitive user input.

3.1) CAD Model

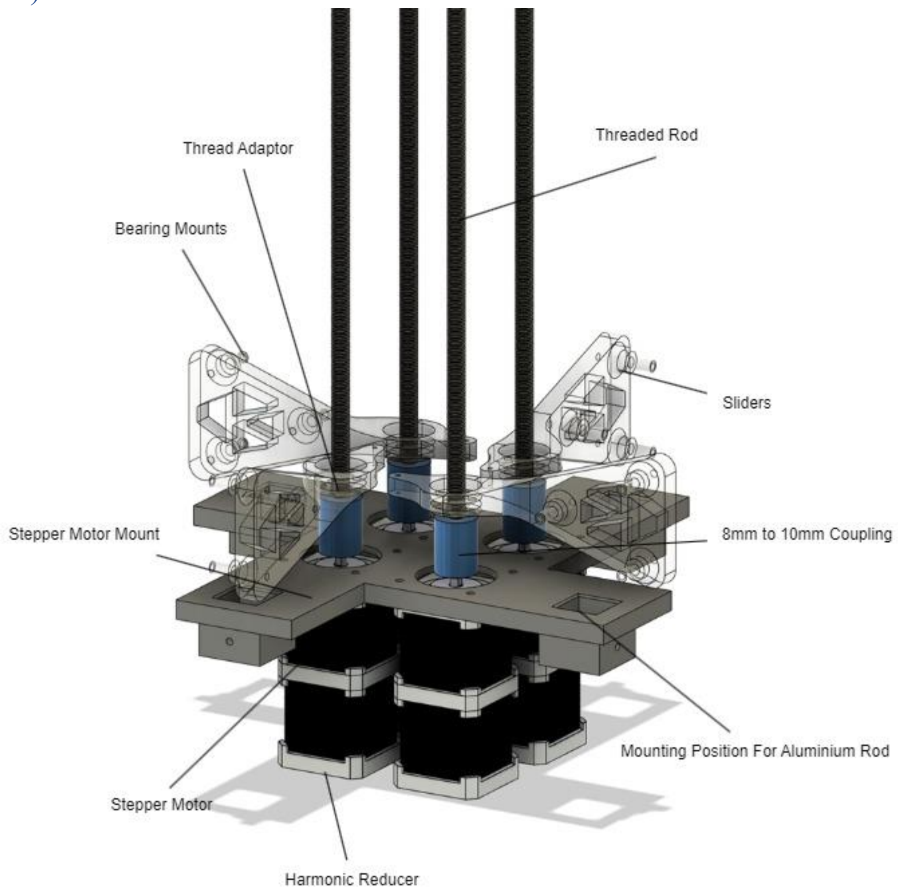


Figure 39: Initial CAD model of driving mechanism

The stepper motors chosen were NEMA 17 motors with a torque of 0.55 Nm. In addition, each stepper was paired with a harmonic reducer. The harmonic reducer is a gearbox which reduces the input speed but increases the output torque. Reducers are commonly used in industrial robots to achieve the high torques required for each joint. Likewise, in the case of the robot, torque takes priority before speed to generate enough force to pull the strings. The reducers chosen have a gear reduction of five times so it can amplify the torque produced by the motor to 2.75 Nm.

Figure 40: NEMA 17 stepper motor and reducer pair

In this design, four of the stepper-reducer motors were utilised giving three degrees of freedom. Each can independently drive a threaded rod via a coupling. The diameter of the threaded rod was 6mm whereas the output shaft diameter of the reducer was 8mm so a 6mm to 8mm adapter was used. To fix the drivers in place, the amount was designed to be bolted into the pre-existing mounting fixtures on the harmonic reducer. The mount also has cutouts to allow a 20mm by 20mm aluminium extrusion to be inserted as the structure support chassis. To convert the rotational movement to linear actuation, a slider was designed to house the threaded adaptor secured by M3 bolts. The slider also has a fixture for the line to actuate the tendons as well as three mounts for bearings which are designed to tightly fit into the grooves of the aluminium extrusion.

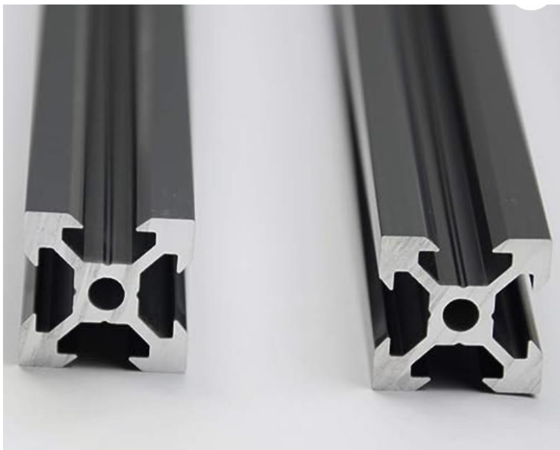


Figure 41: 2020 Aluminium extrusion [30]

3.2) Stress testing

The sliders are responsible for pulling the strings and are thus subjected to high amounts of force and pressure. To ensure the component will hold up to the forces and not fail under load, stress element analysis was carried out in Fusion 360. The model was fixed in the screw mount holes for the thread adaptor since this will be fixed to the threaded rod on the actual build.

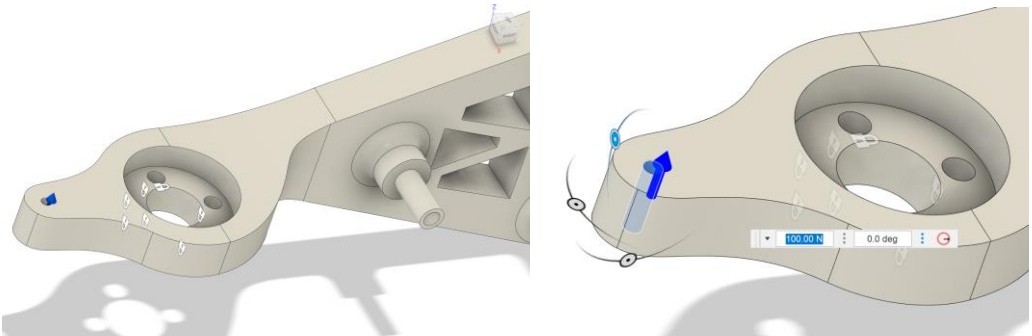


Figure 42,43: Constraints and forces applied in simulation

Then the material (3D printed ABS) was applied to the subject and a force of one hundred Newtons pulling up on the string mount was applied. One hundred Newtons were chosen as a baseline force to determine the maximum load the component could withstand before collapse.

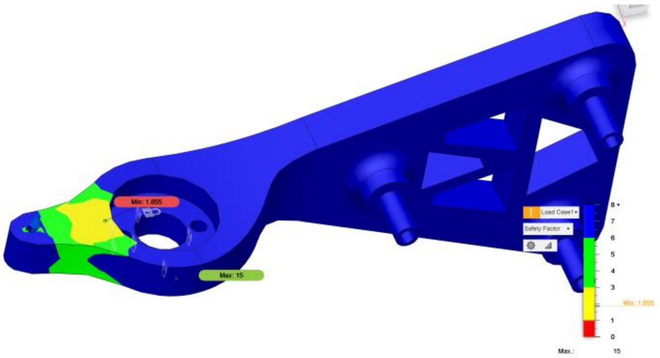


Figure 44: Safety factor simulation results

The simulation was carried out and a minimum safety factor of 1.855 was identified. This means that the slider will fail when a load of 185.5 Newtons or 18.86 Kg was applied.

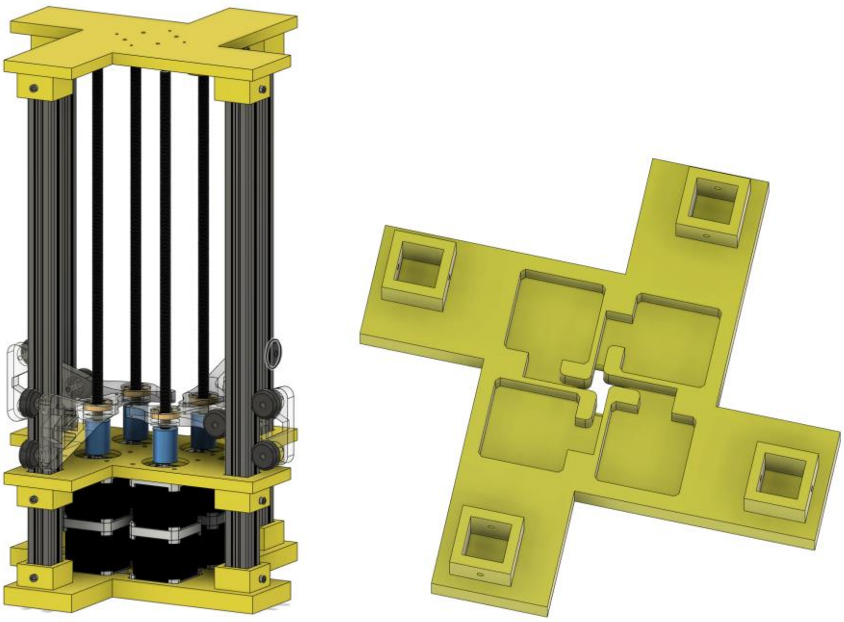


Figure 45: CAD model with base mount on right

Following this, a base mount was added to secure the aluminium extrusion as well as to stabilise the drivers. Routing cutouts were also included to help manage the stepper motor wires. The CAD was updated with the bearings thread adaptor in place as well as the bolts needed to secure the mounts to the aluminium chassis. Additionally, a top mount was added to secure the threaded rods and prevent vibrations during operation. Bearings were chosen for this purpose with the added benefit of reducing friction. Furthermore, it serves as the interphase between the driver unit and the tendon joints with M3 mounting holes on top and cutouts vertically above the sliders to allow the line to pass through.

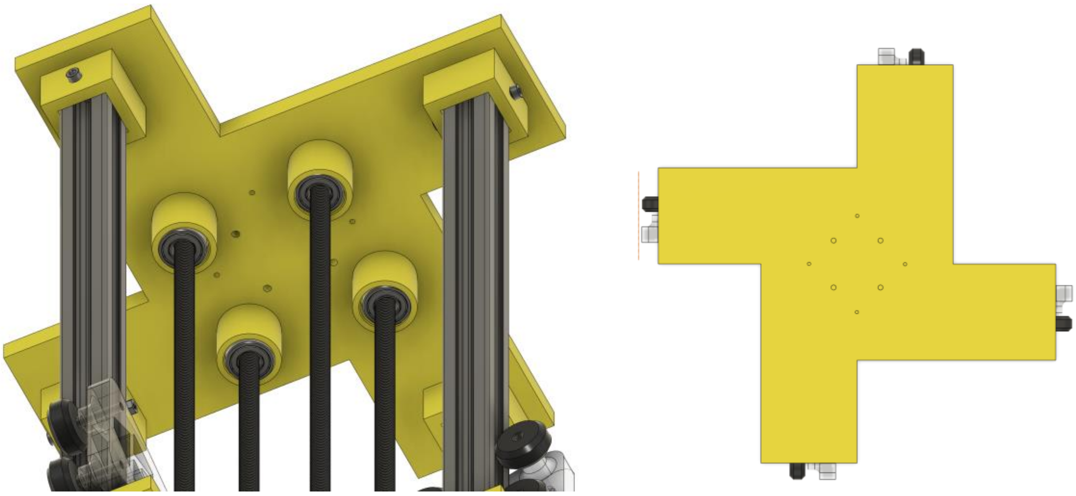


Figure 46: CAD model of top mount

3.3) Electronics

Each of the stepper motors requires much higher voltage and current than an Arduino can output so a separate power source was required. However, this results in no way to control the steppers thus a motor driver module was needed to relay the Arduino code and amplify the signal's voltage and current. A TB6600 was chosen as it offers the necessary performance and cooling required at a low cost.

Figure 47: TB6600 stepper motor driver [31]

The wiring diagram from the Arduino to the TB6600 to the stepper motor is shown below. Each of the ports on the driver can be loosened by a precision screwdriver and then retightened once the wire was inserted.

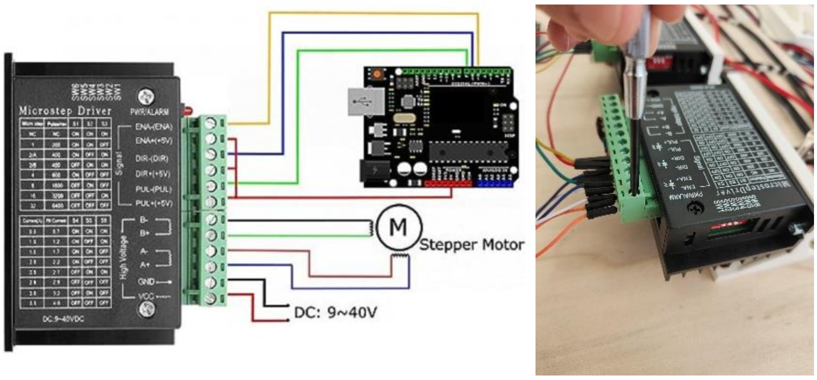


Figure 48,49: Arduino wiring diagram for TB6600 [32]

The setting for the driver needs to be set to the following preset with switches 2,3,4 flipped on so that they are pointing downwards:

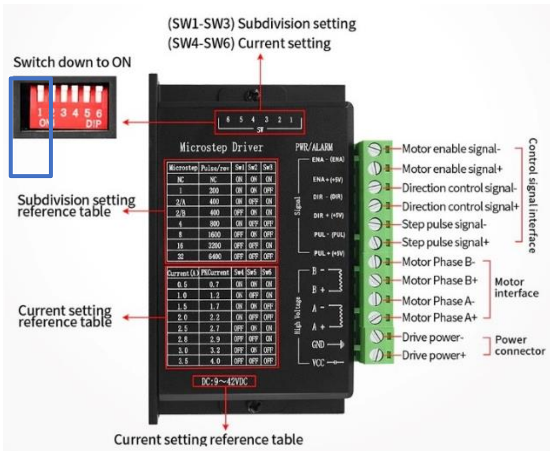


Figure 50: Setting switch position configuration

The ground and VCC pins need to be wired to a power supply capable of generating at least 9V whereas the rest of the pins in the high-voltage section were connected to the stepper motor. Within the signals section, the DIR pin dictates the direction of the motor spin (clockwise for a positive voltage from the Arduino and anticlockwise for a negative signal). The PUL pin detects the pulse width from the Arduino and converts it to the rate of motor rotation based on the average voltage. Thus, a high average voltage with less delay between each pulse width will result in a greater rate of rotation than a low average voltage with more delay between each pulse.

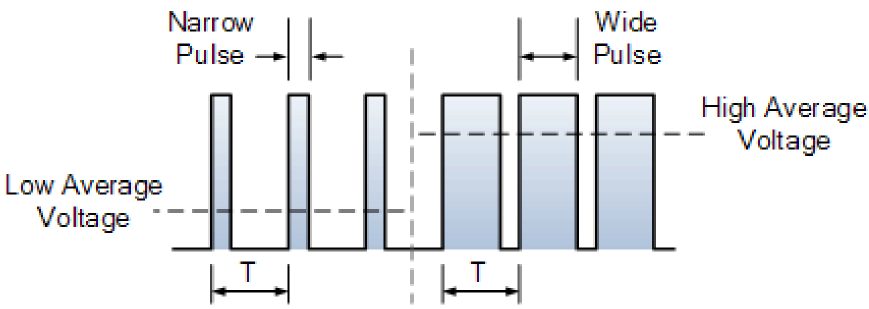


Figure 51: How a stepper motor is controlled by PWM [33]

The enable pin acts as a switch to turn the motor on or off. However, the motor driver was on in its default setting so to save space on the limited Arduino UNO ports, the yellow wire was also connected to ground.

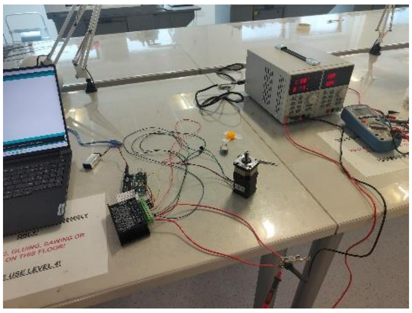


Figure 51: Stepper and controller testing

During this time, an alternative driver was also tested, being the Arduino CNC shield. The module was very compact and plugged directly into an Arduino for a much smaller form factor. The shield can control four motors at once with four built-in mini-stepper controls. However, many failed attempts were made to operate this driver with issues such as overheating and code bugs, so this was eventually discarded to allocate time to other developments.

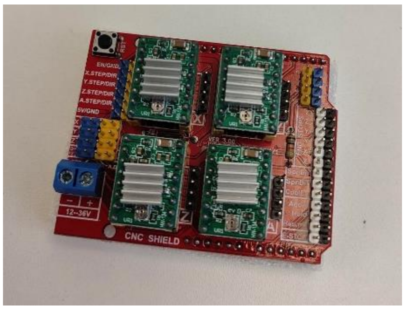


Figure 52: Arduino CNC shield driver

With a successful trial of the TB6600 stepper driver, three more units were made to drive each of the four steppers independently. The DIR and PUL pins are assigned and connected to the Arduino in the following fashion:

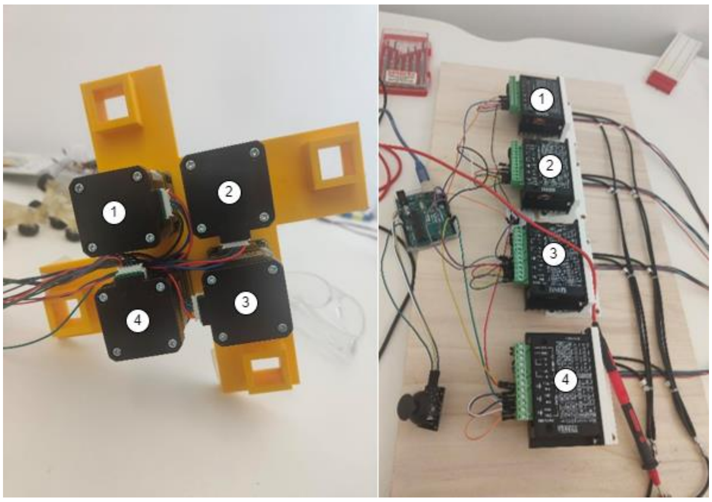


Figure 53,54: Stepper to controller mapping

Stepper motor number	Dir pin on Arduino UNO	PUL pin on Arduino UNO
1	3	2
2	5	4
3	7	6
4	13	12

Table 3: Individual stepper pin assignments to Arduino UNO

Both four VCC voltage and ground cables were spliced and soldered into one wire to allow the entire system to be powered by one power supply. Furthermore, an interface to control the robot was used in the form of a joystick since it was very intuitive and familiar to use. In this case, the SW pin on the right-hand side which detects If the button has been pressed down was not used. All the codes for the driver section of the robot can be found in Appendix 3.

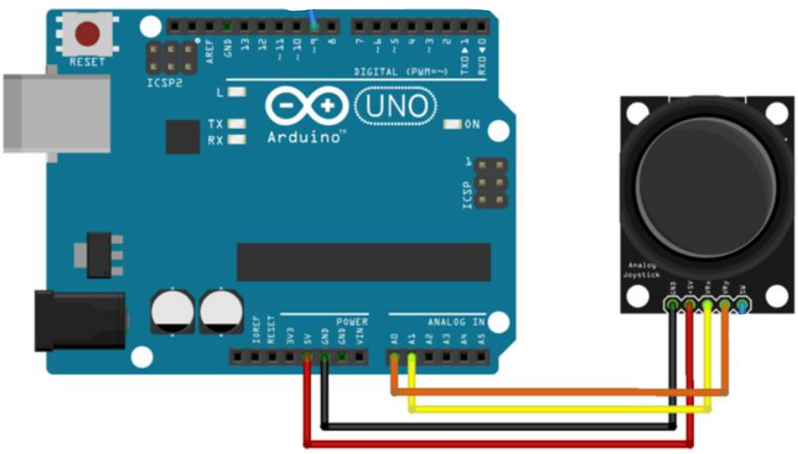
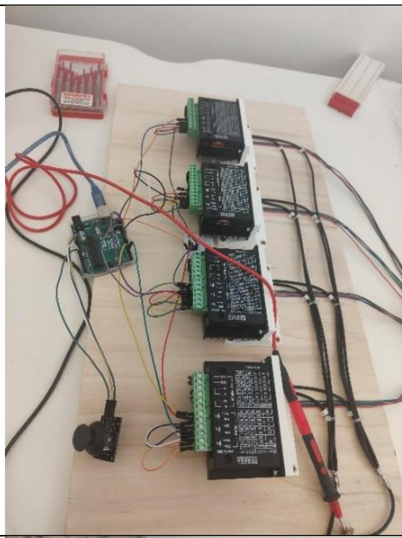
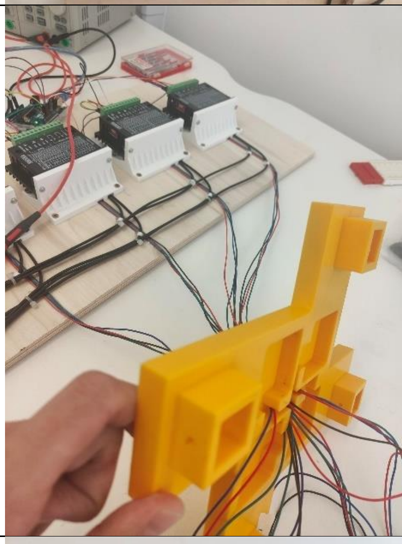
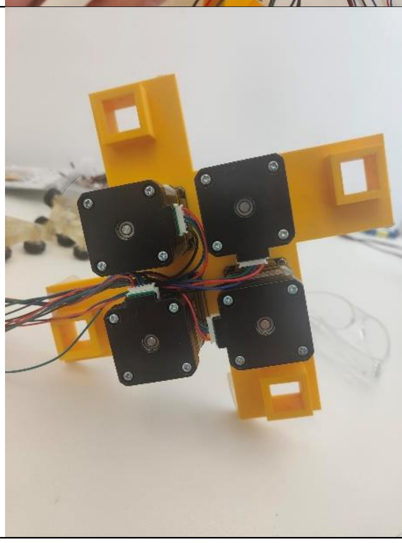
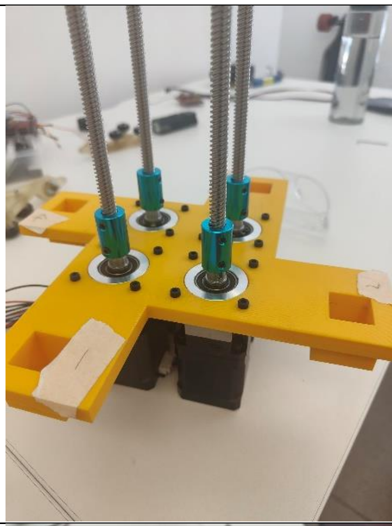
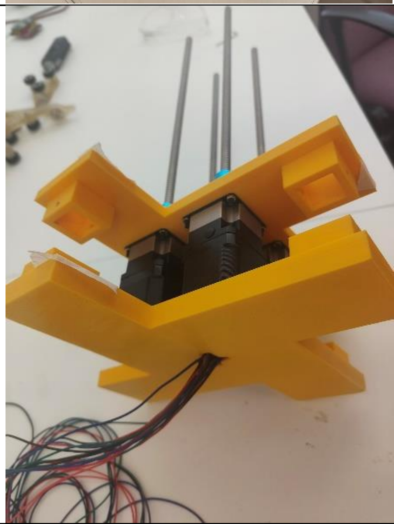


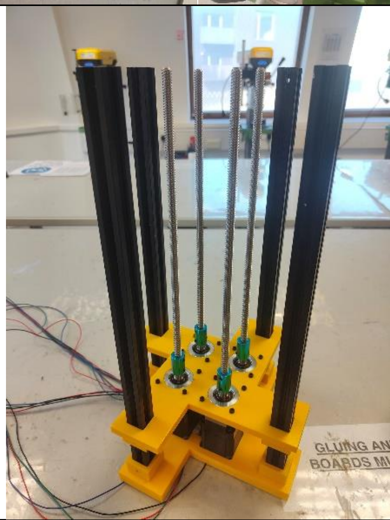
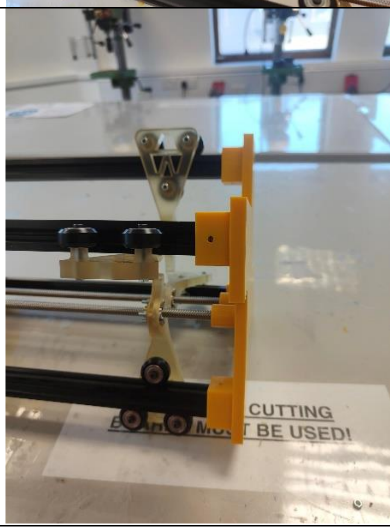
Figure 55: Arduino wiring diagram for joystick [35]

3.4) Manufacture And Assembly

The stepper motor and harmonic reducer were bolted together with the included hardware.	

The stepper motor controllers and joystick were wired and installed onto a wooden board with the 3D printed controller mounts.	
The base mount was fabricated and the stepper motor wires were passed through the centre for convenience.	
The stepper motor mount was 3D printed and the motors were secured by M3 bolts and nuts. Take note to orientate the motors in this fashion.	

The coupling and threaded rod were installed onto each reducer and tightened with an Allen hex key.	
The base mount was attached and secured via a friction fit.	
The sliders were 3D printed via a Harlot Lite Resin 3D printer which offers superior quality and detail to standard extrusion printers. The bearings and thread adaptor were then fitted with M3 bolts and nuts.	 

The aluminium extrusions were cut to length of 400mm by hacksaw. 3mm holes were then drilled in the centre along intervals of 13mm, 78mm and 387mm from one end. This was done on a pillar drill but was also possible with a hand-held cordless drill.	 
The prepared aluminium chassis was inserted into the 3D printed mounts noting the mounting position for M3 bolts.	
The four sliders are slotted into the rails and threaded on by hand rotating the coupling anticlockwise until all 4 reach the middle position along the threaded rod.	
The top mount was 3D printed and the bearings press fitted or with Araldite into the housing. It was then inserted into the main frame.	

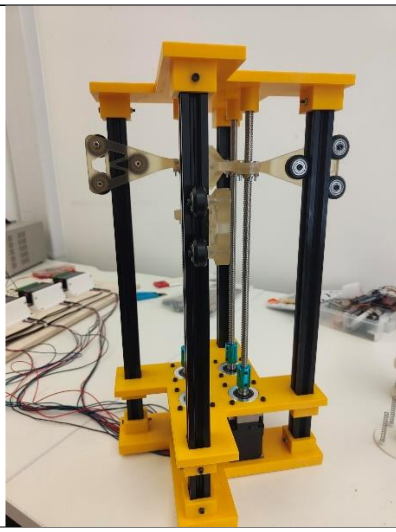
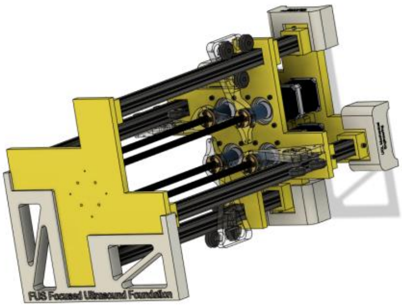
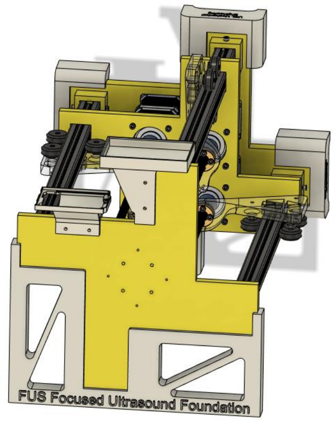
Twelve M3 bolts were added to secure the top, middle and bottom mount to the aluminium extrusion via the pre-drilled holes.	
Four support feet and a holder was also designed and 3D printed so that the prototype can also be oriented in a landscape position on its side.	
To secure the Arduino UNO and LCD to the robot, mounts were designed and fabricated to be attached with M3 bolts.	
The robot was powered by connecting to a power supply set to 18 Volts and 5 Amps.	

Table 4: Manufacture and assembly of driver module

4) Driving Mechanism

From the last prototype, the tendon has been re-iterated to be fitted with compression springs instead of expansion springs. A backbone was also included so that the distance between each ligament was fixed and there would not be any shearing motion. It also acts as support to take the load off the springs improving the rigidity of the tendon. The backbone needs to be able to freely rotate around a pivot so an universal joint was chosen for this purpose.

4.1) CAD Model

Figure 56: CAD model for tendon

The tendon consists of eight ligaments spaced 50mm apart achieving a total length of 385mm. The diameter was 70mm to match that of the driver mechanism. Each ligament was connected with four 5mm inner diameter compression springs and an universal joint. A modular design was chosen for the purpose so that each section can be attached to the next with M3 bolts such that the length of the tendon can be easily adjusted to suit different purposes and needs. The base has four screws positioned to attach to the driving module whereas the subsequent joints only use two to save weight.

4.2) Manufacture And Assembly

The ligaments were 3D printed on a Harlot lite resin printer. The parts were then removed and washed in a tub of isopropyl alcohol.	

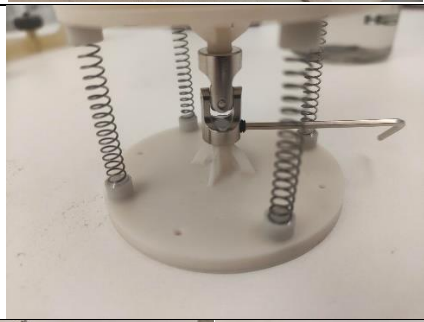
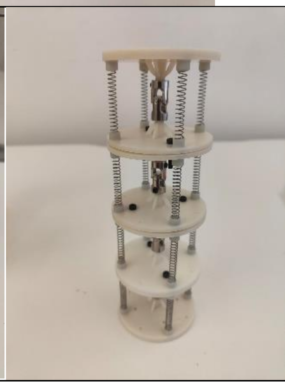
Using a generous amount of epoxy resin or Araldite, the springs were glued onto the ligaments and allowed to cure for four hours.	
The universal joint was attached to the cured section and secured using an Allen hex key.	
Each unit of the tendon was attached to the following section using M3 nuts and bolts and tightened using a hex key. This step was rather cumbersome and an M3 ratchet is highly recommended to ensure a secure fit.	 

Table 5: Manufacture and assembly of tendon

4.3) Testing

Initially, a test run was carried out with a four-section tendon. No end effector was installed to isolate the response under no load. The tendon was bolted to the driver base with four M3 nuts and bolts. A fishing line was then tied around the slider and passed through each section of the ligament before knotting at the end of the tendon. This was repeated for all four actuators using the same method. Finally, the slacks in the lines were removed through tensioning by rotating the threaded rod counterclockwise.

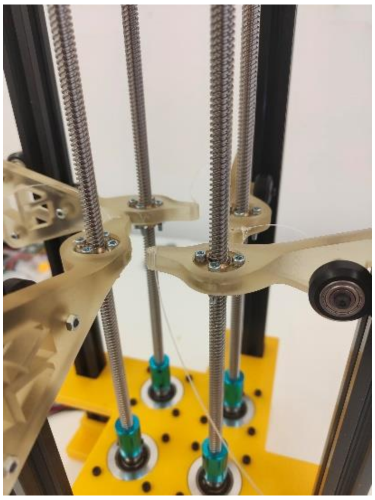


Figure 57: Line tensioning

The results showed the mechanism being functional and achieving manipulation in all directions. There was no sign of the tendon collapsing and all components remained intact.

Figure 58,59,60: Manipulation of tendon with joystick

Upon a successful initial trial, four more sections were added to achieve the required workspace of 300mm. The same procedure was used to set up the test, reattaching and tensioning the fishing lines. However, the tendon was unable to support itself in the upright position and became very unstable failing at the second joint and undergoing collapse.

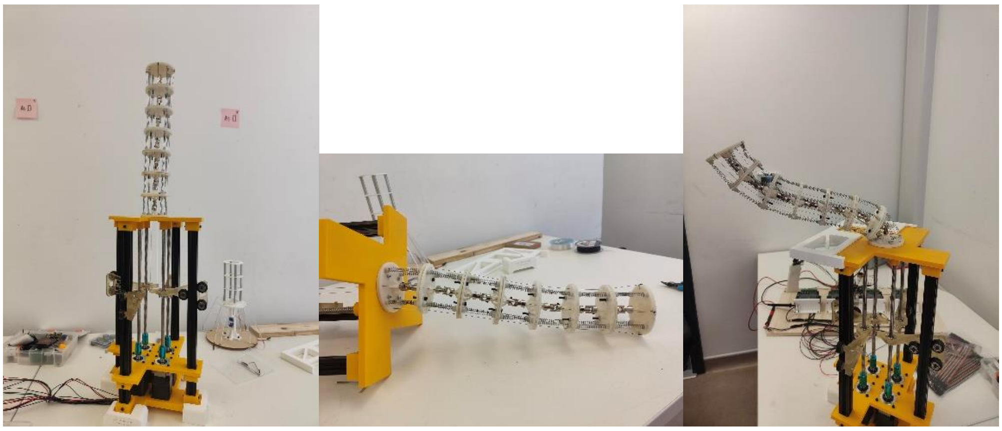


Figure 61,62,63: Failure of tendon with eight sections

4.4) Prototype Evaluation

The initial test was promising in achieving successful actuation of the tendon using stepper motors and an user joystick input. It gave an insight into how the robot would perform and serves as a base for improvement. Stronger springs need to be used since the previous model was unable to support its weight even without the additional load of an ultrasonic transducer. Thus, the backbone strength and the rigidity of the tendon must be increased.

4.5) Design Improvements

To increase the rigidity of the tendon, the 5mm springs can be replaced with stiffer counterparts with a higher spring constant. In addition, reducing the distance between each ligament would increase the force needed to achieve the same displacement. As a result, the new design utilises much stronger, 8mm inner diameter springs with a length reduced to 35mm instead of 48mm. Furthermore, since the universal joints did not offer any resistance to bending, this was replaced with a die spring designed to handle higher loads. The spring was still able to bend in any direction whilst providing support to improve the strength and ability of the tendon to carry a higher load without collapse. The end effector should also be detachable as it was previously discovered that to change transducers, all the strings needed to be cut which would not be the case if a mount was made as the interphase between the tendon and the end effector. Furthermore, a standard housing for the breadboard was included so that a different adaptor can be used for a different-sized ultrasonic transducer whilst maintaining the existing sponsors and simply moving them to the new mount.

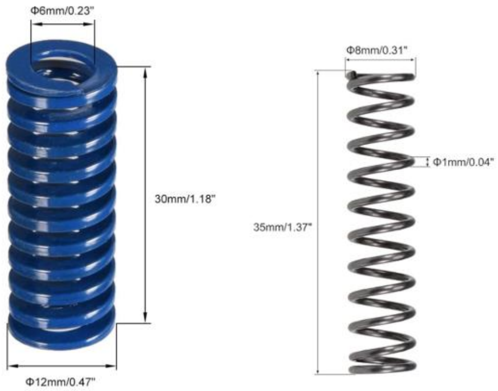


Figure 64: Die spring (left) and 8mm spring (right)

4.6) CAD Model

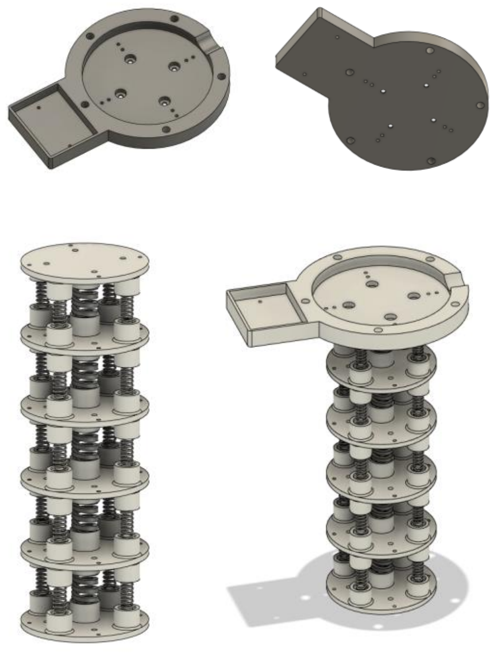


Figure 65: CAD model of improved tendon

The housing for the previous 5mm compression springs was modified to accommodate the larger springs. Furthermore, to prevent joint failure and causing the glued spring to dislocate under load, the wall height was increased from 5mm to 8mm. The mount for the central spring was also remodelled and updated. Finally, the number of bolts holding each joint together was increased from two to four to reduce the joints from deforming and coming apart under load. The detachable end effector was designed to be bolted onto the tendon using M3 bolts and holds the measuring instruments and transducer.

4.7) Manufacture And Assembly

The construction follows an identical process to the previous tendon except with the new parts and Araldite was used to glue everything in place.

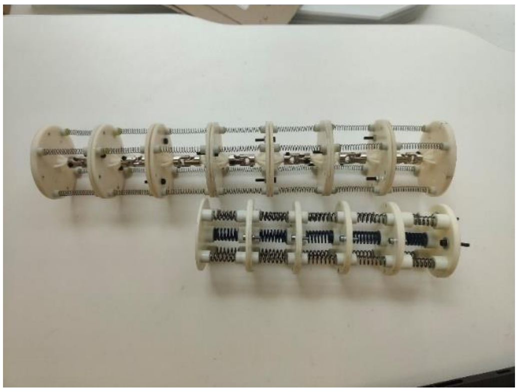


Figure 66: Comparison of old and new tendon design

Four M3 bolts were passed through the transducer mount as attachment points to the tendon. The transducer was then installed onto the mount and cover using M6 bolts after alignment in the correct orientation.

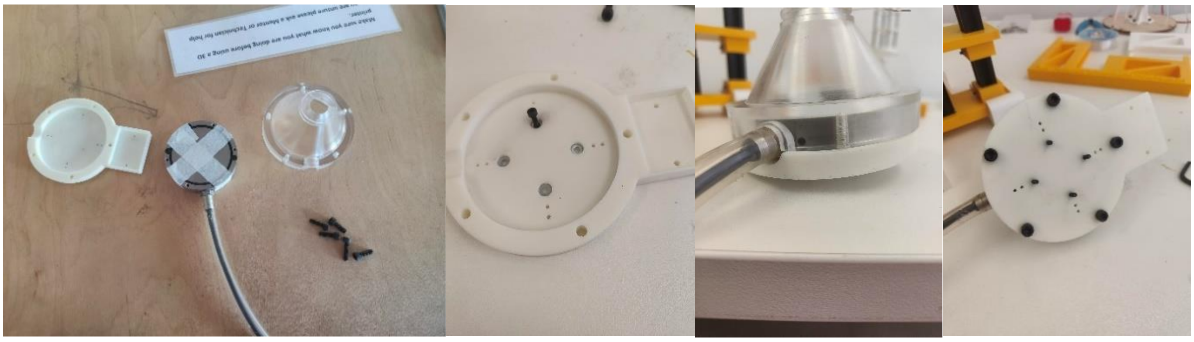


Figure 67,68,69,70: Ultrasonic transducer mount

Following this, the electronics breadboard was attached using two M3 bolts and the force transducer was fixed to the transducer cap with double-sided tape. The LCD and Arduino mounts were also 3D printed and fixed with M3 bolts. The tendon was attached to the base and strings tied and tensioned. Finally, the end effector was attached to the tendon using M3 nuts completing the prototype.

Figure 71,72,73: Completed robot

4.8) Testing

The prototype was tested in both the upright and the landscape orientation. Upon input via the joystick, the robot was successfully manipulated to bend and move the ultrasonic transducer in a semicircular region with the radius being the length from the base of the tendon to the tip of the transducer. All the instruments are accurate in measuring and displaying the orientation, distance to the subject and force exerted on the tip of the transducer.

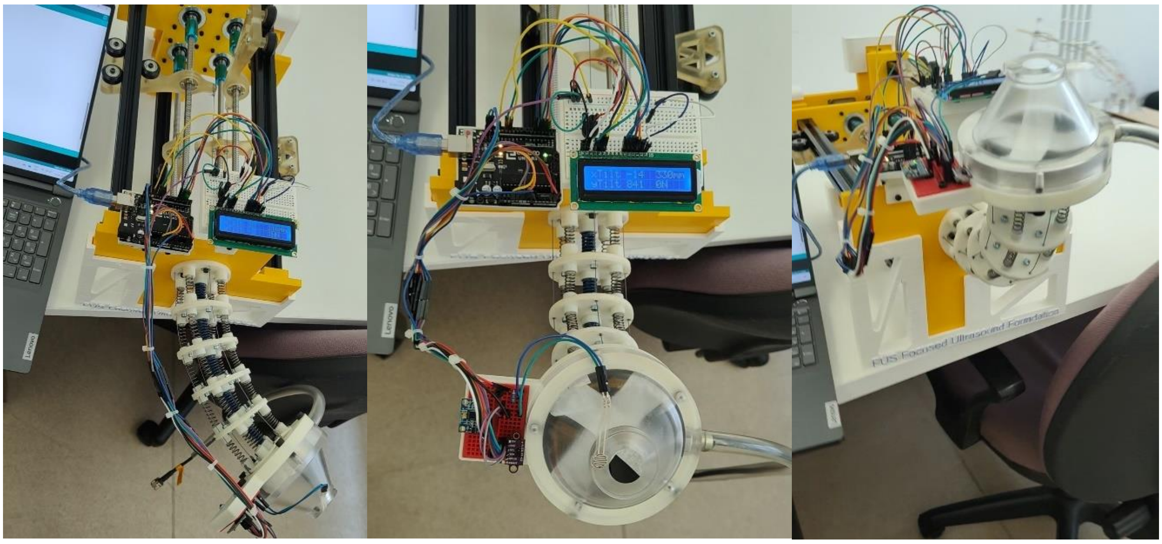


Figure 74,75,76: Manipulation of robot via joystick

The robot was tested to failure pushing on the joystick until the tendon bent back on itself. It was found that there were several weak points of the robot:

- Under intense load, the glue between the tendons and the springs were not strong enough and the springs popped out of their housing. This could be solved with a pin passing from the side of the mount through the spring securing it in place. These can then be reinforced with Araldite.

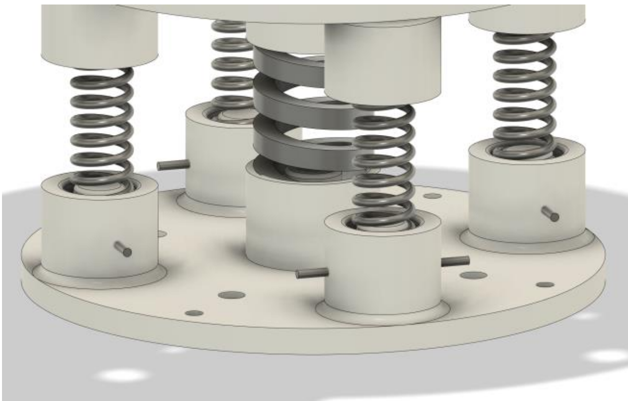


Figure 77: Design suggestion with pin inserts

- The top joint of the tendon was too weak snapping and breaking under intense load from the strings. This could be solved by increasing the thickness of the top joint.

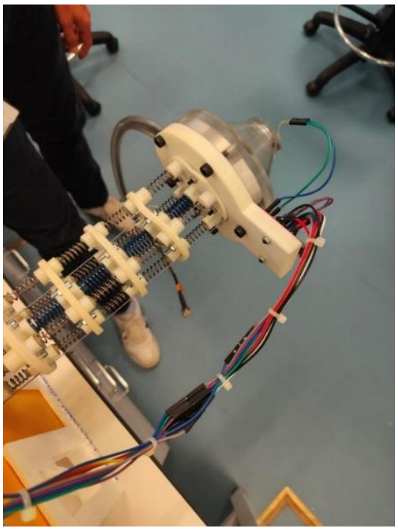


Figure 78: Deforming ligaments and snapped joint

- The ligaments started deforming around the bolt curling up under load. This does not affect the performance of the robot but would become an issue over time causing fatigue in the part leading to eventual failure. This can be solved by adding more bolts around the circumference. However, a better solution would be to replace the 3D-printed ligaments with machined aluminium parts.

4.9) Prototype Evaluation

This prototype was the first time that the transducer and sensors were mounted and manipulated successfully. It showed very promising futures for the project with the robot being able to successfully manipulate the transducer while providing real-time information on the orientation, distance and force applied on the subject. It does have limitations and weaknesses including only being able to reach a fixed radius cone around the tendon and the glued joints failing under load which makes it too unreliable and unpredictable for the next stages of trials. Overall, the prototype was a solid basis for proving all the fundamental features of the tendon driving design but can be significantly improved in future iterations.

5) Cost Of Robot

All the components needed for the robot were broken down in the following table with links to purchase them.

Component	Quantity	Quantity per pack	Cost (£)	Total cost (£)	Link for purchase
M3 nuts and bolts set	1	As needed	8.39	8.39	https://www.amazon.co.uk/Assortment-Stainless-Replacement-Machine-Fastener/dp/B0B3MGZ7T2/ref=sr_1_4?crid=TKKTFT6H22UU&keywords=m3%2Bbolts&qid=1694550983&s=industrial&sprefix=m3%2Bbolt%2Cindustrial%2C75&sr=1-4&th=1
Stepper motor	4	1	6.99	27.96	https://item.taobao.com/item.htm?spm=a21n57.1.0.0.37a0523cbAI6ZF&id=567501925505&ns=1&abbucket=14#detail

Harmonic reducer	4	1	5.45	21.8	https://item.taobao.com/item.htm?spm=a21n57.1.0.0.37a0523cbAI6ZF&id=559484971599&ns=1&abbucket=14#detail
Stepper motor driver	4	1	8.99	35.96	https://www.amazon.co.uk/gp/product/B07SBZ9SM5/ref=ppx_yo_dt_b_asin_title_o06_s00?ie=UTF8&psc=1
100lb braided fishing line	1	1	8.69	8.69	https://www.amazon.co.uk/gp/product/B076FM9GKN/ref=ppx_yo_dt_b_asin_title_o02_s00?ie=UTF8&th=1&psc=1
Compression springs	20	10	6.49	12.98	https://www.amazon.co.uk/gp/product/B08X6PZWT7/ref=ppx_yo_dt_b_asin_title_o03_s00?ie=UTF8&th=1
Die springs	5	2	4.99	14.97	https://www.amazon.co.uk/gp/product/B07LBTMGGR/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&th=1
Ball bearings	4	4	7.49	7.49	https://www.amazon.co.uk/gp/product/B07FXX4K4K/ref=ppx_yo_dt_b_asin_title_o07_s00?ie=UTF8&th=1
Slider wheels	12	10	8.99	17.98	https://www.amazon.co.uk/gp/product/B07SJ3VZ68/ref=ppx_yo_dt_b_asin_title_o05_s01?ie=UTF8&psc=1
Threaded screw	4	2	6.99	11.98	https://www.amazon.co.uk/gp/product/B093SHGY87/ref=ppx_yo_dt_b_asin_title_o04_s00?ie=UTF8&psc=1
2020 Aluminium extrusion (600mm)	4	4	28.99	28.99	https://www.amazon.co.uk/gp/product/B087PVGPRF/ref=ppx_yo_dt_b_asin_title_o05_s00?ie=UTF8&th=1
8mm to 10mm adaptor coupling	4	2	6.99	13.98	https://www.amazon.co.uk/gp/product/B07P967QQ8/ref=ppx_yo_dt_b_asin_title_o08_s00?ie=UTF8&th=1
Arduino Uno starter kit	1	1	36.54	36.54	https://www.amazon.co.uk/gp/product/B01D8KOZF4/ref=ppx_od_dt_b_asin_title_s00?ie=UTF8&psc=1
Arduino jumper cables	1	As needed	8.99	8.99	https://www.amazon.co.uk/gp/product/B0BRM568FM/ref=ppx_yo_dt_b_asin_title_o06_s00?ie=UTF8&th=1
Gyroscope	1	1	4.49	4.49	https://www.amazon.co.uk/gp/product/B07N2ZL34Z/ref=ppx_yo_dt_b_asin_title_o02_s00?ie=UTF8&psc=1
Distance sensor	1	1	6.49	6.49	https://www.amazon.co.uk/gp/product/B086V37JJ7/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&th=1
Force sensor	1	1	4.63	4.63	https://www.amazon.co.uk/gp/product/B07RJS2LVV/ref=ppx_yo_dt_b_asin_title_o09_s00?ie=UTF8&psc=1

1kg PLA plastic filament	2	1	19.54	39.08	https://www.amazon.co.uk/Creality-High-Speed-Resistant-Performance-Dimensional/dp/B0C342YMWQ/ref=sr_1_2_sspa?crid=53M391QI9HQR&keywords=pla+filament&qid=1694550257&sprefix=pla+filament%2Caps%2C95&sr=8-2-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&psc=1
1kg resin printer refill	1	1	21.19	21.19	https://www.amazon.co.uk/gp/product/B09XB3SLC7/ref=ppx_yo_dt_b_asin_title_o06_s00?ie=UTF8&psc=1
					Total sum = £332.58

Table 6: Cost and purchase links for all components and materials

The total cost of the robot comes out to be £332.58 which was below the 500-pound proposal. However, this does not include the costs for machinery and tools to build the robot which are included here:

Component	Cost (£)	Link for purchase
Creality Ender v3	165	https://www.amazon.co.uk/Comgrow-Creality-Ender-Printer-Aluminum/dp/B07BR3F9N6/ref=sr_1_1_sspa?crid=37H4RP2433KVZ&keywords=ender+3&qid=1694553869&sprefix=ender+%2Caps%2C109&sr=8-1-spons&ufe=app_do%3Aamzn1.fos.42a483c5-1df2-46ee-a728-92d018483bf9&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&psc=1
Creality Harlot Lite	149	https://www.amazon.co.uk/Creality-Halot-Mage-Photocuring-High-Precision-8-97x5-03x9-05in-Halot-Mage/dp/B0BQJBVJLC/ref=sr_1_2?crid=3GZHCTD700F42&keywords=harlot%2Blite&qid=1694554065&sprefix=harlot%2Blit%2Caps%2C81&sr=8-
Cordless drill	32.99	https://www.amazon.co.uk/Terratek%C2%AE-Cordless-Lithium-Ion-Screwdriver-Accessory/dp/B00I506718/ref=sr_1_6?crid=5KLQN3C0F7BT&keywords=cordless+drill&qid=1694554128&sprefix=cordless+drill%2Caps%2C87&sr=8-6
Hex key set	3.45	https://www.amazon.co.uk/Rolson-Hex-Key-Set-1-5-10/dp/B001F66HHI/ref=sr_1_7?crid=3IZL2H9GDZRY3&keywords=allen%2Bkey&qid=1694554208&sprefix=allen%2Bkey%2Caps%2C89&sr=8-7&th=1
Soldering iron kit	15.28	https://www.amazon.co.uk/Soldering-Adjustable-Temperature-180-520%C2%B0C-Desoldering/dp/B092VTGGDM/ref=sr_1_5?crid=2SE69E2HYPR85&keywords=soldering+iron+kit&qid=1695925691&sprefix=soldering+iro%2Caps%2C91&sr=8-5
Metal hacksaw	15.99	https://www.amazon.co.uk/AIRAJ-High-Tension-Replaceable-Comfortable-Woodworking/dp/B083BDHQYK/ref=sr_1_1_sspa?crid=1OEJYQDX1LKF8&keywords=metal%2Bhacksaw&qid=1695997243

		&sprefix=metal%2Bhacksaw%2Caps%2C68&sr=8-1-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&th=1
Araldite	6.29	https://www.amazon.co.uk/Araldite%C2%AE-Standard-24ml-Syringe-Epoxy/dp/B006JYPUSI/ref=sr_1_1_sspa?crid=CH02OTKDZW95&keywords=araldite&qid=1694554162&sprefix=arayl%2Caps%2C75&sr=8-1-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&psc=1

Table 6: Cost and purchase links for tools and machinery

IV – Conclusion

A) Suggestions For Future Research

Future prototypes should aim to improve the capability and reliability of the robot whilst keeping existing features including the modular nature of the tendon and the ability to swap to different sensors without having to redesign the sensor circuit. The current design was mainly hardware-focused and more research should be focused on the simulation and coding aspect of the tendon. Simulations will help achieve a better understanding of the dynamic behaviour of the tendon and offer guidance with the selection of spring constants for different tendon lengths and weights of the ultrasonic transducer. This will make the design more calculated and less trial and error.

Currently, the design only has three rotational degrees of freedom but was not able to move linearly. Future designs should increase the degrees of freedom making the robot much more capable of reaching places within 3D space. To increase the degrees of freedom, the whole mechanism can be mounted onto a CNC gantry. This adds three more degrees of freedom allowing the robot to achieve 6 degrees of freedom and position itself anywhere within space.

Another solution could be to implement a tendon-locking system developed by the Diller micro-robotics lab at the University of Toronto. [35] The mechanism inhibits relative motion after the mechanism has been engaged.

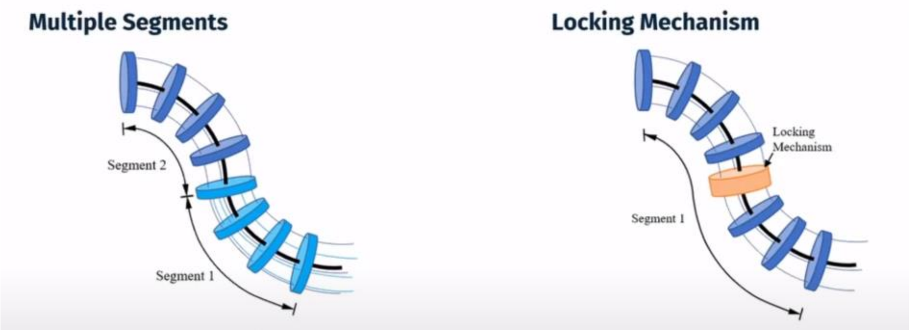


Figure 79: Locking mechanism

Initially, the entire tendon can be manipulated as one single segment. However, at any time, locking mechanisms can be used to clamp the strings and keep the latter section of the tendon fixed in place. From this point onwards, the initial section of the robot can be manipulated without changing the curvature of the second half. This can be repeated for numerous locking mechanisms. Thus, multiple degrees of freedom can be achieved without the need for additional segments. This not only eliminates the additional strings required for other segments but also maintains the number of driving stepper motors to the current four rather than having to add more driving units.

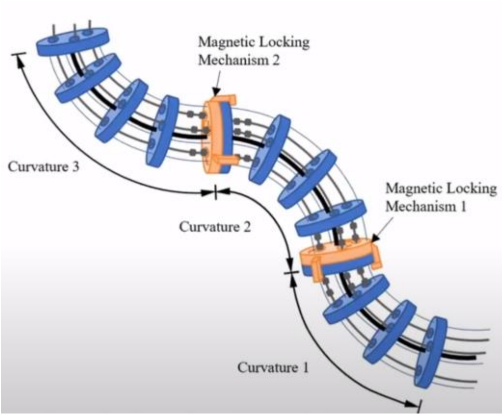


Figure 80: Incorporation of multiple locking mechanisms

The code for actuation can also be developed to become much more powerful including algorithms to automate the tendon and apply ultrasound along a pre-determined path. However, this would require further development from the mathematical dynamic modelling of the tendon.

Figure 81: Cartesian gantry system [36]

Another potential field of research lies within the miniaturisation of tendon-driven robots. The tendons can be downscaled to fit micro high-intensity focused ultrasound transducers such as the Siansonic FUS transducer with a diameter of 4-6mm.

Figure 82: Micro transducers by Siansonic [37]

These micro tendons can then be fitted with endoscopes and perform in-vitro treatment from within the human body. The end effector can also easily be changed to other surgical tools such as a scalpel. Due to their small size, the surgeon would be able to insert and accurately guide the tendon within the human body to the target location.

A) Summary

In conclusion, the solution to the inaccessibility of FUS manipulators has been met with a robotic manipulator. Thorough research was carried out to identify the optimal type of manipulator and extensive background research was completed on the topic. Following this, a simple prototype was made to assess the feasibility of the robot and provide useful feedback on its performance. Two more prototypes were made after this each with their iterations in improving parts of the design or trying out other potential options. Extensive testing was also carried out at each stage providing feedback to further improve the design. For the final prototype, a total of thirty-four iterations were carried out to achieve the current design.

Figure 83: Evolution of all three prototypes

There have been many challenges along the way including programming bugs and circuit wiring. Each iteration brought along discoveries and weaknesses within the design which were rectified and improved in the next iteration. However, in the end, the robot was successfully able to manipulate a FUS transducer using a joystick input. Distance, gyroscope and pressure sensors were also successfully integrated and relayed through an onboard LCD. The aim to keep the total cost under 500 pounds has also been met with all the materials and components required summing to 332.58 pounds.

Figure 84: Failed and discarded 3D prints

I am thrilled by the progress and results achieved in this project, and the outcomes hold great promise for advancements in focused ultrasound research. I encourage fellow researchers to engage with the robot, explore its potential, and contribute to its ongoing development. I extend my gratitude to all the researchers whose findings have been invaluable in the development of the robot.

I also want to express my deep appreciation to Dr Reza Haqshenas for his unwavering support and mentorship throughout the project.

Lastly, I would like to extend special thanks to the Focused Ultrasound Foundation (FUS) for their generous funding and approval. Their support has been indispensable in bringing this project to life.

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VI – Appendix

A) Appendix.1

```
#include <Servo.h>

Servo myservo;  // create servo object to control a servo

int potpin = 0;

int val;


void setup() {

 myservo.attach(9);

}


void loop() {

val = analogRead(potpin);

val = map(val, 0, 1023, 0, 180);

myservo.write(val);

delay(15);

}
```

B) Appendix.2

```
#include <Stepper.h>

  int Xspeed;

  int Xspeedmap1;

  int Xspeedmap2;

  int Yspeed;

  int Yspeedmap1;

  int Yspeedmap2;

  const int stepX=2;

  const int dirX=3;

   const int stepY=4;

  const int dirY=5;

   const int stepZ=6;
```

```
  const int dirZ=7;
   const int stepA=12;
  const int dirA=13;



void setup() {
  pinMode(stepX,OUTPUT);
  pinMode(dirX,OUTPUT);
  pinMode(stepY,OUTPUT);
  pinMode(dirY,OUTPUT);
  p3-inMode(stepZ,OUTPUT);
  pinMode(dirZ,OUTPUT);
  pinMode(stepA,OUTPUT);
  pinMode(dirA,OUTPUT);
  Serial.begin(9600);

}
void loop() {

Xspeed=analogRead(A0);
Xspeedmap1=map(Xspeed,0,1023,100,4000);
   Xspeedmap2=map(Xspeed,0,1023,4000,100);

   Yspeed=analogRead(A1);
Yspeedmap1=map(Yspeed,0,1023,40,4000);
   Yspeedmap2=map(Yspeed,0,1023,4000,40);

  if (Xspeed<510){
       digitalWrite(dirX,LOW);
       digitalWrite(stepX,LOW);
```

```
      digitalWrite(stepX,HIGH);
      digitalWrite(dirY,HIGH);
      digitalWrite(stepY,LOW);
      digitalWrite(stepY,HIGH);
      delayMicroseconds(Xspeedmap1);
  }
  if (Xspeed>530){
      digitalWrite(dirX,HIGH);
      digitalWrite(stepX,LOW);
      digitalWrite(stepX,HIGH);
      digitalWrite(dirY,LOW);
      digitalWrite(stepY,LOW);
      digitalWrite(stepY,HIGH);
      delayMicroseconds(Xspeedmap2);
     }

 if (Yspeed<510){
      digitalWrite(dirZ,LOW);
      digitalWrite(stepZ,LOW);
      digitalWrite(stepZ,HIGH);
      digitalWrite(dirA,HIGH);
      digitalWrite(stepA,LOW);
      digitalWrite(stepA,HIGH);
      delayMicroseconds(Yspeedmap1);
     }

 if (Yspeed>530){
      digitalWrite(dirZ,HIGH);
      digitalWrite(stepZ,LOW);
      digitalWrite(stepZ,HIGH);
```

```
    digitalWrite(dirA,LOW);
    digitalWrite(stepA,LOW);
    digitalWrite(stepA,HIGH);
    delayMicroseconds(Yspeedmap2);
   }


  }
```

C) Appendix.3

```
#include "Wire.h"
#include "I2Cdev.h"
#include "MPU6050.h"
#include <Wire.h>
#include <VL53L0X.h>
#include <LiquidCrystal.h>

const int rs = 12, en = 11, d4 = 5, d5 = 4, d6 = 3, d7 = 2;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);

VL53L0X sensor;
int fsrPin = 0;     // the FSR and 10K pulldown are connected to a0
int fsrReading;     // the analog reading from the FSR resistor divider
int fsrVoltage;     // the analog reading converted to voltage
unsigned long fsrResistance;  // The voltage converted to resistance, can be very big so make
"long"
unsigned long fsrConductance;
long fsrForce;       // Finally, the resistance converted to force

MPU6050 mpu;
int16_t ax, ay, az;
```

```
int16_t gx, gy, gz;
struct MyData {
  int X;
  int Y;
  int Z;
};

MyData data;

void setup()
{
  pinMode(12,INPUT_PULLUP);
  digitalWrite(12,HIGH);
  Serial.begin(9600);
  Wire.begin();
  lcd.begin(16, 2);
  sensor.init();
  sensor.setTimeout(500);

  // Start continuous back-to-back mode (take readings as
  // fast as possible).  To use continuous timed mode
  // instead, provide a desired inter-measurement period in
  // ms (e.g. sensor.startContinuous(100)).
  sensor.startContinuous();
  Serial.begin(9600);
  Wire.begin();
  mpu.initialize();
  //pinMode(LED_BUILTIN, OUTPUT);
}
```

```
void loop()
{
  fsrReading = analogRead(fsrPin);
  // analog voltage reading ranges from about 0 to 1023 which maps to 0V to 5V (= 5000mV)
  fsrVoltage = map(fsrReading, 0, 1023, 0, 5000);

  if (fsrVoltage == 0) {
    Serial.println("No pressure");
  } else {
    // The voltage = Vcc * R / (R + FSR) where R = 10K and Vcc = 5V
    // so FSR = ((Vcc - V) * R) / V        yay math!
    fsrResistance = 5000 - fsrVoltage;     // fsrVoltage was in millivolts so 5V = 5000mV
    fsrResistance *= 10000;                // 10K resistor
    fsrResistance /= fsrVoltage;

    fsrConductance = 1000000;           // we measure in micromhos so
    fsrConductance /= fsrResistance;

    // Use the two FSR guide graphs to approximate the force
    if (fsrConductance <= 1000) {
      fsrForce = fsrConductance / 80;
      Serial.print("Force in Newtons: ");
      Serial.println(fsrForce);
    } else {
      fsrForce = fsrConductance - 1000;
      fsrForce /= 30;
      Serial.print("Force in Newtons: ");
      Serial.println(fsrForce);
    }
  }
```

```
Serial.println("--------------------");
delay(1000);
int distance =sensor.readRangeContinuousMillimeters();
//int distance =sensor.startContinuous(100);

distance = distance-64;
Serial.print("Distance: ");
Serial.print(distance);
Serial.print("mm");
if (sensor.timeoutOccurred()) { Serial.print(" TIMEOUT"); }

Serial.println();
mpu.getMotion6(&ax, &ay, &az, &gx, &gy, &gz);
data.X = map(ax, -17000, 17000, 0, 255 )-140; // X axis data
data.Y = map(ay, -17000, 17000, 0, 255)-2;
data.Z = map(az, -17000, 17000, 0, 255);  // Y axis data
Serial.print("X-Tilt = ");
Serial.print(data.X);
Serial.print("  ");
Serial.print("Y-Tilt = ");
Serial.print(data.Y);
Serial.print("  ");
Serial.print("  ");
Serial.println();
lcd.setCursor(0, 0);
lcd.print("xTilt ");
lcd.print(data.X);
lcd.setCursor(11, 0);
lcd.print(distance);
lcd.print("mm");
```

```
  lcd.setCursor(0, 1);
  lcd.print("yTilt ");
  lcd.print(data.Y);
  lcd.setCursor(11, 1);
  lcd.print(fsrForce);
  lcd.print("N");

}
```