**University of Nottingham**

**Department of Mechanical, Materials and Manufacturing Engineering**

**MMME4085 (Group Design and Make)**

Group 3 - Space Gym

# Critical Design Review

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# Executive Summary

## Acronyms

To ensure ease of readability, a table of acronyms, and their meanings, has been created.

| Acronym | Meaning |
|---|---|
| NASA | National Aeronautics and Space Administration |
| ARED | Advanced Resistive Exercise Device |
| BS EN | British Standard of European ISO Standard |
| COLBERT | T2 Combined Operational Load Bearing External Resistance Treadmill |
| ISS | International Space Station |
| GA | General Assembly |
| CAD | Computer-Aided Design |
| FEA | Finite Element Analysis |
| PPE | Personal Protective Equipment |

## The Why, The What, and The How

This project presented the challenge of designing a piece of exercise equipment that could be used in a weightless environment to counteract the effects of muscular atrophy that astronauts experience during space flight.

A folding treadmill was designed to stimulate muscle growth in the legs and condition the cardiovascular musculature of the astronauts. The treadmill was also designed to be able to be used in a home setting by the public.

A concept demonstration model was designed to be presented to the customer at the end of the project. Additionally, a 'space concept' was designed in Solidworks to prove that the concept demonstration could work. The space concept makes use of space-grade materials, such as carbon fibre and titanium, to meet the 5kg weight limit.

In the concept demonstration, the treadmill utilises Rexroth frames to create an external structure that the internal components can be fastened to. Bearings, injected with grease, are used to provide viscous resistance proportional to the speed of the belt, as per the requirements.

The user is fastened to the treadmill using a harness and cables. The cables are used to generate a force that simulates a gravitational pull downwards. It has been designed so that the downward force the user experience, is greater than the 9.81m/s$^2$ felt on earth. This increases the difficulty of the workout thus leading to greater muscular hypertrophy. Furthermore, the treadmill is designed to be used at an incline, which results in an increased cardiovascular load.

To provide user feedback, a hall-sensor and magnet are used to measure the speed of the belt. This data is sent, via Bluetooth, to a mobile phone application, coded in C, that presents the user with data of their workout in a presentable format.

Finally, a full fabrication plan, alongside health and safety risk analysis, was generated to ensure the project could be completed and a treadmill could be delivered appropriately.

## Background and Further Development

NASA exercise equipment was considered when evaluating the various systems that could be used to create exercise apparatus in a weightless environment. The two designs that were researched were the ARED and the T2 treadmill. The ARED uses piston and cylinder assemblies to simulate the use of free weights, like those found in a conventional gym. It allows for 29 different exercises to be performed. The COLBERT is a treadmill with elastic straps over the shoulders and around the waist to keep the user in contact with the treadmill belt. Both systems are attached using a vibration isolation system to limit the forces transmitted to the ISS.

*Figure 2: T2 COLBERT [1]*

*Figure 1: ARED [2]*

Conventional gym equipment was also considered, with several ways of generating resistive force studied. Some of the first concepts generated included a leg press and bicep curl machine. However conventional methods of producing resistive force used in gyms would not work in a zero-gravity environment. Vacuum and hydraulic cylinders were considered to produce the force for the bicep curl and leg press machines, respectively.

Another crucial factor given thought was whether the machines had adjustable forces. This is somewhat difficult to achieve whilst utilising pistons. The leg press concept involved changing out the pistons to achieve a different resistance. The bicep curl concept utilized a frame with various cable lengths which results in varying resistance forces.

Finally, exercise machines that can be found in the home were explored. Some changes to these machines had to be made to ensure that they were suitable for use in a weightless environment. The remaining three initial concepts were based on an exercise bike, a treadmill, and a stepper machine. Conversely to the bicep curl and leg press designs, these designs are based on cardio conditioning rather than strength conditioning. The bike machine makes use of a flywheel and belt system driven by pedals. This design achieves adjustable force using an adjustable contact area on the brake pad.

Similarly, the stepper machine concept involved using pedals that the user steps on, with a constant resistance generated via two hydraulic cylinders positioned under the pedals. It would have to be fixed to a desired surface if in a zero-gravity environment. The two pedals move up and down with opposing motions using a piece connected to the centre of the frame. Similarly, to the other designs using cylinders, the forces are only adjustable by changing the cylinders.

The final design, a folding treadmill, uses a harness connected to the treadmill via cables as the method to create resistance. The resistance is adjusted by altering the tension of the cables which can be used to simulate varying degrees of gravity.

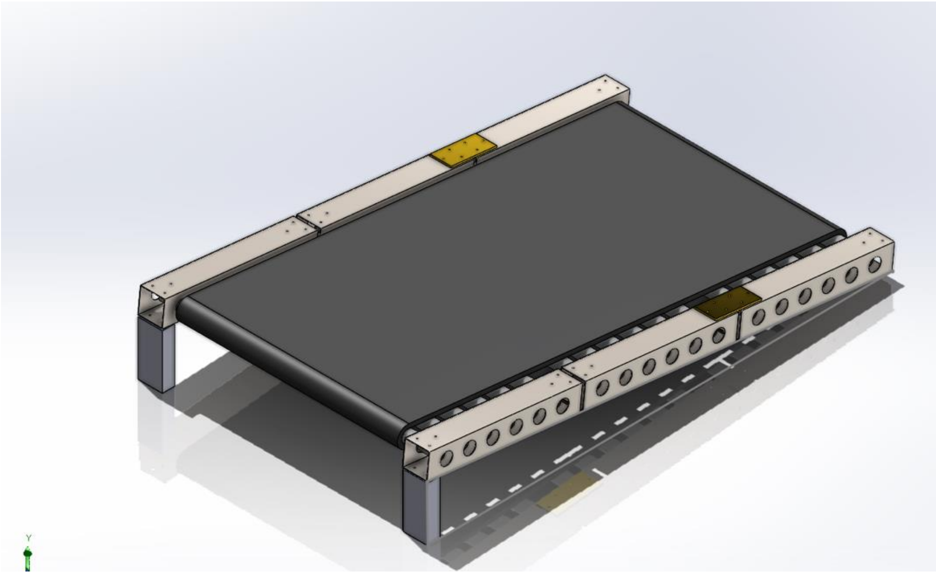


*Figure 3: Initial treadmill design*

Several factors were considered to ensure the designs are appropriate for use in space. Firstly, due to transportation considerations, the design must be stowed in a small area and meet a strict weight requirement. This will limit the designs and requires intelligent solutions to overcome. In addition, the user of the machine will need to be restrained for best use. In the initial concepts, this is generally done either using foot straps or a harness system. Safety is also of utmost importance. For this project BS EN 957 Standards for stationary training equipment were considered most appropriate. The final design must comply with these standards.

The folding treadmill concept was selected to be developed further by employing a design decision matrix. The final design of the treadmill uses 40mm Rexroth bars to create an external structure. Internal components, such as the handles and baseboards, were fastened to the bars via twist-locking T-nuts. This design philosophy, of having a frame to build off, was chosen to decrease the complexity of the assembly while increasing the number of 'off-the-shelf' parts chosen. As the system is to be sold for home use, the set-up time must be kept to a minimum to ensure the treadmill's design is inclusive.

The z-fold nature of the design leads to an elegant solution in creating a treadmill large enough to provide a suitable area to run on while simultaneously following the space envelope requirement of $600mm^3$. Additionally, the collapsible nature of the handles is another elegant solution to the space requirement.

To generate viscous resistance, many concepts were discussed throughout the design phase. Originally, a pulley system connected to a generator was used to generate viscous resistance. However, after many iterations, it was deemed too difficult to design within the strict statement of requirements. The final concept utilises greased bearings to generate a frictional force to slow the belt down proportionally to the speed of the user.

Initially, the pulley generator concept was chosen due to its ability to generate a readable voltage. This voltage would be proportional to the speed of the treadmill; therefore, the cadence of the user could be calculated by measuring the voltage. However, a more elegant solution was created utilising a hall sensor and magnet. The magnet is placed on the roller and as the roller spins, the magnet moves over the hall sensor. As the magnet passes over the sensor, a clipped signal is generated, which can be sent to a microprocessor. A continuous timer, by using the millis () function, is used to calculate the time taken for the roller to complete two rotations (to minimise error). With this digital information, the speed of the user can be calculated. As the information has been digitised, other details, such as total distance, top speed, and average speed, to name but a few, can be calculated and presented to the user via an app that is easy to read. This app can be developed further to include a social system that would allow users to compare their times and speeds. This increases the future value of the product which would allow for the treadmill to be sold at a higher price.

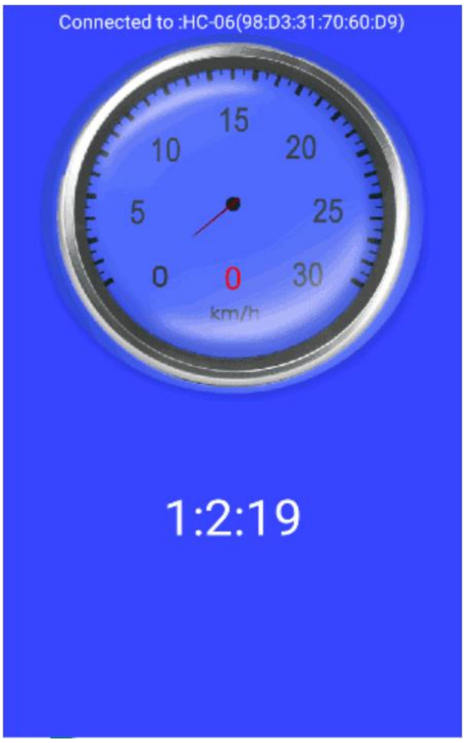



*Figure 4: Designed UI for the app*

## The Statement of Requirements

The statement of requirements are outlined in an easy to read table. Method of demonstrating compliance, and status of compliance are given to provide insight into the success of the project. For the deliverable to be called a success, it must complete all the requirements.

| No. | Requirement | Method of Demonstrating Compliance | Status of compliance |
|---|---|---|---|
| 1 | The weight of the system must not exceed 5Kg. | Weight Test | Compliance will be confirmed by testing. The mass of the design in Solidworks is ~23.5kg. Using material and design substitutions, the 'space' treadmill can be made at 5kg. |
| 2 | The system must follow the BS EN 957-6 Standards for stationary training equipment | Safety Inspection observed by qualified personnel to sign off on design | Compliance by design - as shown by Compliance of BS-EN health and safety standards |
| 3 | The system must be stowed in a 600x600x600mm space envelope | Measure Test | Compliance by design - as shown by folding mechanism. Testing will be done throughout to confirm compliance |
| 4 | The force resisting motion should be proportional to the velocity of the simulated exercise and be adjustable. | Calculate and Measure Force | Compliance by design – The friction is proportional to the reaction force which is proportional to the cord tension allowing for compliance. Bearings with damping grease provide viscous resistance which is proportional to the user's speed. |
| 5 | The system must be manufactured using corrosion resistant materials. | Materials Test | Compliance by design – corrosion resistant materials are used exclusively. |
| 6 | The budget of £350 should not be exceeded. | Review Purchase History | Compliance confirmed by budgeting table; increased budget approved by module convenor |
| 7 | The device should be usable in zero-gravity environments. | Testing and Calculations | Compliance by design – Use of handles and harness allows use in a zero-gravity environment |
| 8 | The device should be easy to set up within 10 mins by one person using simple tools. | Testing | Compliance by design- number of parts to assemble for set up is limited and no specialised tools are needed. |
| 9 | The device must dissipate a minimum of 150W of power to ensure effective use. | Calculations | Compliance is demonstrated through performance calculations detailing the torque required to overcome the resistance generated by the bearing system. |
| 10 | The design must be usable by a person with maximum mass of 81kg. | Calculations and Testing | Compliance is confirmed via structural calculations. In addition, testing will be carried out prior to use to ensure the device will not structurally fail. |
| 11 | The forces the user will experience on the device must be the same as the forces the user would experience on earth at a minimum (i.e. $g \geq 9.81 m/s^2$). | Calculations and Testing | Compliance is confirmed via cable tension calculations. In addition, testing will be carried out prior to use to ensure the cables provide an adequate resistance. |
| 12 | The device must have minimum useable length of 700mm | Measure Test | Compliance is demonstrated through the CAD model and can be verified by measuring the device once manufactured. |

*Table 1: The Statement of Requirements*

The statement of requirements is a living document and as such has been updated throughout the design process. It contains engineering design specific attributes such as requirement 12. Additionally, key functions of the system have been outlined such as requirement 4.

# Design Description

## Design Description

The design is described in the following section, ladled diagrams have been produced to aid in the understanding of the final design. Refer to the drawings in the appendix for additional information.

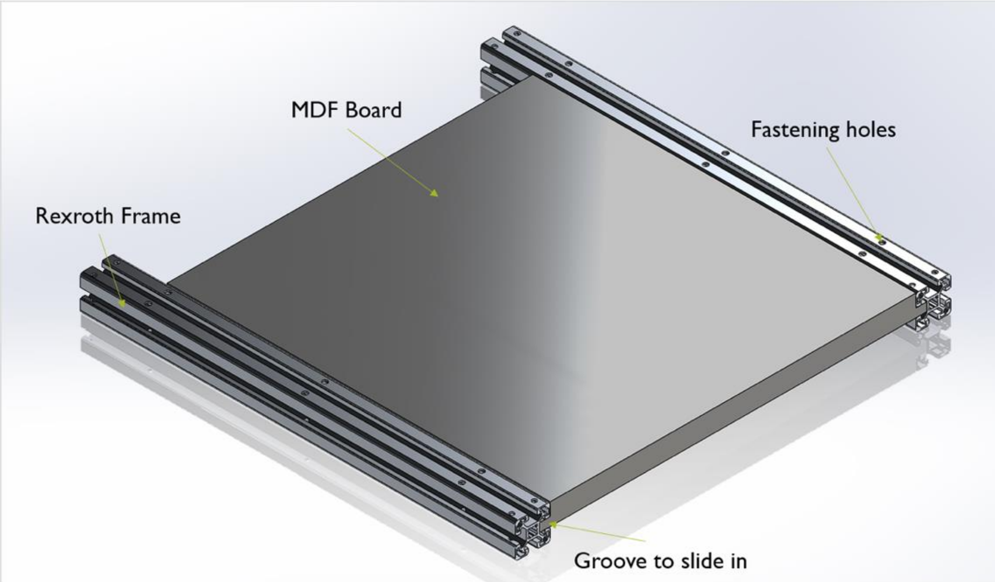



*Figure 5: One of the two end Units. The middle Unit has the MDF Board the length of the frames.*

Rexroth frames are used to create an external shell. MDF boards create a surface for the belt to slide over. These boards are slid through the grooves located in the frames. Bolts and nuts are used to fasten the boards to the frames. Each board has two frames connected to it. These are known as units.

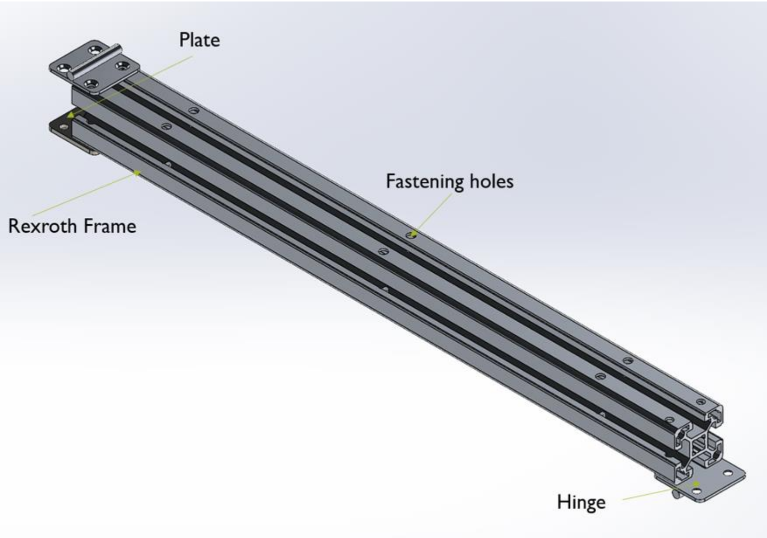



*Figure 6: One of the middle frames. This includes the two hinges and one plate.*

Hinges and plates are used to create the hinging mechanism. This connects each unit to the other.

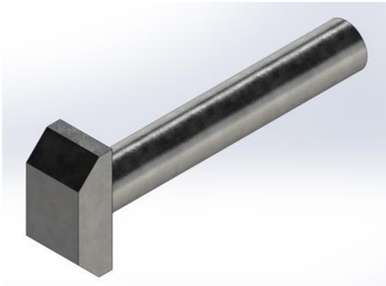


*Figure 7: CAD Model of T Bolt that slides into the frames. Twist to lock in place.*

T Bolts are used to fasten the feet and shafts to the frame. These bolts lock into the frame and can be adjusted. This means the angle of the treadmill and tension in the belt can be adjusted which aids in completing requirement 4.

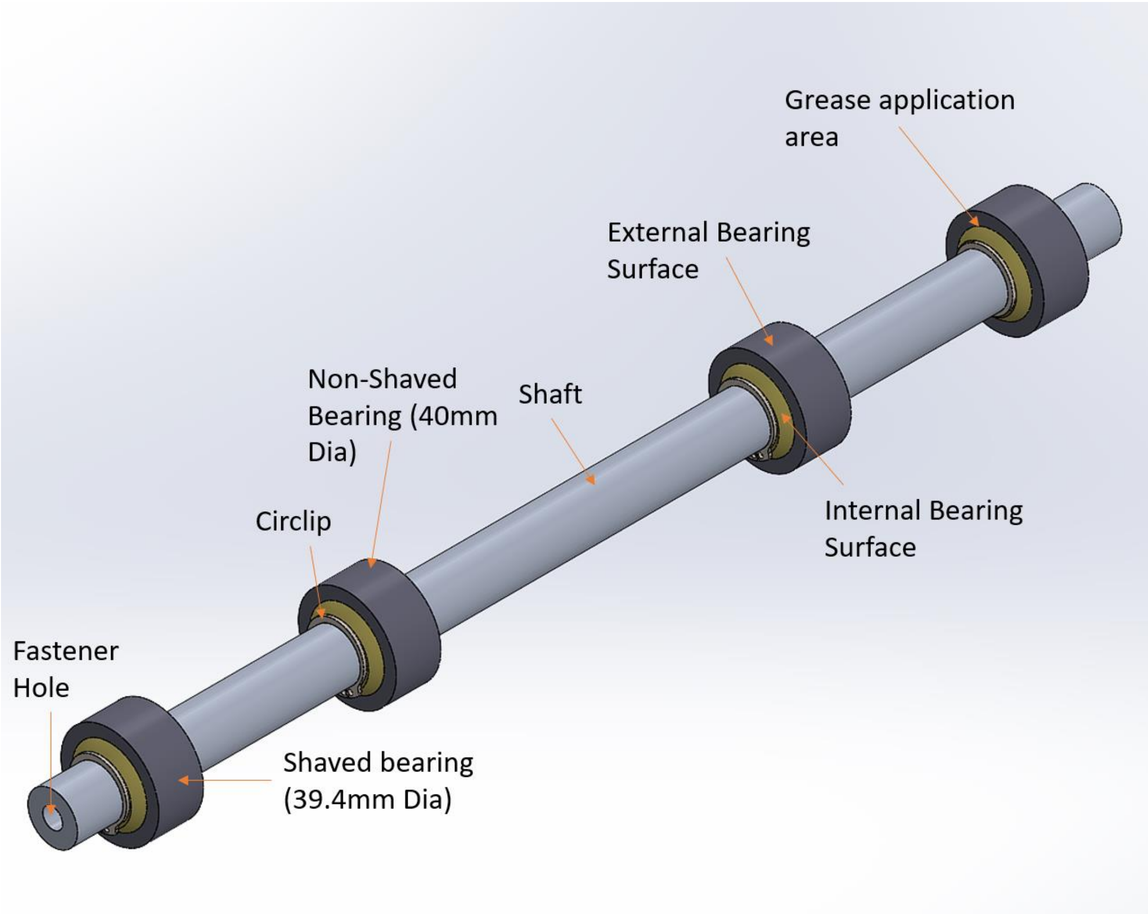



*Figure 8: Rotational pulley system including the shaft, bearings and circlips.*

Over the shafts, bearings, and circlips, are used to create the rotational pulley system that the belt will slide over. The two outermost bearings, on the front shaft, are shaved down to create a crowned profile for the belt to slide over. This crowned profile generates a different tension throughout the edge of the belt which ensures the belt will not slip from side to side. This is an elegant and mechanical way to ensure the belt remains aligned. The viscous grease is applied to the interface between the outer rim and the inner bearing. This generates the viscous resistance as per requirement 4. Manufacturing tolerances could lead to misalignment of the bearings; therefore, bearings were chosen with a large pivot angle. This is another method of ensuring the belt stays centred. The pivot angle also makes adding the grease easier. Grooves have been cut into the shaft to allow for the circlips to fasten the bearings. This is an additional way the system has been 'designed for assembly' as the shafts can be mass produced and assembly only requires the sliding of bearings and inserting of clips into the pre-cut groove. This shows how the design philosophy is maintained throughout.

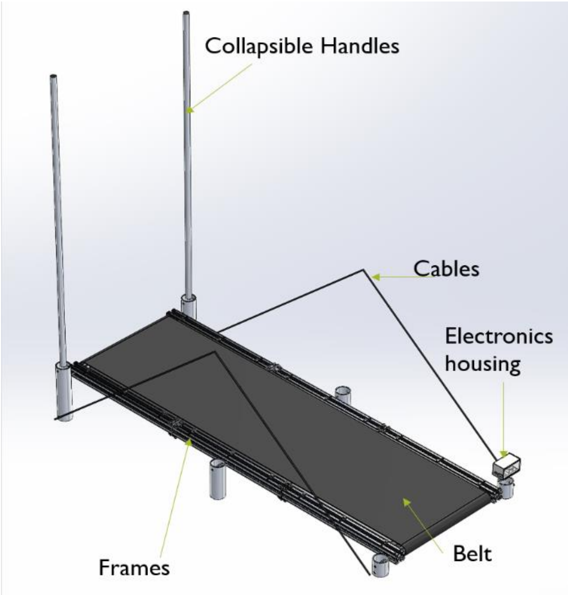



*Figure 9: CAD Render of the final concept demonstration model with the belt*

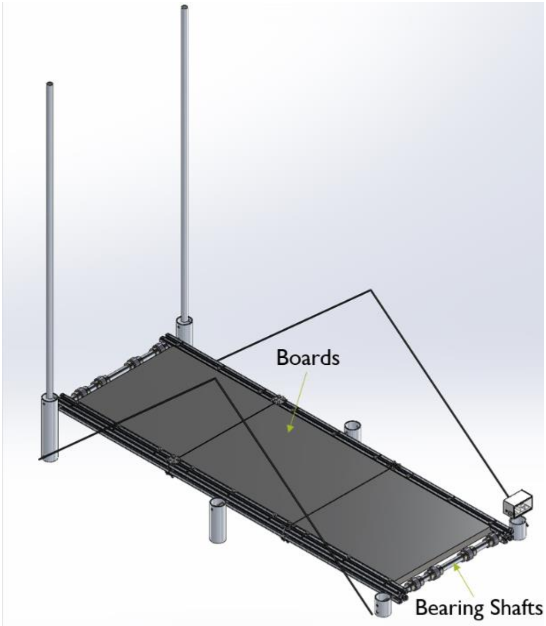



*Figure 10: CAD Render of the final concept demonstration model without the belt*

A belt is placed over the boards and rollers to create a moving surface for the user to move over. Feet, modelled out of pipes, are attached to the frame using T-Bolts. The collapsible handles can be placed in any of the feet. This allows the user to change where they want their handles to be and therefore allows different difficulties of walking. For instance, if the handles are placed at the back feet, the user can walk backwards which is imperative for tibialis anterior muscle. Therefore, the capabilities of the treadmill have been increased. Additionally, the feet have holes for the cables to attach to, allowing for an elegant solution for fastening the cables to the system. This allows the user to change the direction of the force generated to meet with their personal workout plan.

Finally, the design completes all functions and attributes required. All statement of requirements, that are compliant through design, have been fulfilled. Key design choices have been justified.

A space concept was designed to achieve the 5Kg weight limit without cost constraints.

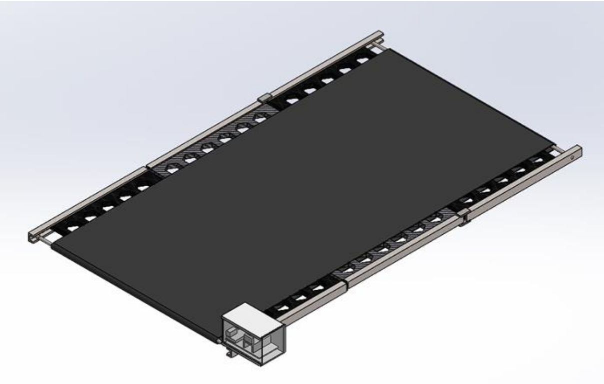


*Figure 11: 'Space' concept model with belt included*

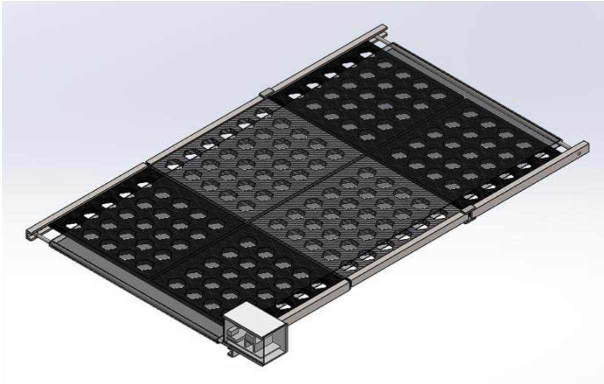
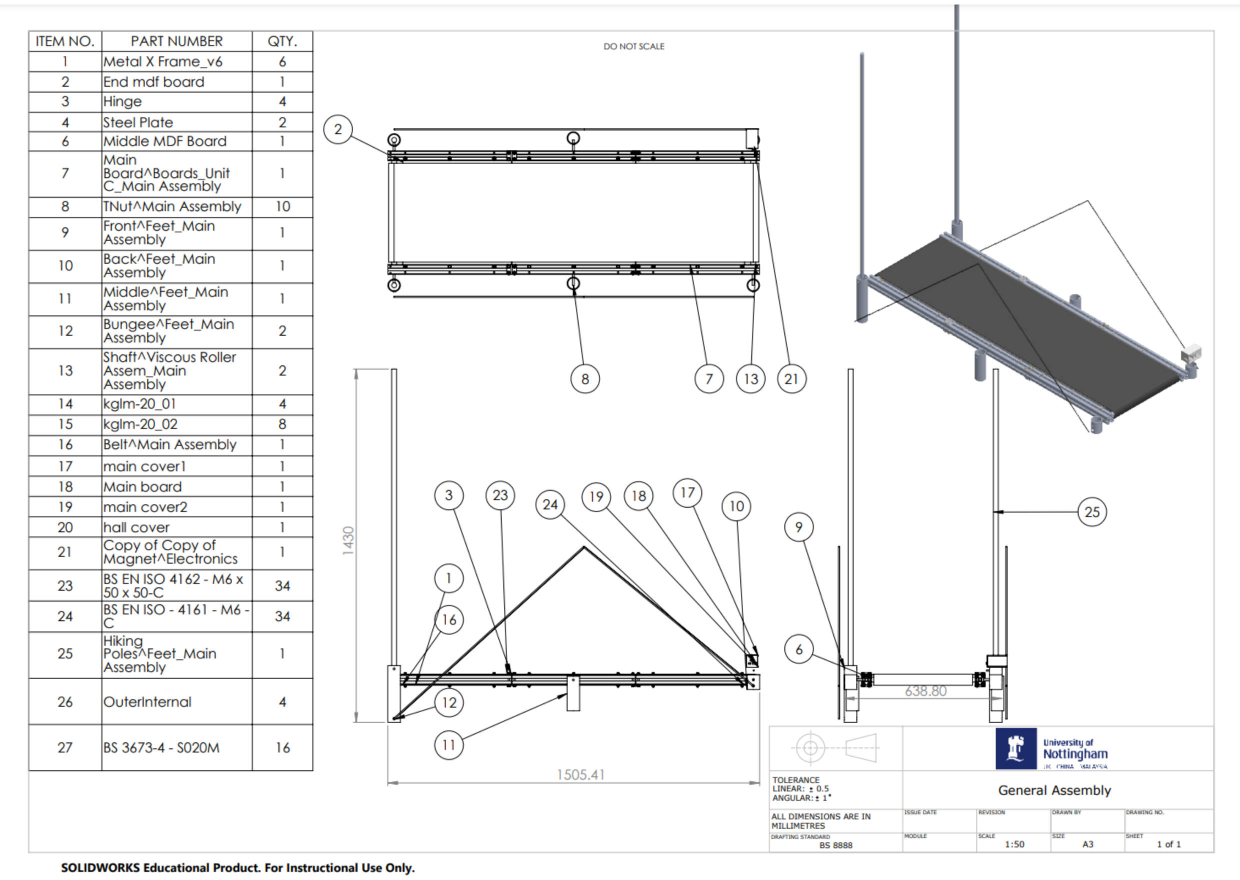


*Figure 12: Space concept model without belt*

## Drawings

### General Assembly



| ITEM NO. | PART NUMBER | QTY. |
|---|---|---|
| 1 | Metal X Frame_v6 | 6 |
| 2 | End mdf board | 1 |
| 3 | Hinge | 4 |
| 4 | Steel Plate | 2 |
| 6 | Middle MDF Board | 1 |
| 7 | Main Board^Boards_Unit C_Main Assembly | 1 |
| 8 | TNut^Main Assembly | 10 |
| 9 | Front^Feet_Main Assembly | 1 |
| 10 | Back^Feet_Main Assembly | 1 |
| 11 | Middle^Feet_Main Assembly | 1 |
| 12 | Bungee^Feet_Main Assembly | 2 |
| 13 | Shaft^Viscous Roller Assem_Main Assembly | 2 |
| 14 | kglm-20_01 | 4 |
| 15 | kglm-20_02 | 8 |
| 16 | Belt^Main Assembly | 1 |
| 17 | main cover1 | 1 |
| 18 | Main board | 1 |
| 19 | main cover2 | 1 |
| 20 | hall cover | 1 |
| 21 | Copy of Copy of Magnet^Electronics | 1 |
| 23 | BS EN ISO 4162 - M6 x 50 x 50-C | 34 |
| 24 | BS EN ISO - 4161 - M6 - C | 34 |
| 25 | Hiking Poles^Feet_Main Assembly | 1 |
| 26 | OuterInternal | 4 |
| 27 | BS 3673-4 - S020M | 16 |

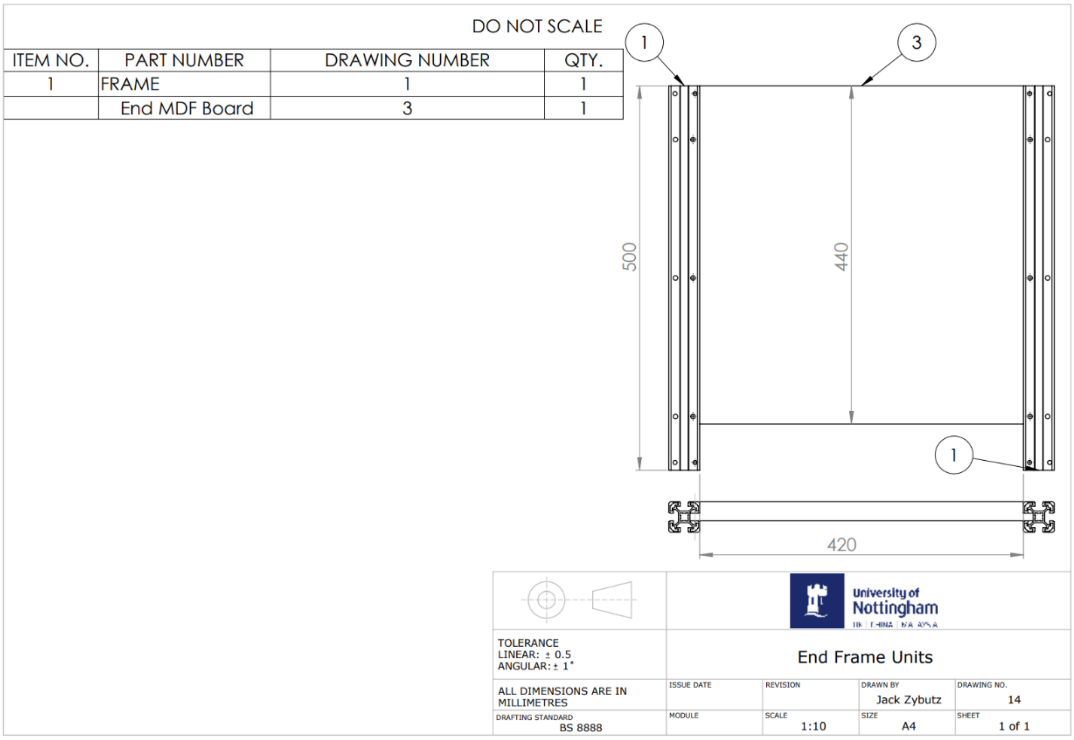


*Figure 13: General Assembly Drawing of the treadmill including bill of materials*

This is the GA drawing for the final concept. Included are a bill of materials, with ballooning on the model and overall dimensions. The design intent of how the sub-assemblies work together is outlined here.

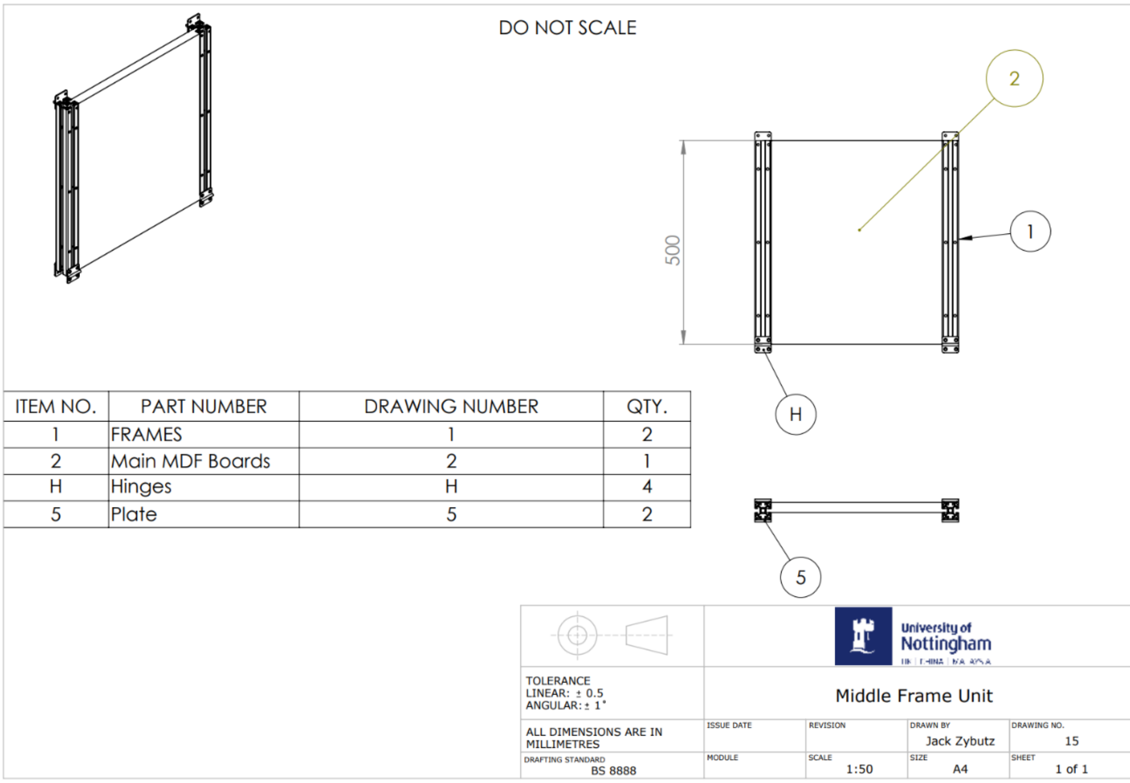
## Assembly Drawings

These are the sub-assembly GA drawings. Fitting and tolerances have been included for the dynamic viscous resistance Bearing Shaft Assembly. By minimising the number of parts required, the ease of manufacture and assembly is maintained.




| ITEM NO. | PART NUMBER | DRAWING NUMBER | QTY. |
|---|---|---|---|
| 1 | FRAME | 1 | 1 |
| | End MDF Board | 3 | 1 |

*Figure 14: End Frame Units Sub-Assembly Drawing*




| ITEM NO. | PART NUMBER | DRAWING NUMBER | QTY. |
|---|---|---|---|
| 1 | FRAMES | 1 | 2 |
| 2 | Main MDF Boards | 2 | 1 |
| H | Hinges | H | 4 |
| 5 | Plate | 5 | 2 |

**SOLIDWORKS Educational Product. For Instructional Use Only.**

*Figure 15: Middle Frame Unit Sub-Assembly Drawing*

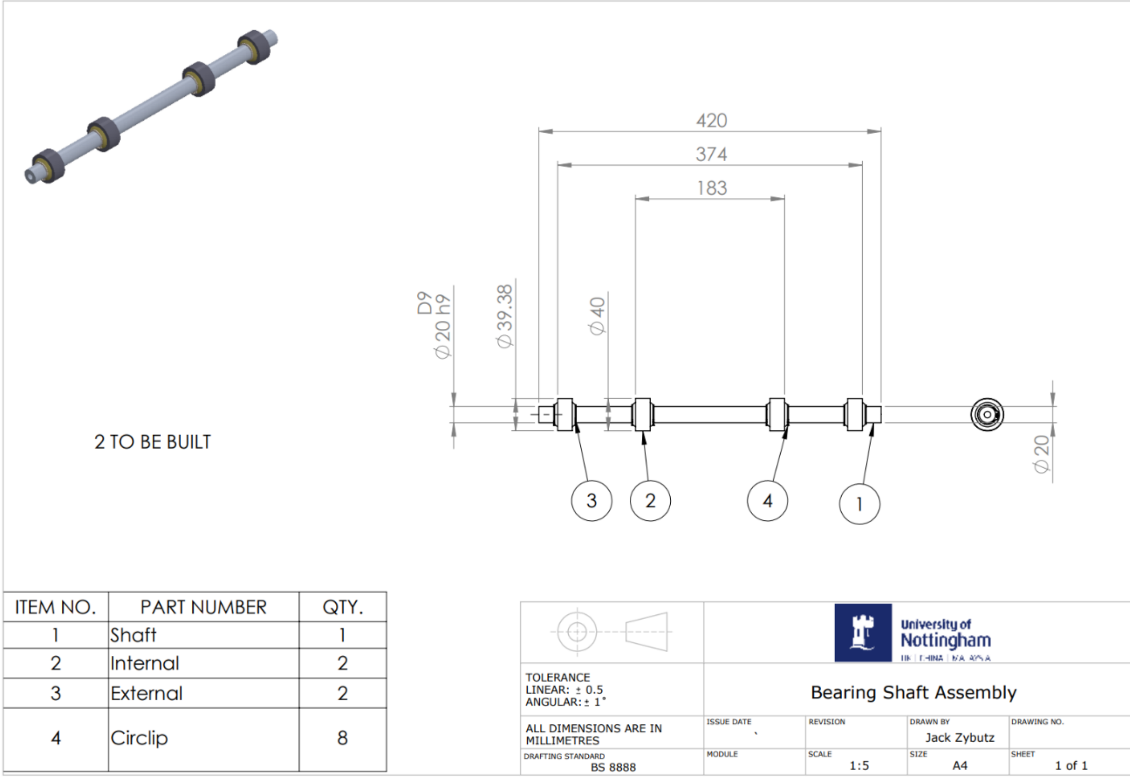





*Figure 16: Bearing-shaft Sub-Assembly Drawing with D9/h9 free running fit tolerances*

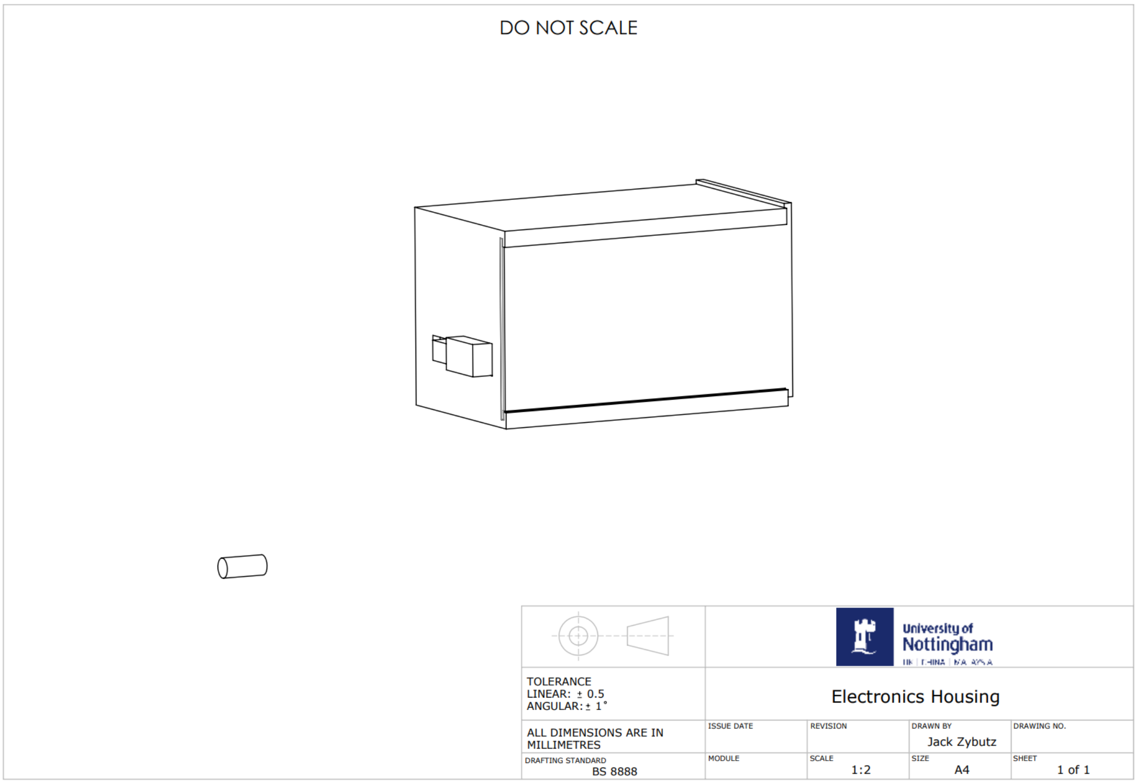





*Figure 17: Electronics Housing Sub-Assembly Drawing*

## Detailed Drawings

To ensure ease of readability, only key detail drawings have been presented in this section of the report.

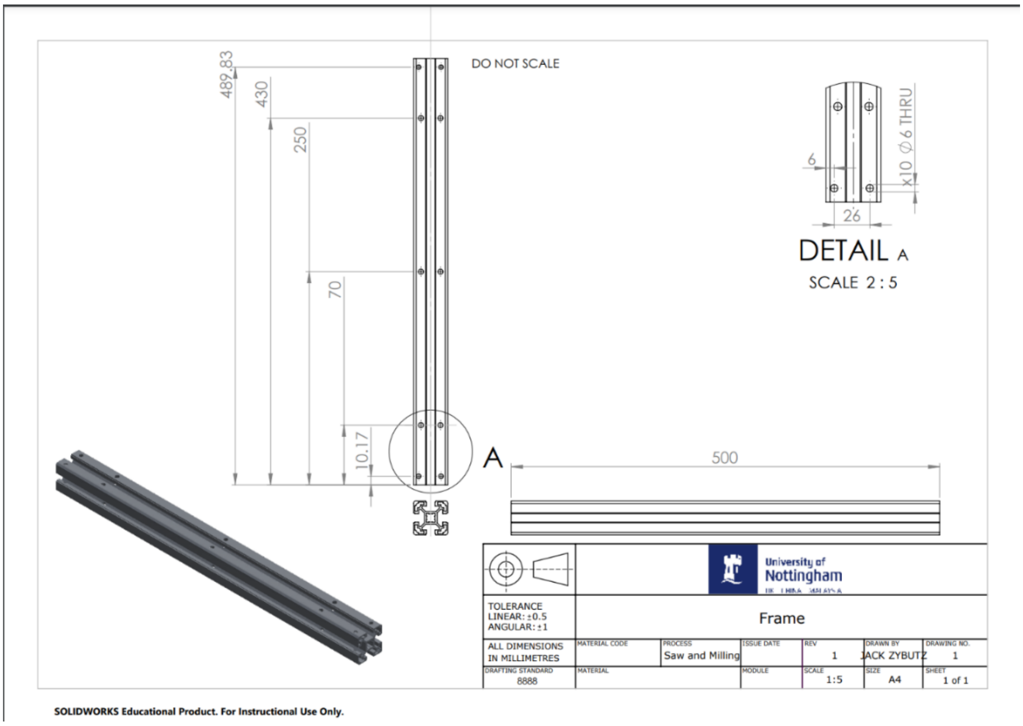



*Figure 18: Frame Detailed Drawing*

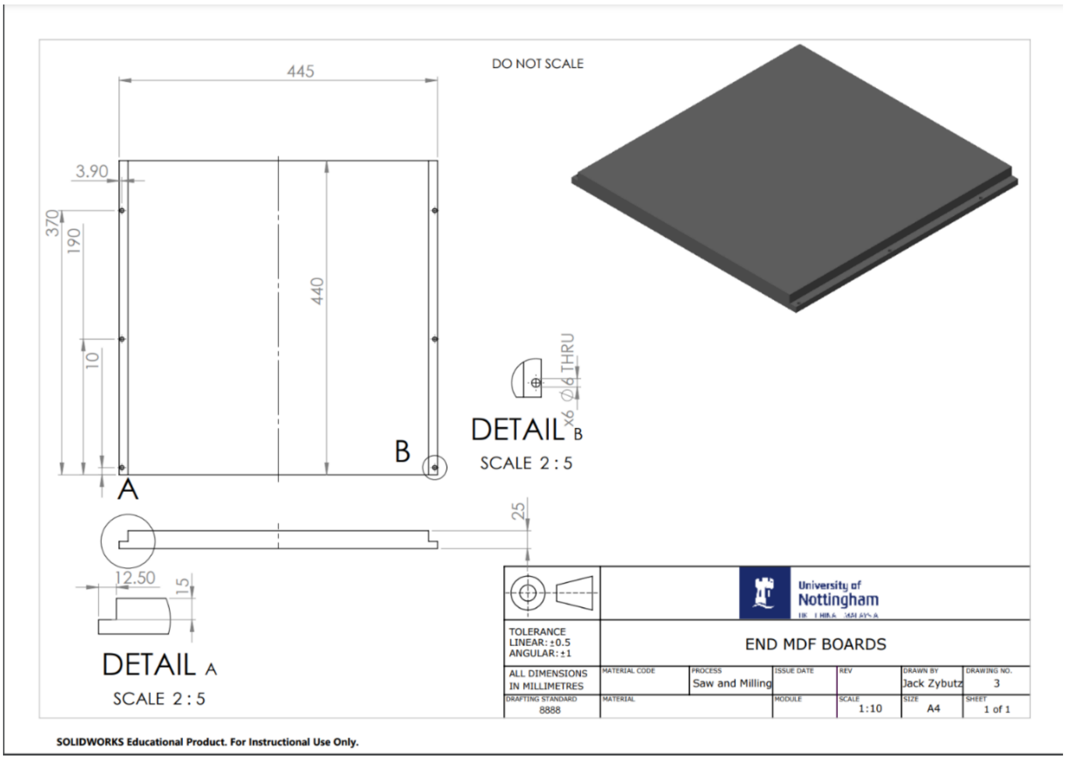



*Figure 19: End MDF Boards Detailed Drawing*

All detail drawings can be found in the Appendix section of this report.

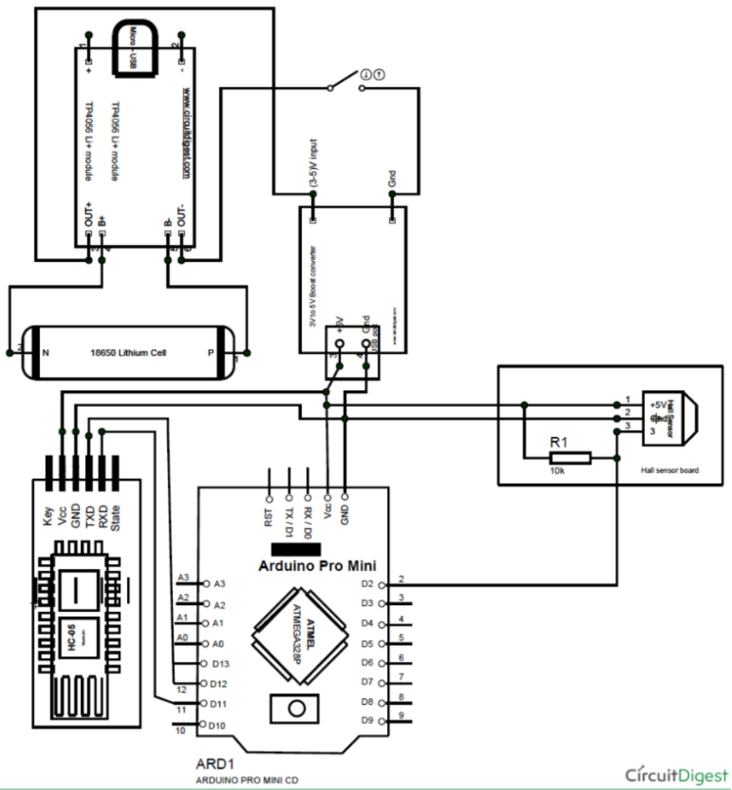



*Figure 20: Electrical schematics including hall sensor, Arduino and lithium cell*

```c
#include <SoftwareSerial.h>
SoftwareSerial Cycle_BT(11, 12);
//SoftwareSerial Cycle_BT(11, 12);  // RX, TX
int ledpin=13;
int BluetoothData;
float radius_of_wheel=0.33; //ENTER THE RADIUS OF THE ROLLER HERE
volatile byte rotation;
float timetaken,rpm,dtime;
int v;
unsigned long pevtime;
void setup()
{
  Cycle_BT.begin(9600); //Start BT communication at 9600 buadrate
  //pinMode(ledpin, OUTPUT); //LED pin aoutput for debugging
  attachInterrupt (0, magnet_detect, RISING); //second pin of arudion used an an indicator
  rotation=rpm=pevtime=0; //Init all variables
}
void loop()
{
  /*To drop to zero if vehicle stopped*/
 if(millis()-dtime>1500) //no magnet found for 1500ms
 {
  rpm= v = 0; // make rpm and velocity as zero
  Cycle_BT.write(v);
  dtime=millis();
 }
 v = radius_of_wheel * rpm * 0.37699; //0.33 is the radius of the wheel in meter
}
void magnet_detect() //Called whenever a magnet is detected
{
  rotation++;
  dtime=millis();
  if(rotation>=2)
  {
    timetaken = millis()-pevtime; //time in millisec for two rotations
    rpm=(1000/timetaken)*60;    //formulae to calculate rpm
    pevtime = millis();
    rotation=0;
    Cycle_BT.write(v);
    //Cycle_BT.println("Magnet detected...."); //enable while testing the hardware
```

*Figure 21: Arduino code written in C*

## Electrical

# Concept Demonstration Calculations

## Structural

### Board Bending

The treadmill boards are modelled as a beam with a singular point force acting at the middle as shown in figure 22. This assumption is made as this will cause the maximum displacement.

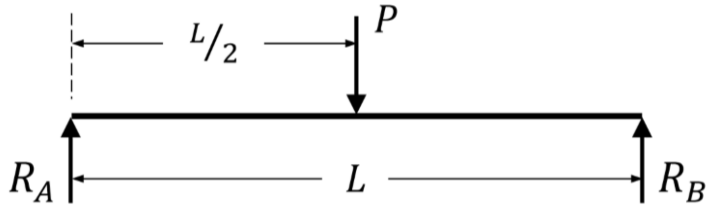



*Figure 22: Bending moment diagram.*

This gives the bending moment equation:

$$EIy = \frac{Rax^3}{6} - \frac{P\langle x - L/2\rangle^3}{6} + Ax + B$$

To find the thickness of the boards. The value of displacement is set to 5mm. This is because any more displacement would result in the treadmill being unsteady for the user.

Therefore, the boundary conditions used to find A and B are:

At x=L/2, y = 0.005 and at x = 0, y = 0

The second boundary conditions solve for B = 0. The first condition gives the equation for A:

$$A = \frac{2}{L}\left(EI \times 0.005 - \frac{\left(707 \times \frac{L^3}{2}\right)}{6}\right)$$

The final equation comes to:

$$EIy = \frac{Rax^3}{6} - \frac{P\langle x - L/2\rangle^3}{6} + \frac{2}{L}\left(EI \times 0.005 - \frac{\left(707 \times \frac{L^3}{2}\right)}{6}\right)$$

The value of P used was P = 1.5*mass*9.81. The value of 1.5 was taken from a study on the ground reaction forces at different speeds of human walking and running [3]. The speed of 3m/s was used as a factor of safety as the treadmill will not realistically be used at this speed.

As the treadmill is at a 6.78° incline, the force was resolved to be perpendicular to the beam:

$P = 1.5 \times 81 \times 11.72 \times \cos 6.78 = 1414N$ and $R_a = \frac{P}{2} = 707N$

$Y = 0.005$; $L = 0.42m$, $x = {}^{L}/_{2} = 0.21m$; $E = 2.3GPa$ (MDF wood)

$I = \frac{bd^3}{12}$, where b = 0.5m from the design and d is the thickness.

$$2.3 \times 10^9 \times \frac{0.5 \times d^3}{12} \times 0.005 = \frac{707 \times 0.21^3}{6} - \frac{P \times 0}{6} + (2/0.42)\left(2.3x10^9 \times \frac{0.5 \times d^3}{12} \times 0.005 - \frac{707 \times 0.21^3}{6}\right)$$

$$479166.667d^3 = 1.09125 + (2/0.42)(479166.667d^3 - 1.09125)$$

$$4.10517 = 1802579.365d^3$$

$$2.277 \times 10^{-6} = d^3$$

$$13.15 \times 10^{-3}m = d$$

$$d = 13.2mm$$

Therefore, the thickness of the boards needs to be a minimum of 13.2 mm.

To include a factor of safety, the boards chosen for the final concept demonstration is 25mm.

## Frame Bending

The frame bending uses the same layout as the boards. Therefore, the same equation is used:

$$EIy = \frac{Rax^3}{6} - \frac{P\langle x - L/2\rangle^3}{6} + \frac{2}{L}\left(EI \times 0.005 - \frac{\left(707 \times \frac{L}{2}^3\right)}{6}\right)$$

This time the deflection was calculated from the values below:

E = $69 \times 10^9$Pa; I = 9.1cm$^4$ = 9.1 x$10^{-8}$ m$^4$ (taken from the data sheet of the Rexroth frames); Ra = 592N; L=1.6m

$$6279y = 60.33 + (7848.75y - 75.4125)$$
$$15.08 = 1569.75y$$
$$y = 0.0096m = 9.6mm$$

The deflection is over 5mm which exceeds the value of deflection for the treadmill to be stable when calculating the boards, so a middle supporting leg was added to the design. With the middle leg the length changes to 0.8m and x = 0.4. The force will decrease, as whilst your foot is in between the front and middle leg or the back and middle leg the other foot is most likely to be in contact taking some of the load. However, 1183N was still used as a worst-case scenario.

E = 69x10^9^, I = 9.1cm^3^ = 9.1 x10^-8^ Ra = 592N L=0.8m solve for y

$$6279y = 7.54 - 18.85 + 15697.5y$$
$$y = \frac{11.31}{9418} = 1.20089mm$$

Therefore, the frame deflection will only be 1.2mm and will be stable.

## Frame Stress

For the stresses in the frames there is a direct stress and a steer stress.

$$\sigma = {}^{F}/_{A},\ F = 1183N,\ A = 0.048m^2$$

$$\sigma = {}^{1183}/_{0.048} = 0.0246MPa$$

$$\tau = {}^{Tr}/_{J}$$

Modelling the bar with a circular cross section with a radius of 20mm for simplified torsion equations.

$J = \pi \times 0.02^4 / 2 = 2.513\times10^{-7}$

$\tau = 1183 \times 0.21 \times 0.02 / 2.513\times10^{-7} = 19.7MPa$

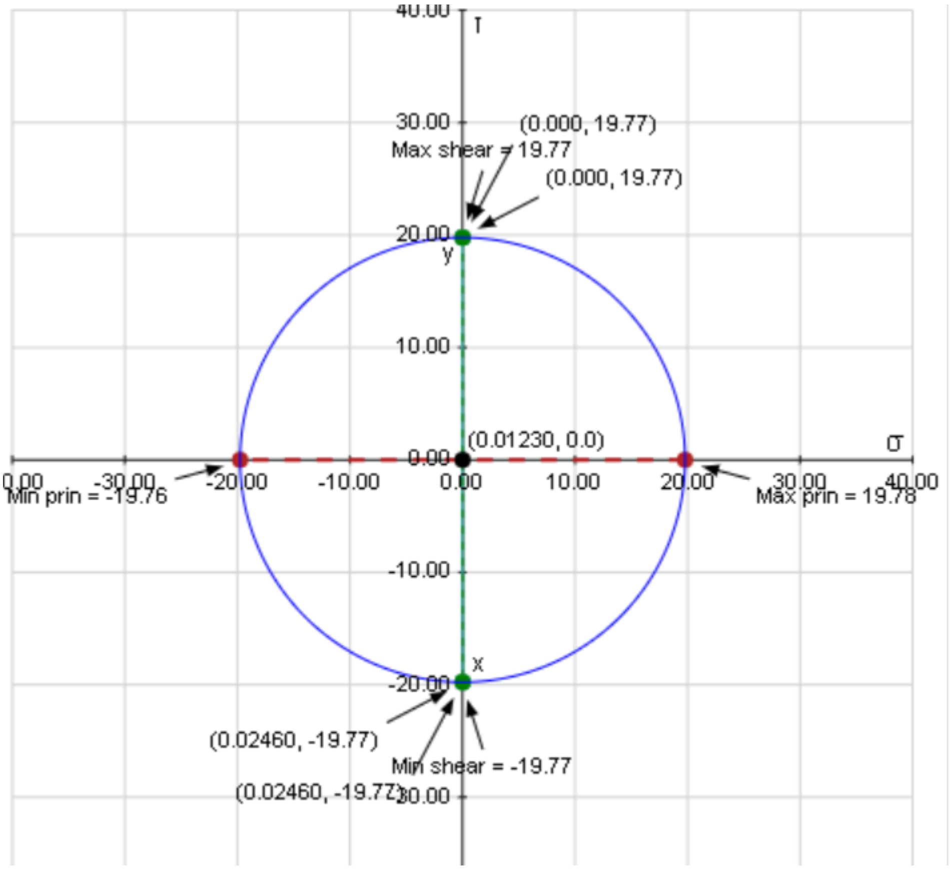



*Figure 23: Mohr's Circle for frame stresses [4]*

The principal stresses are -19.76MPa and 19.78MPa.

Aluminium has a maximum yield strength of 55MPa and an UTS 310MPa, so the frame is strong enough and wont fail. Aluminium has a maximum yield strength of 55MPa and an UTS 310MPa, so the frame is strong enough and will not fail.

## Minimum Belt Length

| Height | Women's Step Length (inches) | Women's Stride Length (inches) | Men's Step Length (inches) | Men's Stride Length (inches) |
|---|---|---|---|---|
| 5 ft. 0 in. | 24.8 | 49.6 | 24.9 | 49.8 |
| 5 ft. 1 in. | 25.2 | 50.4 | 25.3 | 50.63 |
| 5 ft. 2 in. | 25.6 | 51.2 | 25.7 | 51.46 |
| 5 ft. 3 in. | 26.0 | 52.0 | 26.1 | 52.29 |
| 5 ft. 5 in. | 26.4 | 52.9 | 26.6 | 53.12 |
| 5 ft. 5 in. | 26.8 | 53.7 | 27.0 | 53.95 |
| 5 ft. 6 in. | 27.3 | 54.5 | 27.4 | 54.78 |
| 5 ft. 7 in. | 27.7 | 55.3 | 27.8 | 55.61 |
| 5 ft. 8 in. | 28.1 | 56.2 | 28.2 | 56.44 |
| 5 ft. 9 in. | 28.5 | 57.0 | 28.6 | 57.27 |
| 5 ft. 10 in. | 28.9 | 57.8 | 29.1 | 58.1 |

*Table 2: Chart of average step length and stride length by height [5]*

To determine the minimum length the treadmill belt must cover, the average stride length was found.

Average step length is 26 inches = 660mm

The minimum length of the treadmill belt should therefore be 660mm.

## Shaft Diameter

$$d = \left[\frac{32n_s}{\pi}\sqrt{\left(\frac{M}{\sigma_e}\right)^2 + \frac{3}{4}\left(\frac{T}{\sigma_y}\right)^2}\right]^{\frac{1}{3}}$$

Where:

d = shaft diameter (mm)

$n_s$ = reserve factor

M = maximum bending moment (Nmm)

$\sigma_e$ = endurance stress (MPa)

T = maximum transmitted torque

$\sigma_y$ = yield strength (MPa)

A reserve factor of between 2~2.5 is used for average materials.

To work out the minimum diameter for the roller shaft, the variables seen in the equation (above) are required.

Yield strength for aluminum is 27575200 Pa = 27.5752 MPa
Endurance stress is 0.4 x UTS = 0.4 x 310 MPa = 124 MPa
Reserve factor is (actual strength/required strength) and since required strength is low reserve factor of 2.5 is chosen.

To work out the moment the tension in the belt is needed. This is calculated using the equation (below).
Using the equation below, where m is belt mass per meter, l is belt span and f is belt frequency

$$T = 4ml^2f^2$$

- m = 2.8 kg/m
- l = 1.454m
- f = 6.482 Hz
- This gives a tension value of 994.86 N.

Using the belt tension, the maximum bending moment can be calculated. The shaft can be modelled as a shaft with a uniformly distributed load (tension) applied along the length.
The maximum bending moment is found to be $\frac{WL}{8} = \frac{T\times 0.420}{8}$ = 52.230Nm = 52230 Nmm.
Substituting the known values into the equation above:

$$d = \left[\frac{32 \times 2.5}{\pi}\sqrt{\left(\frac{52230}{124}\right)^2 + \frac{3}{4}\left(\frac{T}{27.5752}\right)^2}\right]^{1/3}$$

Assuming the torque in the shaft is similar to the maximum bending moment of 32412 Nmm, the minimum diameter is 35.07mm. The diameter used for the roller shaft is 40mm to accommodate for the assumptions made and the bearings used.

## Crowned Pulley Design

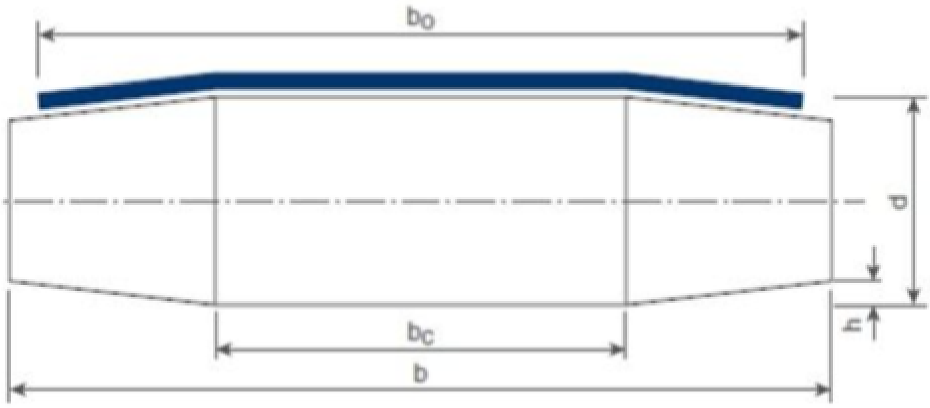



*Figure 24: Crowned pulley diagram*

In order to ensure the belt is aligned, a crowned pulley system has been designed. The diagram outlines what the overall profile of the dynamic bearing shaft sub-assembly will look like.

$$b_O = 381.8182mm$$
$$d = 40mm$$
$$b_c = \frac{B0}{2} = 190.9mm$$
$$b = B0 \times 1.1 = 420mm$$
$$h = \left(\frac{d + 100}{450}\right) = 0.311mm$$

Therefore, 0.622 (2h) of material is needed to be removed from the outer bearings.

Internal bearings need to be spaced 190.9mm across.

Having a crowned pulley design, creates a varied tension profile across the width of the belt. This keeps the belt aligned.

## Tightening Torque

Bolt stress area, $A_s = \frac{\pi}{4} \times \left(\frac{d_2+d_1}{2}\right)^2$, where $d_2$ is the pitch diameter and $d_1$ is the minor diameter.

$$A_s = \frac{\pi}{4} \times \left(\frac{5.350 + 4.773}{2}\right)^2 = 20.121mm^2$$

The maximum pre-tension load, $F_{max} = 0.75 \times A_s \times \sigma_p$, where $\sigma_p$ is the proof stress. This gives:

$$F_{max} = 0.75 \times 20.121 \times 225 = 3395.41875N$$

It is assumed that the lowest bolt grade of 4.6 is being used as the actual bolt grade being used is unknown.

Torque, $T = F \times \frac{d_m}{2} \times \frac{\tan\alpha}{(1-\mu_t \times \sec\theta \times \tan\alpha)} + F \times \frac{d_m}{2} \times \frac{\mu_t \times \sec\theta}{(1-\mu_t \times \sec\theta \times \tan\alpha)} + F \times \frac{\mu_n \times D_m}{2}$, where $d_m$ is the mean bolt diameter, $D_m$ is the nut mean diameter, $\alpha$ is the helix angle, $\theta$ is the included angle and $\mu_t$ and $\mu_n$ are the coefficient of friction in the threads and nut face respectively.

For an M6 thread, $\theta = 30$, $\alpha = 15.85$, $d_m = \frac{d+d_1}{2} = \frac{6+4.773}{2} = 5.3865mm$, $D_m = 1.25 \times 6 = 7.5$, $\mu_t = \mu_n = 0.15$ which is standard for a steel and steel interface.

$$T = 3395.41875 \times \frac{5.3865}{2} \times \frac{\tan 15.85}{(1 - 0.15 \times \sec 30 \times \tan 15.85)} + 3395.41875 \times \frac{5.3865}{2} \times \frac{0.15 \times \sec 30}{(1 - 0.15 \times \sec 30 \times \tan 15.85)} + 3395.41875 \times \frac{0.15 \times 7.5}{2}$$

$$T = 2730.59 + 1665.83 + 1909.92 = 6306.34Nmm$$

Therefore, the maximum tightening torque is 6.30Nm for the M6 bolts that interact with the frame. However, if higher grade bolts were to be used, the maximum tightening torque would increase.

## Performance

### Grease Selection

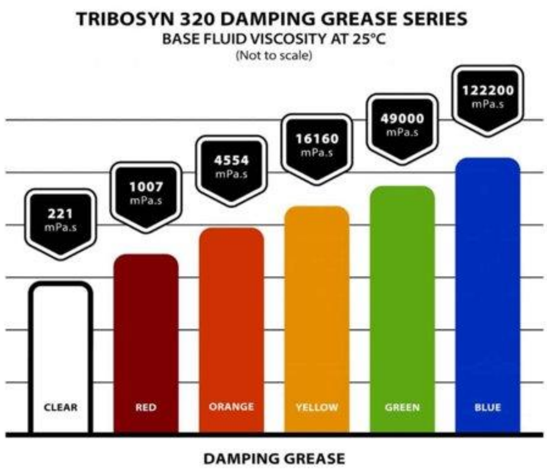



*Figure 25: Different viscosities of damping grease available [6]*

After performing the calculations in the viscous resistance section on each type of damping grease, the yellow damping grease provided the best torque and power qualities which were similar that of a conventional treadmill.

## Viscous resistance

The equation for the viscous resistance provided by a collar bearing:

$$T = \frac{\mu\pi^2 N}{60t}(R1^2 - R2^2)$$

N is the speed of the shaft in rpm. The angular velocity is related to the linear velocity by the equation: ω = V/r.

V = 1.5m/s and r = 20mm = 0.02m

Therefore, the angular velocity is ω = 75 rads/s, converting to rpm gives N = 716 rpm,

μ = 16.2 kg/ms (yellow damping oil); t = 1mm or 0.001m; R1 = 0.02m and R2 = 0.01m (bearing dimensions)

From these values the torque from each bearing is:

T = 0.2857Nm

Since there are 8 bearings the total torque is:

$T_{tot}$ = 2.2857Nm

The power generates is P = τ * ω = 171.4 watts which is similar to a standard treadmill.

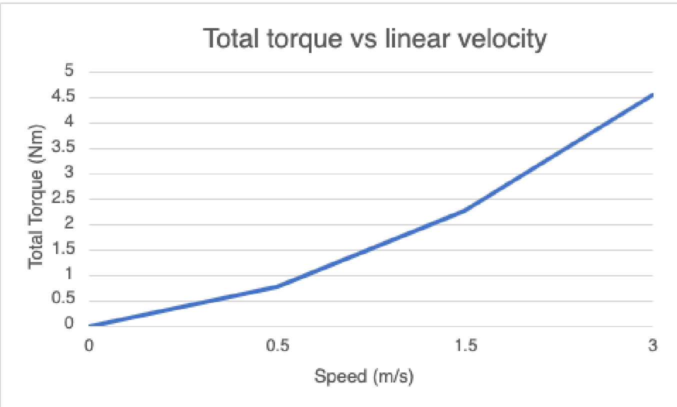



*Figure 26: A graph showing total torque generated vs linear velocity for the bearings*

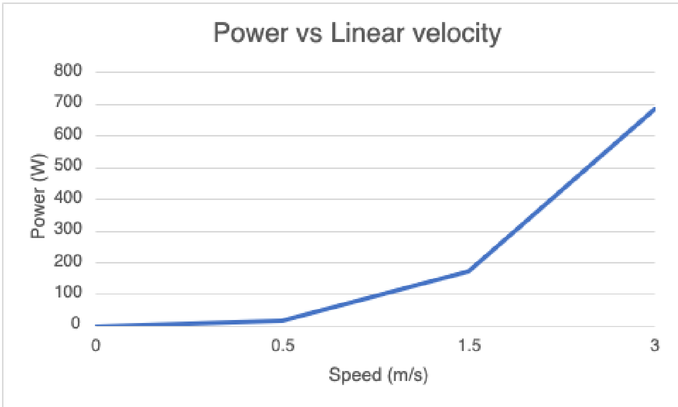



*Figure 27: A graph showing power generated vs linear velocity for the bearings*

Figures 26 and 27 clearly show a relationship between speed user and torque and power generated by the bearings. This proportionality aids to satisfy requirement 4.

## Temperature Rise

$$W = \frac{T - t}{P}$$

Where:

W = total heat dissipation per degree above ambient temperature [W/C]

T = Estimated average bearing operating temperature [C]

t= ambient temperature [C] = 21

P= bearing frictional power loss [W] = 171.4

$T_{max}$ = 130 C

$T_{min}$ = -40 C

$$W_{max} = \frac{130 - 21}{171.4} = 0.636W/C$$

$$W_{min} = \frac{-40 - 21}{171.4} = -0.356W/C$$

**Typical Properties of Tribosyn® 320 Series**

| Colour | Clear | Red | Orange | Yellow | Green | Blue |
|---|---|---|---|---|---|---|
| Appearance | Smooth & Transparent | | | | | |
| Dropping Point | >260°C | | | | | |
| Oil Separation | None | | | | | |
| Evaporation | <0.5% | | | | | |
| Oxidative Stability (150°C) | Excellent | | | | | |

*Figure 28: Properties of selected damping grease*

Assume power generation of 200W to include a factor of safety in the design.

A Rheometer, submerged in a temperature-controlled water bath, will be used to verify the change in viscosity in relation to temperature rise

## Greasing Frequency

$$T = K\left[\left(\frac{14000000}{n} \times \sqrt{D}\right) - 4D\right]$$
$$T \ = \ Regreasing\ frequency\ in\ hours$$
$$N = Shaft\ RPM \ = \ 1432RPM$$
$$D = Internal\ diameter\ of\ bearing \ = \ 20mm$$
$$K = product\ of\ correcting\ factors$$
$$Ft = Temperature = 1$$
$$Fc = Contamination = 1$$
$$Fm = Moisture = 1$$
$$Fv = vibration = 0.3$$
$$Fp = Position = 1$$
$$Fd = Bearing\ Design = 5$$
$$K = Ft \times Fc \times Fm \times Fv \times Fp \times Fd = 1.5$$
$$T = 1.5\left[\left(\frac{14000000}{1432} \times \sqrt{20}\right) - 80\right]$$
$$T = 65462.99\text{Hrs} \ = \ 7.5\text{ Years}$$

Bearings only need to be regreased every 7.5 years therefore this is not a concern during testing and presentation.

### Belt Length

$$D = Diameter\ of\ Roller = 40mm$$
$$L = Center\ Distance\ between\ Rollers = 1454.33mm$$
$$A = (D + D) \times \frac{\pi}{2} = 80 \times \frac{\pi}{2} = 125.66m$$
$$B = 2L = 2908.66mm$$
$$Belt\ Length = A + B = 3034.32mm$$

The minimum belt length must be 3034.32mm. A belt length of ******* has been ordered to factor in manufacturing tolerances.

### Friction at Interfaces

Friction Coefficient of MDF laminated is around 0.33 [7].

With a force of 1183N and using the equation F x μ = $F_{fric}$, where μ is the coefficient of friction

$F_f$ = 1183 * 0.33 = 390.39N,

This is the equivalent of lifting 39Kg. As this value is very too high, silicone oil is used to lubricate the boards. The coefficient of friction for silicone oil is 0.04 [8].

$F_r$ = 1183 * 0.04 = 47.32N

The force we are applying will be lower than this also as this is the force when running at 6 mph. More likely the force we be around 950N giving a friction force of 38N. The same lubrication with be used in the space model assuming that the surface tension should keep it all together.

### Cable Tension

Gravity is simulated using elastic cords attached to hooks at the base of the treadmill feet.

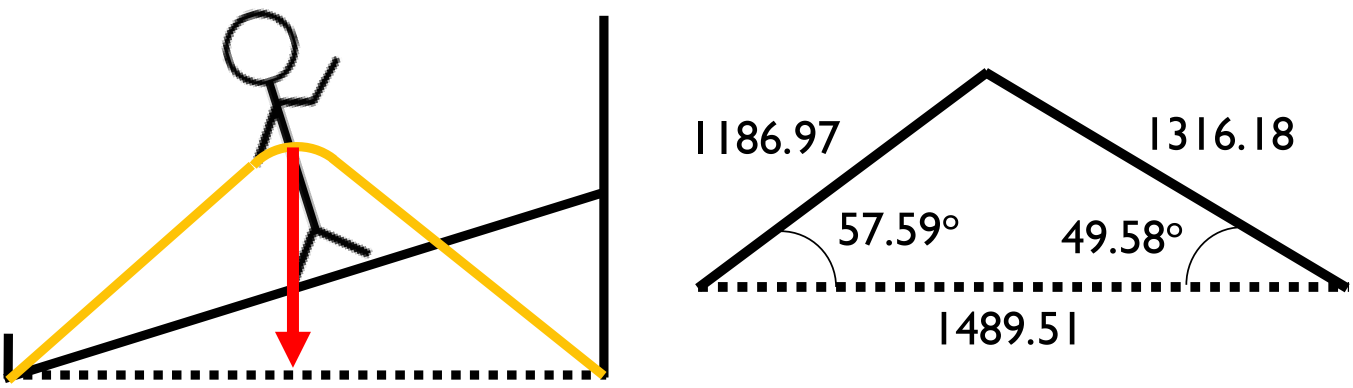



*Figure 29: Diagram showing key measurements in cable tension calculations.*

The left image shows the user on the treadmill with the cords (yellow) pulling them into the treadmill.
The diagram below displays the angles and lengths of the cords attached at the user's waist via a harness.
These dimensions are calculated using a hip height of 920mmm [9].

The gravity simulated is 120% of the earth's gravity resulting in a simulated gravity of 11.772ms$^{-2}$. For adults aged 18-64, the 50th percentile male weight is 81kg [10]. This gives a force of 953.532N.

There is one cable on each side of the treadmill, so tension created is halved for each cord:

$T = \frac{953.532}{2 \times \sin 57.59 \times \sin 49.58} = 296.95N$ of tension in each cord.

The force acting on the user will act directly downwards if the user is on the middle of the treadmill (red).
The tension in the cords will be calibrated during testing using adjustable bungee cords.

## Weight

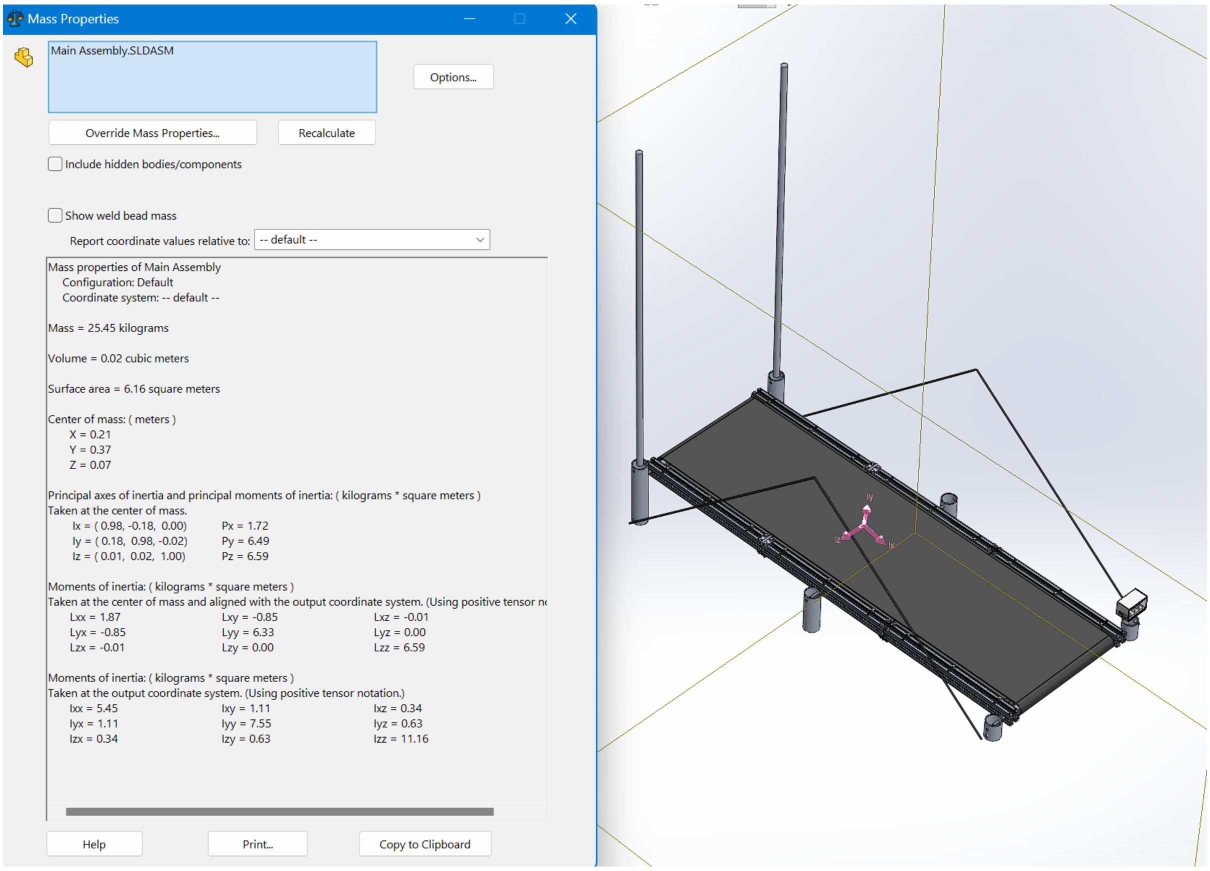



*Figure 30: Mass estimation of concept demonstration treadmill using SOLIDOWORKS*

Final Mass of 25.45Kg for the concept demonstration. This is an estimate due to variations in Solidworks materials and manufacturing tolerances. The final mass of the system will be evaluated during the testing phase.

## Computer-Based Simulations

A fine mesh was used during FEA to ensure accuracy in the simulations.

### Displacement Analysis

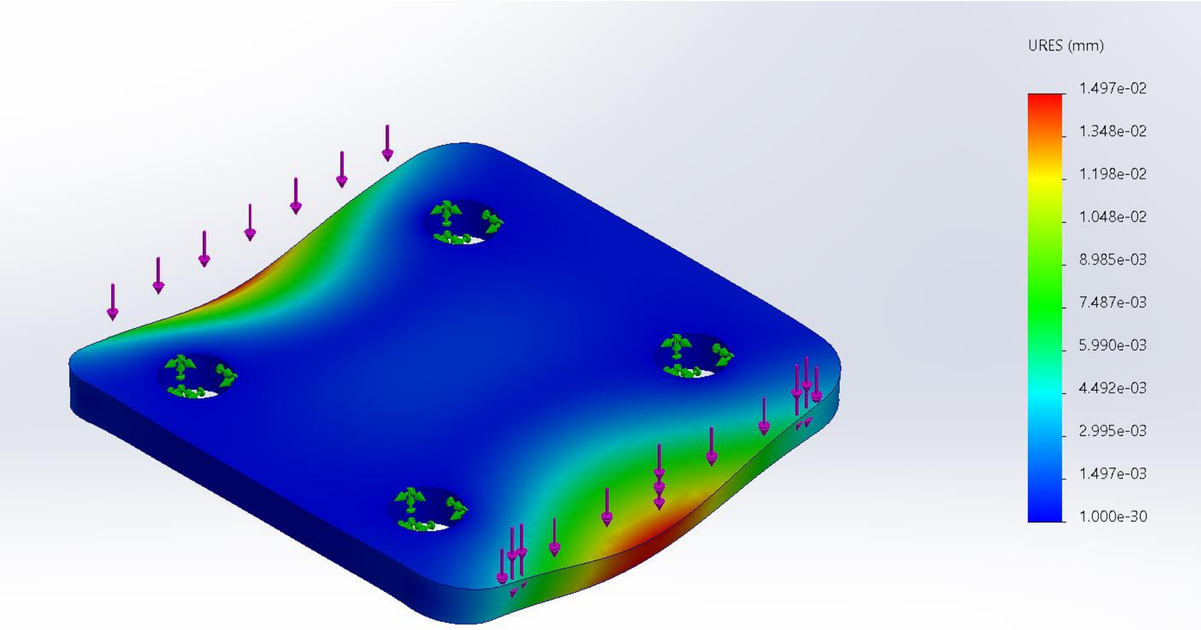



*Figure 31: Displacement plot for the steel plate using SOLIDWORKS FEA*

This static study ensures that the plate, supporting the frames, will not fail as the maximum displacement is 0.01497mm.

### Factor of Safety Plot

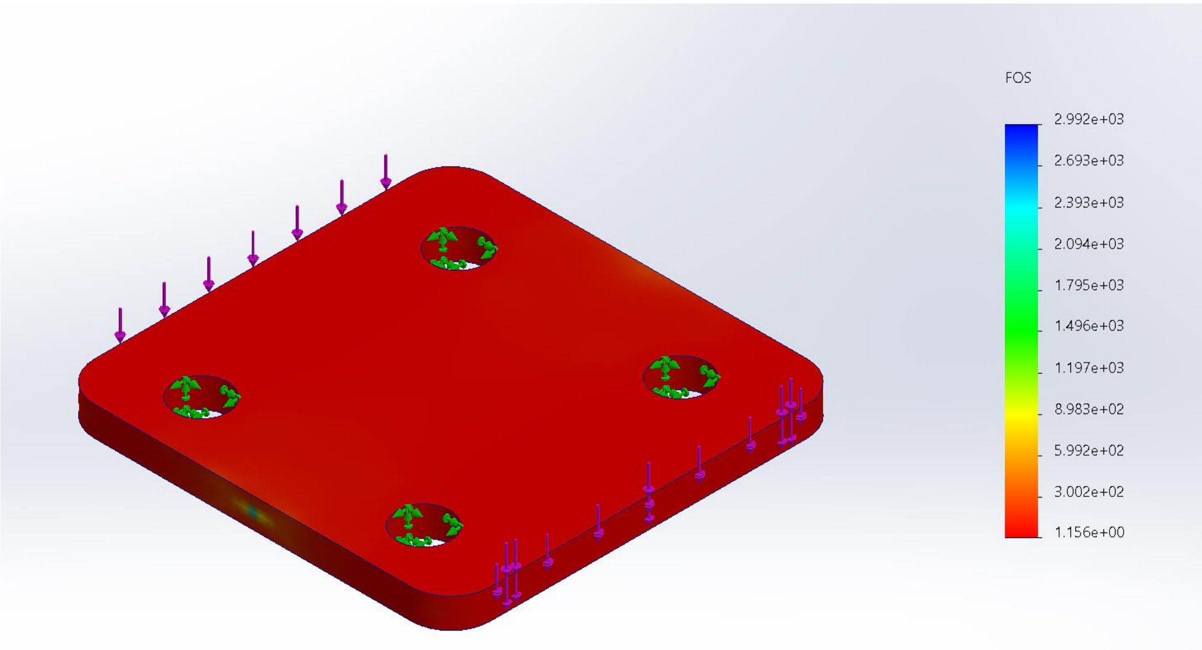



*Figure 32: Factor of safety plot for the steel plate using SOLIDWORKS FEA*

Factor of safety plot shows that the plate is suitable safe for additional loads.

# Space Concept Calculations

These calculations are used to guide the design process for the Solidworks model. FEA was then used to refine the model.

## Structural

### Board Bending

Using carbon fibre boards with a 7GPa young's modulus;

$$7x10^9 \times \frac{0.5\ x\ d^3}{12} x0.005 = \frac{592x0.21^3}{6} - \frac{Px0}{6} + \left(\frac{2}{0.42}\right)\left(7x10^9 \times \frac{0.5\ x\ d^3}{12} \times 0.005 - \frac{592x0.21^3}{6}\right)$$

$$1458333.3d^3 = 0.913752 + \left(\frac{2}{0.42}\right)(1458333.3d^3 - 0.913752)$$
$$5486111.111d^3 = 3.437448$$

$$d = 8.5mm$$

The minimum thickness of the carbon fibre boards must be 8.5mm This has been designed to in Solidworks.

### Frame Bending

The treadmill is used with the frames in contact with the floor, therefore they will not bend.

### Frame Stress

Using titanium and a different frame with a different cross-sectional area

$$\sigma = \frac{F}{A}$$
$$F = 1183N\ and\ A = 0.024m^2$$
$$\sigma = \frac{1183}{0.024} = 49.3KPa$$
$$\tau = \frac{Tr}{J}$$

Modelling the bar as a circle with radius 20mm for simplified torsion equation:

$$J = \frac{\pi\ x\ 0.0015^4}{2} = 7.952x10^{-8}$$
$$\tau = \frac{1183x0.21x0.015}{7.952x10^{-8}} = 46.86MPa$$

Maximum tensile stress of titanium is 240MPa and UTS is 1000MPa so the frames will not break.

## Shaft Diameter

$$d = \left[\frac{32n_s}{\pi}\sqrt{\left(\frac{M}{\sigma_e}\right)^2 + \frac{3}{4}\left(\frac{T}{\sigma_y}\right)^2}\right]^{\frac{1}{3}}$$

Where:

d = shaft diameter (mm)

$n_s$ = reserve factor

M = maximum bending moment (Nmm)

$\sigma_e$ = endurance stress (MPa)

T = maximum transmitted torque

$\sigma_y$ = yield strength (MPa)

A reserve factor of between 2~2.5 is used for average materials.

To work out the minimum diameter for the roller shaft, the variables seen in the diagram (above) are needed.

Yield strength for titanium is 241000000 Pa = 241 MPa.
Endurance stress is 0.4 x UTS = 0.4 x 1170 MPa = 468 MPa.
Reserve factor is (actual strength/required strength) and since required strength is low reserve factor of 2.5 is chosen.

To work out the moment the tension in the belt is needed. This is calculated using the equation (below).
Using the equation below, where m is belt mass per meter, L is belt span and f is belt frequency.

$$T = 4ml^2f^2$$

- m = 1.4 kg/m
- l = 0.67m
- $f^2$ = 1.68 Hz
- This gives a tension value of 19.90 N.

Using the belt tension, the maximum bending moment can be calculated. The shaft can be modelled as a shaft with a uniformly distributed load (tension) applied along the length.
The maximum bending moment is found to be $\frac{WL}{8} = \frac{T\times 0.406}{8}$ = 1.009799Nm = 1009.779Nmm.
Substituting the known values into the equation above:

$$d = \left[\frac{32 \times 2.5}{\pi}\sqrt{\left(\frac{1009.779}{468}\right)^2 + \frac{3}{4}\left(\frac{T}{241}\right)^2}\right]^{1/3}$$

Assuming the torque in the shaft is similar to the maximum bending moment of 1009.779 Nmm, the minimum diameter is 4.75. The diameter used for the pulley shaft is 8mm to accommodate for the assumptions made and the bearings used.

# Performance

## Weight

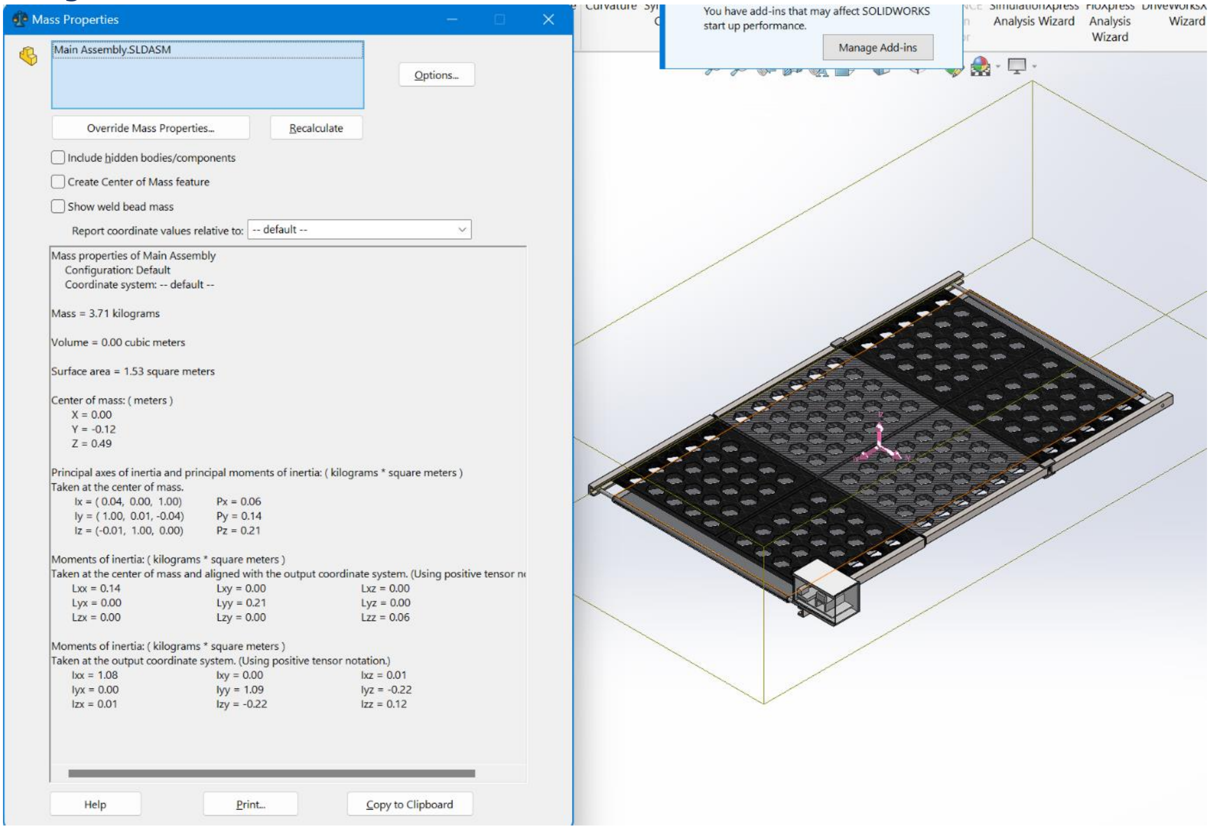



*Figure 33: Mass estimation of the space concept in SOLIDWORKS*

Final weight of the space CAD model is 3.71Kg. An allowance of 1.29Kg has been given for the cables and harness which is more than appropriate.

# Computer Based Calculations

## Topology study

For the space gym, carbon fibre was used to increase the strength and reduce the overall weight of the boards.

The properties for carbon fibre were taken from the mass density on Solidworks and the properties from the table below:

| Property | Value | Units |
|---|---|---|
| Elastic Modulus in X | 30457919.08 | psi |
| Poisson's Ration in XY | 0.28 | N/A |
| Shear Modulus in XY | 11457979.08 | psi |
| Mass Density | 0.27818 | lb/in^3 |
| Tensile Strength in X | 104982.01 | psi |
| Compressive Strength in X | | psi |
| Yield Strength | 89984.59 | psi |
| Thermal Expansion Coefficient in X | 1.3e-005 | /°F |
| Thermal Conductivity in X | 0.000668738 | Btu/(in·sec·°F) |
| Specific Heat | 0.109869 | Btu/(lb·°F) |
| Material Damping Ratio | | N/A |

*Figure 34: Carbon fibre material properties [11]*

A finite element analysis was used to find the areas in the boards where hexagons can be cut to reduce the weight further. This first study showed that the middle of the boards were subject to the largest stresses, and the weight could be reduced on either side of the middle.

Stress:

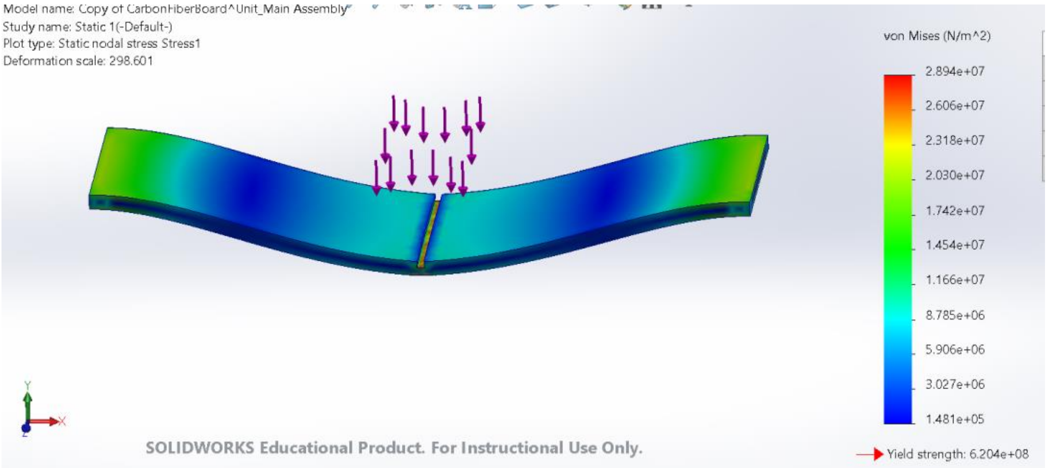



*Figure 35: Stress plot on the carbon fibre boards using SOLIDWORKS FEA*

Deflection:

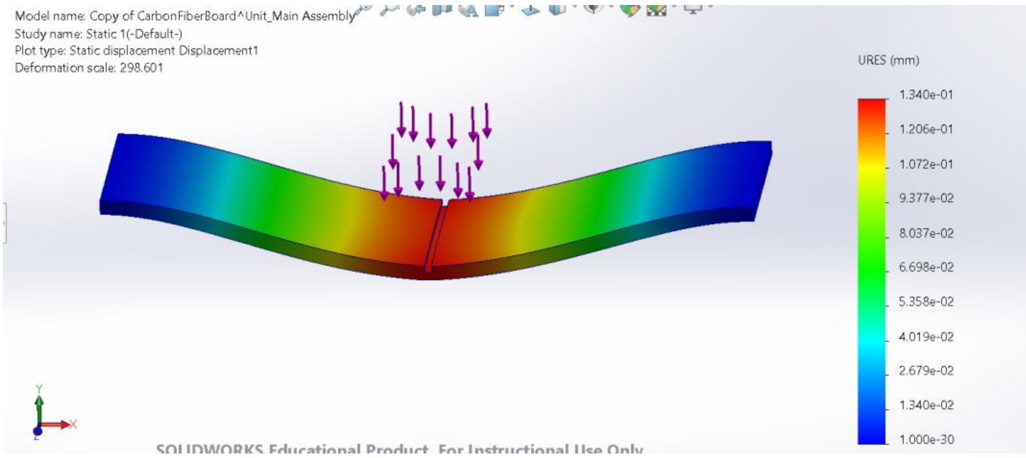



*Figure 36: Deflection plot on the carbon fibre boards using SOLIDWORKS FEA*

Once adding Hexagons 11mm size and 5mm cut into the board. The boards are 9mm thick and weigh 1.2kg each. As shown again by the analysis the boards are still well in the von Mises yield criteria shown on solid works and still have minimal deflection.

Stress:

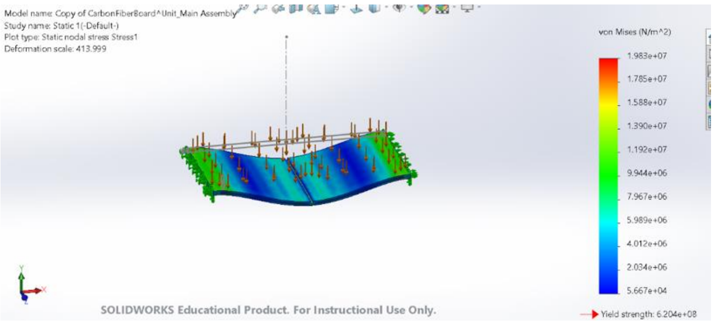



Figure 37: Stress plot on refined carbon fibre boards using SOLIDWORKS FEA

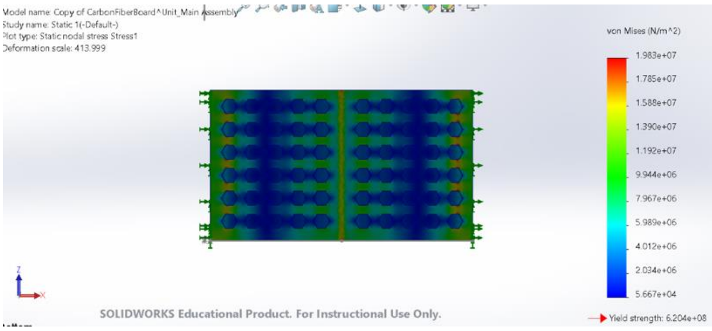



Figure 38: Stress plot on refined carbon fibre boards using SOLIDWORKS FEA (plan view)

Deflection:

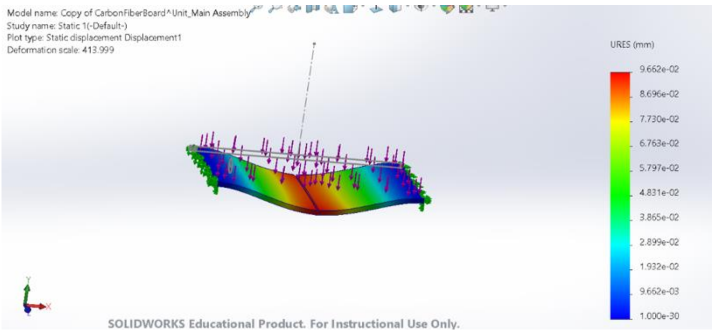



Figure 39: Deflection plot on refined carbon fibre boards using SOLIDWORKS FEA

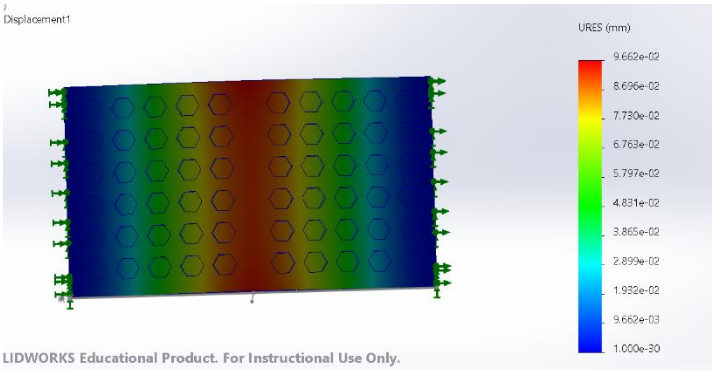



Figure 40: Deflection plot on refined carbon fibre boards using SOLIDWORKS FEA (plan view)

To reduce the weight further we increased the size of the 11mm Hexagons to 12mm with a 7mm cut. The boards were also reduced to 8mm thick. These boards are just under 1kg each.

Stress:

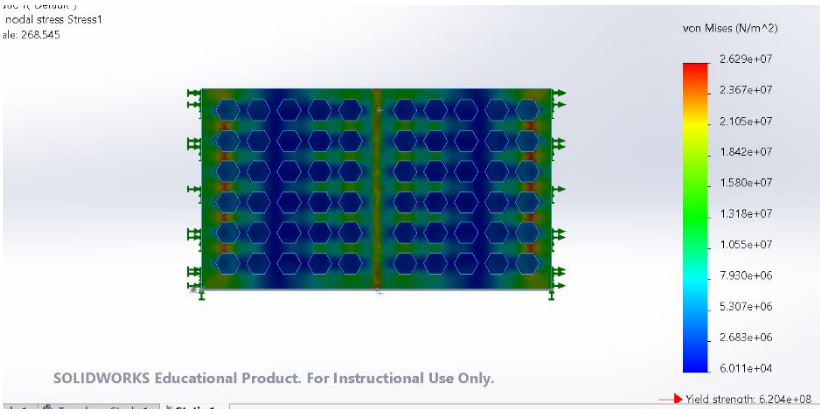



Figure 41: Stress plot on fully refined carbon fibre boards using SOLIDWORKS FEA

Deflection:

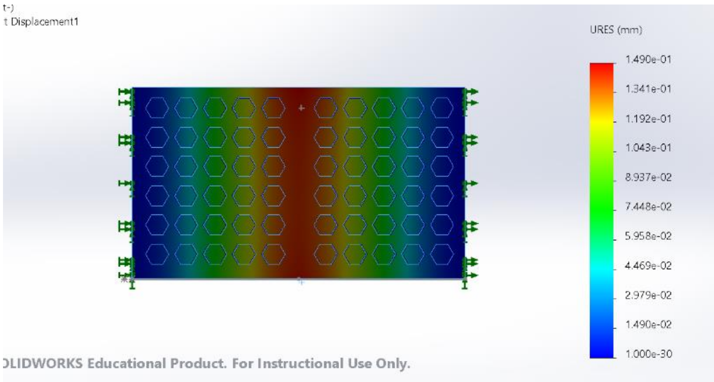



*Figure 42: Deflection plot on fully refined carbon fibre boards using SOLIDWORKS FEA (plan view)*

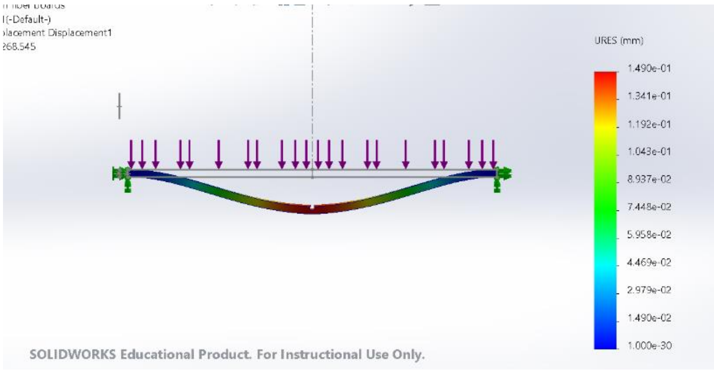



Figure 43: Deflection plot on fully refined carbon fibre boards using SOLIDWORKS FEA (side view)

Maximum displacement – 0.14mm
These FEA simulations have verified the 'space' boards have been suitably designed.

## Frame Static Studies

For the frames, a static test was run with a remote load applied. This was done as the force is applied on the boards not directly on the frames. As shown below the frames are more than strong enough the hold the loads applied. The following results were produced:

Deflection:

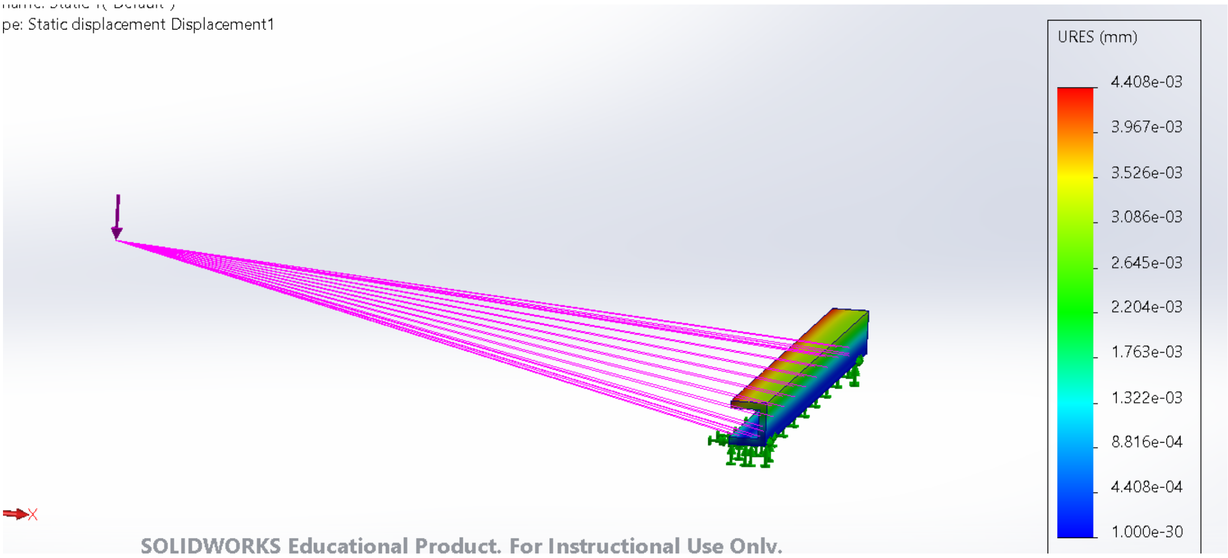



*Figure 44: Deflection plot on the frames using SOLIDWORKS static test.*

Stress:

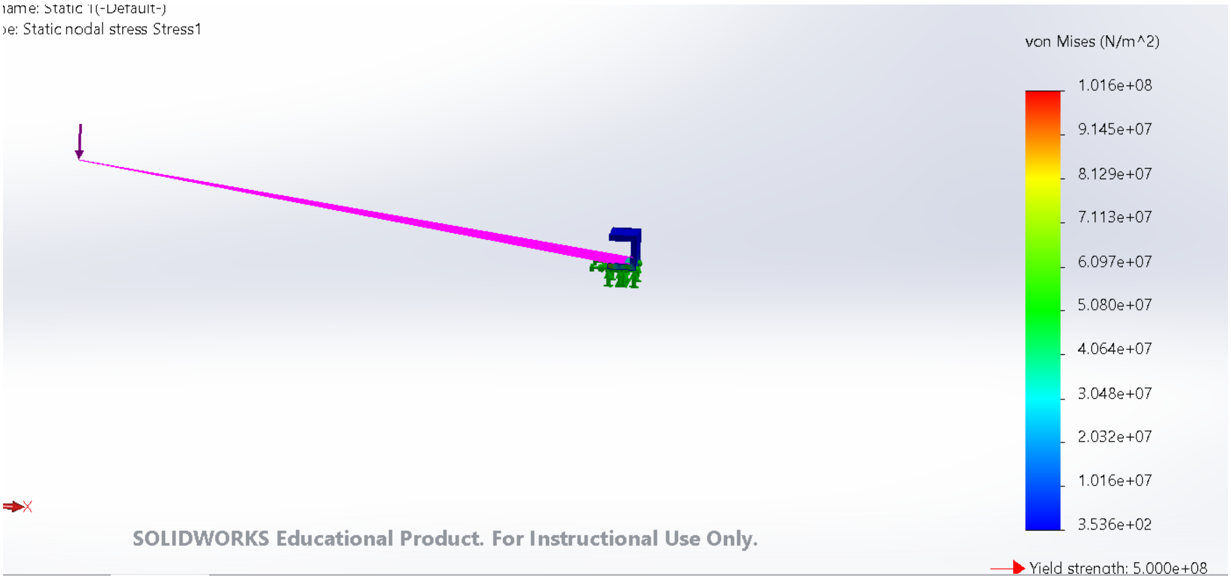



*Figure 45: Stress plot on the frames using SOLIDWORKS static test.*

As the boards are in between the titanium frames this FEA may not be accurate but from the model we can be sure that the frames will not break.

## Budgeting

Total budget: £460.84. The budget increase from £350 to £500 has been approved by the module convenor Alastair Campbell-Ritchie.

The University has a 20% discount on all RS Component orders. This has not been factored into the budget.

### Mechanical Budget

| Item | Supplier | Price | Quantity per Unit | Quantity To Order | Sub Total | Lead Times (Days) |
|---|---|---|---|---|---|---|
| Plain Bearings | igus | £7.76 | 1 | 8 | £62.11 | 1 |
| MDF Boards | cutmyplastic | £63.78 | 1 | 1 | £63.78 | 5 |
| Belt | Repuestos Fitness | £100.96 | 1 | 1 | £100.96 | 6 |
| All Feet | Metal Supermarkets | £54.40 | 1 | 1 | £54.40 | |
| Hinges | RS Components | £13.17 | 2 | 2 | £26.34 | 1 |
| Steel Plate | Metals4U | £0.76 | 1 | 1 | £0.76 | 4 |
| M8 T Bolt | RS Components | £11.97 | 10 | 1 | £11.97 | 1 |
| Circlip | RS Components | £7.42 | 50 | 1 | £7.42 | 1 |
| Roller Shaft | UoN L-2 Stores | £9.07 | 1 | 1 | £9.07 | |
| Cables | Amazon | £18.99 | 4 | 1 | £18.99 | 1* |
| Hiking Poles | Decathlon | £5.99 | 1 | 2 | £11.98 | 3 |
| Dampening Grease | NewGate Simms | £25.00 | 1 | 1 | £25.00 | 5 |
| **TOTAL** | | | | | £392.78 | |

*Table 3: Mechanical budget with suppliers, price and lead times. Total mechanical spend amounts to £392.78.*

Note – Re. CDR review feedback, MDF board is available in 25mm thickness.

### Electronic Budget

| Item | Supplier | Price | Quantity per Unit | Quantity To Order | Sub Total | Lead Times (Days) |
|---|---|---|---|---|---|---|
| Arduino | Arduino | £21.00 | 1 | 1 | £21.00 | Ordered |
| 3V to 5V DC-DC Boost converter with USB output charger | Amazon | £6.41 | 1 | 1 | £6.41 | Ordered |
| TP4056 Lithium battery Module | Amazon | £7.25 | 1 | 1 | £7.25 | Ordered |
| Bluetooth Module (HC-05/HC-06) | Amazon | £12.99 | 1 | 1 | £12.99 | Ordered |
| Hall effect sensor (US1881/04E) | Spark Fun | £1.00 | 1 | 1 | £1.00 | Ordered |
| 18650 Lithium Cell | Argos | £14.00 | 1 | 1 | £14.00 | Ordered |
| Small piece of magnets | First4Magnets | £5.41 | 4 | 1 | £5.41 | |
| Perf Board | | | | | £0.00 | |
| Berg sticks connectors (Male and female) | | | | | £0.00 | |
| **TOTAL** | | | | | £68.06 | |

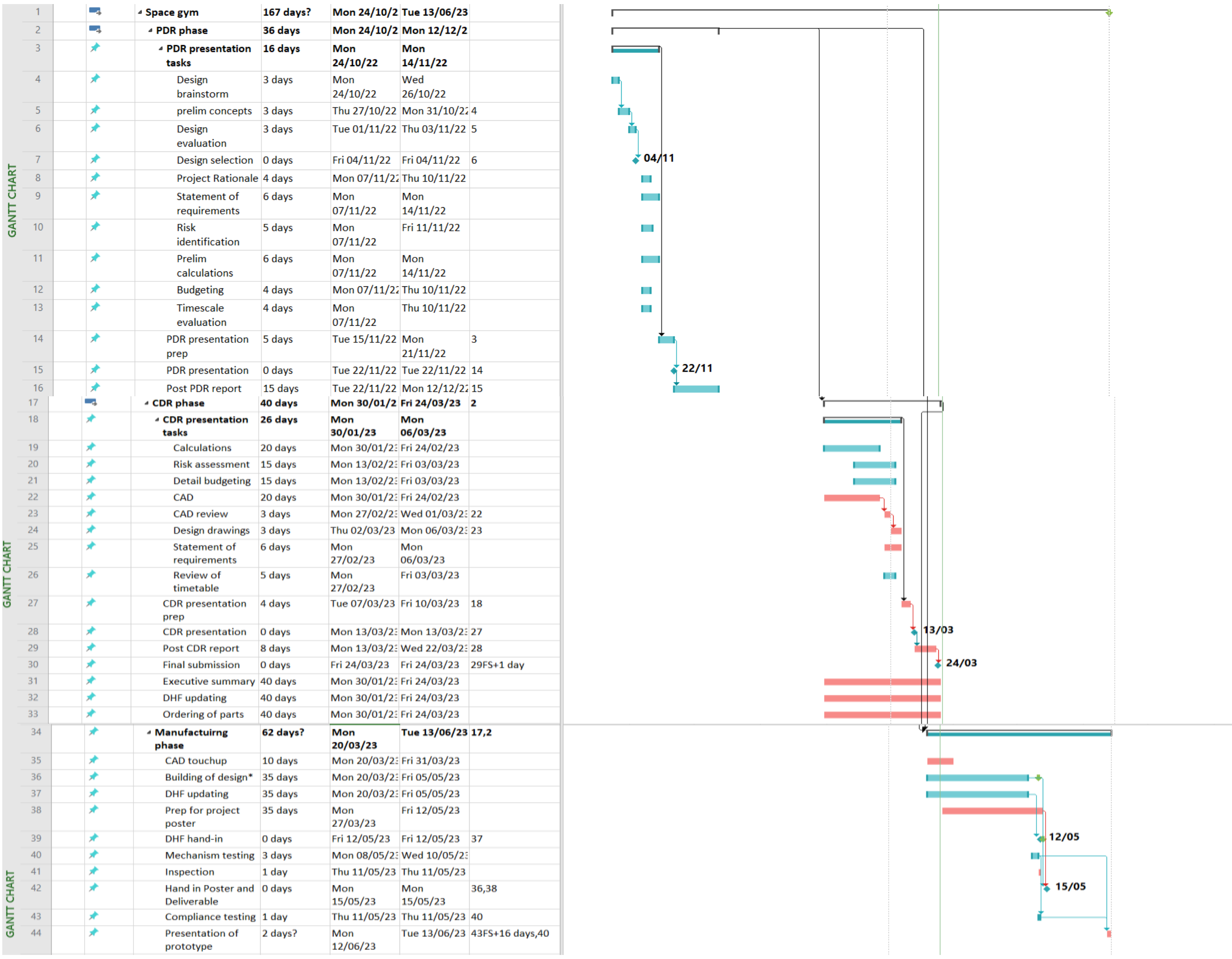
*Table 4: Electrical budget with suppliers, price, and lead times. Total electrical spend amounts to £68.06.*

## Contingency Plan

In case of parts not being available from certain suppliers, we have selected some backup suppliers to ensure parts can be ordered if unavailable from the first-choice supplier.

| **Item** | **Backup Supplier** |
|---|---|
| Plain Bearings | RS Components |
| MDF Board | Woodsheets.com |
| Feet | Gym Parts by Expert Fitness UK |
| T-Bolts | Metals4U |
| Shaft Collar | On Fabrication |
| Roller Shaft | Misumi |
| Hiking Poles | Go Outdoors |
| Magnets | Amazon (all amazon products can be sources from alternative amazon suppliers) |

# Project Timetables




| | | | | | |
|---|---|---|---|---|---|
| 1 | Space gym | 167 days? | Mon 24/10/2 | Tue 13/06/23 | |
| 2 | PDR phase | 36 days | Mon 24/10/2 | Mon 12/12/2 | |
| 3 | PDR presentation tasks | 16 days | Mon 24/10/22 | Mon 14/11/22 | |
| 4 | Design brainstorm | 3 days | Mon 24/10/22 | Wed 26/10/22 | |
| 5 | prelim concepts | 3 days | Thu 27/10/22 | Mon 31/10/2: | 4 |
| 6 | Design evaluation | 3 days | Tue 01/11/22 | Thu 03/11/22 | 5 |
| 7 | Design selection | 0 days | Fri 04/11/22 | Fri 04/11/22 | 6 |
| 8 | Project Rationale | 4 days | Mon 07/11/2: | Thu 10/11/22 | |
| 9 | Statement of requirements | 6 days | Mon 07/11/22 | Mon 14/11/22 | |
| 10 | Risk identification | 5 days | Mon 07/11/22 | Fri 11/11/22 | |
| 11 | Prelim calculations | 6 days | Mon 07/11/22 | Mon 14/11/22 | |
| 12 | Budgeting | 4 days | Mon 07/11/2: | Thu 10/11/22 | |
| 13 | Timescale evaluation | 4 days | Mon 07/11/22 | Thu 10/11/22 | |
| 14 | PDR presentation prep | 5 days | Tue 15/11/22 | Mon 21/11/22 | 3 |
| 15 | PDR presentation | 0 days | Tue 22/11/22 | Tue 22/11/22 | 14 |
| 16 | Post PDR report | 15 days | Tue 22/11/22 | Mon 12/12/2: | 15 |
| 17 | CDR phase | 40 days | Mon 30/01/2 | Fri 24/03/23 | 2 |
| 18 | CDR presentation tasks | 26 days | Mon 30/01/23 | Mon 06/03/23 | |
| 19 | Calculations | 20 days | Mon 30/01/2: | Fri 24/02/23 | |
| 20 | Risk assessment | 15 days | Mon 13/02/2: | Fri 03/03/23 | |
| 21 | Detail budgeting | 15 days | Mon 13/02/2: | Fri 03/03/23 | |
| 22 | CAD | 20 days | Mon 30/01/2: | Fri 24/02/23 | |
| 23 | CAD review | 3 days | Mon 27/02/2: | Wed 01/03/2: | 22 |
| 24 | Design drawings | 3 days | Thu 02/03/23 | Mon 06/03/2: | 23 |
| 25 | Statement of requirements | 6 days | Mon 27/02/23 | Mon 06/03/23 | |
| 26 | Review of timetable | 5 days | Mon 27/02/23 | Fri 03/03/23 | |
| 27 | CDR presentation prep | 4 days | Tue 07/03/23 | Fri 10/03/23 | 18 |
| 28 | CDR presentation | 0 days | Mon 13/03/2: | Mon 13/03/2: | 27 |
| 29 | Post CDR report | 8 days | Mon 13/03/2: | Wed 22/03/2: | 28 |
| 30 | Final submission | 0 days | Fri 24/03/23 | Fri 24/03/23 | 29FS+1 day |
| 31 | Executive summary | 40 days | Mon 30/01/2: | Fri 24/03/23 | |
| 32 | DHF updating | 40 days | Mon 30/01/2: | Fri 24/03/23 | |
| 33 | Ordering of parts | 40 days | Mon 30/01/2: | Fri 24/03/23 | |
| 34 | Manufactuirng phase | 62 days? | Mon 20/03/23 | Tue 13/06/23 | 17,2 |
| 35 | CAD touchup | 10 days | Mon 20/03/2: | Fri 31/03/23 | |
| 36 | Building of design* | 35 days | Mon 20/03/2: | Fri 05/05/23 | |
| 37 | DHF updating | 35 days | Mon 20/03/2: | Fri 05/05/23 | |
| 38 | Prep for project poster | 35 days | Mon 27/03/23 | Fri 12/05/23 | |
| 39 | DHF hand-in | 0 days | Fri 12/05/23 | Fri 12/05/23 | 37 |
| 40 | Mechanism testing | 3 days | Mon 08/05/2: | Wed 10/05/2: | |
| 41 | Inspection | 1 day | Thu 11/05/23 | Thu 11/05/23 | |
| 42 | Hand in Poster and Deliverable | 0 days | Mon 15/05/23 | Mon 15/05/23 | 36,38 |
| 43 | Compliance testing | 1 day | Thu 11/05/23 | Thu 11/05/23 | 40 |
| 44 | Presentation of prototype | 2 days? | Mon 12/06/23 | Tue 13/06/23 | 43FS+16 days,40 |

*Figure 46: Gantt Chart displaying project timetable*

## Gantt Chart

The project is timetabled using a Gantt chart. This allows the project's health to be continuously monitored.

A critical path is generated which outlines the shortest path of tasks required to complete the project. If delays occur to the critical path, the project's health could deteriorate.

This Gantt chart is split into phases: the PDR, CDR, and manufacturing phases. Each of these phases and then split into various tasks. Not only does this allow for the project's health to be monitored, but it also breaks down the large project into several 'more easily digestible' tasks which makes the project easier to complete.

Milestones are included throughout the Gantt chart, highlighted as diamonds. This signifies significant progress throughout the project. Milestones include, but are not limited to, the CDR presentation and the post-CDR report document.

Additionally, green arrows represent hard deadlines that must be met. For instance, the green arrow next to the 'building of design' indicates the hard deadline for the 10$^{th}$ of May. Moreover, the asterisk next to this task indicates that it can be completed throughout the easter vacation. This is dependent on group member and workshop availability.

In the GDM handbook, the presentation is confirmed to be between the 5$^{th}$ and 7$^{th}$ of June. However, the compliance testing must be completed before the 11$^{th}$ of May. This is included in the Gantt chart as a time lag.

## Full Fabrication Plan

### Manufacturing

The manufacturing plan is an outline of the operations needed to build the treadmill. It describes the machines and special tools needed to complete these tasks as well as the group members responsible for each operation. The manufacturing plan is a simplified description of the operation, and the process sheets should be referred to for a more detailed description.

Manufacturing Plan

The University of Nottingham

| Sequence No | Part/Operation Description | Operator | Equipment Needed | Estimated Fabrication Time (minutes) | Notes |
|---|---|---|---|---|---|
| **1.** | Frame manufacture: Mark and cut 3m length Rexroth frames to 6 equal frames of required length. | Ben, Nana | Buzzsaw | 90 | Mark length using pencil and ruler. |
| **2.** | Drill 16x M3 pilot holes. Drill x16 M6 through holes total on the frames for hinges. | Amil | Milling | 180 | Allows attachment of hinges |
| **3.** | Drill 6x M3 pilot holes. Drill x6 more M6 through holes total for boards. | Ben | Milling | 90 | Allows attachment of boards |
| **4.** | Attach hinges to Rexroth frames using M8 bolts and nuts. | Nana | Spanner/Ratchet | 60 | |
| **5.** | MDF board manufacture: Cut Large MDF board into 3 new MDF boards. 2 end boards with the same width and length and 1 middle board with a different length, all the same thickness. | Amil | Buzzsaw | 120 | Mark with pencil and ruler where cuts are required |
| **6.** | Cut out notch on all MDF boards on both long edges. | Amil | Milling Machine | 180 | |

| Group No 3 | Sheet 1 of 6 |
|---|---|

## Manufacturing Plan

| | | | | | |
|---|---|---|---|---|---|
| **7.** | Bearing shaft manufacturing: Cut 1000mm aluminium shaft into two shafts of required lengths. | Harry | Buzzsaw | 60 | Mark length needed using pencil and ruler |
| **8.** | Drill pilot hole of M4. Drill M8 holes into each side of both shafts of required depth. | Harry | Milling machine | 90 | |
| **9.** | Cut circlip grooves into the shaft ensuring they are only 0.5mm deep. | Harry | Lathe | 90 | |
| **10.** | Bearing manufacture: Of the 8 bearings available sand down 4 of the bearings by 0.622 mm. | Nana | File | 90 | |
| **11.** | Add viscous grease to inside of all 8 bearings. Then move the pivot around to spread the grease throughout the bearing. | Nana | | 60 | |
| **12.** | Slide 4 bearings on each bearing shaft, with the sanded down bearings being closest to the frame (external) and the non-altered bearing should be closest to the centre of the shaft (internal). Each bearing should be placed in between the circlip grooves. | Nana, Ben | | 90 | |

| | |
|---|---|
| **Group No**<br>**3** | **Sheet 2 of 6** |

## Manufacturing Plan

| | | | | | |
|---|---|---|---|---|---|
| **13.** | Insert circlips into the circlip grooves on each side of each bearing. | Nana | | 60 | Bearings should not be able to move along the shaft |
| **14.** | Use super glue and bicarbonate of soda to glue magnet (used for hall sensor) to one of the edge bearings on the rear roller. | Nana | | 30 | |
| **15.** | Paint markings on belt at appropriate positions. | Harry | Paint and paintbrush | 60 | Refer to BSI standards for spacing |
| **16.** | Slide in all boards into frames, drill 3 through holes per board (through the frames). | Amil, Jack | Milling machine | 120 | Make sure frame and boards line up |
| **17.** | Lock boards in place by sliding bolts through frame and boards securing with a nut on the other side. | Jack | | 30 | |
| **18.** | Wrap belt around the boards and the shafts. | Jack | | 40 | The belt should not be tensioned at this point |
| **19.** | Attach bearing shafts to frame either side by pulling the belt around the shaft and the tightening the T-nuts which should tension the | Amil | | 60 | |

| | |
|---|---|
| **Group No**<br>**3** | **Sheet 3 of 6** |

## Manufacturing Plan

| | | | | | |
|---|---|---|---|---|---|
| | belt at the same time. Do this for both bearing shafts. | | | | |
| **20.** | Front feet manufacturing: cut tubes 2x to size (2 equal length tubes). | Ben, Amil | Buzzsaw | 180 | |
| **21.** | Drill M8 through holes into both tubes for a T Nut and M10 through hole for hook. | Ben | Milling machine | 120 | |
| **22.** | Rear feet manufacturing: cut aluminium tube to two tubes of desired length. | Harry | Buzz saw | 60 | |
| **23.** | Drill x2 M6 through holes on both 60mm aluminium tubes. | Harry | Milling machine | 90 | |
| **24.** | Middle feet manufacturing: cut down remaining aluminium tube into 2 tubes of required length. | Jack | Buzzsaw | 60 | Remainder of aluminium tube comes from spare material for rear feet |
| **25.** | Drill M6 through hole in both tubes. | Jack | Milling machine | 60 | |
| **26.** | Electronic assembly: 3D print housing for electronics. | Harry | 3D printer | Multiple days (passive) | |
| **27.** | Shave down any excess plastic protruding from the housing. | Harry | Filer | 60 | |



## Manufacturing Plan

| | | | | | |
|---|---|---|---|---|---|
| **28.** | Steel plate manufacturing: Cut 40x80x3mm metal sheet into 2 sheets. | Nana | Buzzsaw | 60 | |
| **29.** | Drill 4x M6 through holes into plate. | Nana | Milling machine | 80 | |
| **30.** | Solder electronic components to Arduino board. | | | 240 | This is to be done by electrical technicians. |
| **31.** | Super glue + bicarbonate of soda to attach housing to frame and let dry. | Jack | | 40 (overnight to dry) | |
| **32.** | Bolt (M6 bolt) on all feet to frame. | Amil | | 90 | |
| **33.** | Attach hall sensor with adhesive to housing/ frame near where magnet is attached. Test the hall sensor. | Jack | | 40 (overnight to dry) | Location of hall sensor not imperative |
| **34.** | Connect phone to Arduino using Bluetooth before the app is started up. | User | | 10 | |
| **35.** | Set up telescopic handles by extending both the smallest and medium diameter out of the largest diameter tube for both sides. Slide a M6 bolt through the holes. Tighten using an M6 nut to keep bolt in place | User | | 50 | Holes should be located as follows: (Top largest, bottom medium / Top medium, bottom smallest) |

# Manufacturing Plan

| | | | | | |
|---|---|---|---|---|---|
| **36.** | Remove nuts used to keep hinges in place and attach the steel plate using the same bolts used to attach hinges. Reapply nuts to bolts now also keeping steel plate in place | User | | 70 | Bolts used should be long enough to go through hinges frame and steel plate. |
| **37.** | Attach hooks from harness to M10 holes in both the front and back feet | User | | 20 | Bungee ropes should be appropriately tense |
| **38.** | Open app, expand hiking poles, insert hiking poles in front feet and use treadmill | User | | 2 | |

*Figure 47: Manufacturing plan including operations, operators and estimated times*

## Process Sheet

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| **1.** | Mark area and cut board 1400x450x25mm down to 2 440x445x25mm boards | Buzzsaw | | Use rule and pencil to mark cutting points |
| **2.** | Cut 12.5x15mm notch into long edge of both boards | | | Refer to drawings for clear dimensions |
| **3.** | File sharp edges. | | File | |
| **4.** | Clean part. | | | |
| **5.** | Slide boards in frames as guides for next drilling operation | | | Slide all 3 MDF boards into Rexroth frames at the same. |
| **6.** | Drill 6x M6 through holes using frame holes as a guide. | Milling machine | | Complete operation in tandem to frames operation No.4 |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 3 | 2 | End MDF Boards | MDF | |

*Figure 48: Process sheet for End MDF boards, outlining manufacturing process*

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| **1.** | Mark lengths referring to drawing, use sawing station to cut 3m long Rexroth frames into 6 sections of 500mm length. | Buzzsaw | - | Use rule and pencil to mark cutting points |
| **2.** | Drill x4 per frame M6 through holes total for hinges 6mm from long edge and 10.17mm from short edge. | Milling machine | - | |
| **3.** | Slide in boards into frame as guides for next drilling operation | - | - | |
| **4.** | Drill x3 per side per frame M6 holes for boards referring to detailed drawings for placement. | Milling machine | - | Do operation in tandem to middle MDF board operation NO. 7 and end MDF boards operation No. 6 |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 1 | 1 | Treadmill Frames | Aluminium | |

*Figure 49: Process sheet for treadmill frames, outlining manufacturing process*

## Testing Plan

The testing plan outlines how the system will be tested. It provides a logical step-by-step plan to ensure that the user and the device will remain safe. Testing risks have been outlined in the risk assessment section of this report.

The University of Nottingham

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| 1. | Durability testing - incrementally add weights to treadmill to ascertain the mechanical strength of the treadmill | - | Weights | Weight is incrementally added until 81kg is reached |
| 2. | Endurance testing - Add weights onto to the treadmill over an extended period, drop masses from set distance (10mm) and check structural integrity when treadmill is impacted | - | Weights | Masses in question should 0.75 x the user's weight |
| 3. | Temperature testing – use temperature probe around high-risk areas such as between bearing and roller, area between belt and roller as well. Ensure grease remains between –40 and 130 deg. C to maintain correct viscosity. | - | Thermometer | |
| 4. | Viscous resistance testing – The viscous fluid applied to the bearings to allow a resistive force will have its viscosity checked via a rheometer | - | Rheometer | |
| 5. | Electric compliance – Measure current and voltage in circuit under use to check potential power surges that could damage electronic components | - | Voltmeter | |
| 6. | Folding package testing – During folding check if treadmill locking system is engaged and that the entire running track is safely locked away as well | - | | |
| 7. | App compliance – Check Arduino coding and connectivity to phone to allow app to work. | - | Phone<br>Laptop | Check for functions of apps – accuracy of speed measurements that the app will report back to user |
| 8. | Noise testing – Measure sound pressure level that user is exposed to. 70 dBA for over 24 hours (maximum value to offset damage to ear), as for negating indoor interference the maximum would be 45 dBA | - | Sound pressure level meter | |
| 9. | Tension testing – using newton meter to see if the force produced by the harnesses is adequate for simulating different gravity as well as supporting the user | - | Newton meter | |

*Table 5: Testing plan outlining operations to test safety and requirement compliance.*

## Health and Safety

The risks outlined in tables 6, 7 and 8 are rated on a severity scale, 1-lowest to 5-highest, with a probability scale of 1-lowest to 3-highest. Both values are multiplied to give an RPN that helps distinguish the most prevalent risks in manufacturing and testing. For example, in the manufacturing risks; Drilling, milling, and turning have an RPN of 10 – signifying the substantial risk that comes with the process. The mitigation for these three risks is to wear the proper lab PPE as well as using the swarf guard to stop harm caused by projectile swarf. This was considered effective mitigation.

### Manufacturing Risk Assessment Table

| Possible risks | Normal Case | | | Worst Case | | | RPN | | Mitigation |
|---|---|---|---|---|---|---|---|---|---|
| | Associated Harms | Severity | Probability | Associated Harms | Probability | Severity | RPN- Normal case | RPN - Worst case | |
| **Short circuiting of electronics** | Electric shock/fire and damage to the treadmill | 5 | 2 | Electric shock causes grievous body harm/death to user | 1 | 5 | 10 | 5 | Standard lab PPE and safety button to deactivate electronic circuit. Also checking the maximum allowance for voltage and current. |
| **Sharp edges on objects** | Piercing/cutting damage | 3 | 2 | Cut by sharp objects leads to loss of a limb | 1 | 5 | 6 | 5 | Standard lab PPE and ensure care is taken when manufacturing parts for handling. |
| **Drilling** | Cut limbs and eye injury | 5 | 2 | Limbs pierced by drill (grievous body harm) | 1 | 5 | 10 | 5 | Standard lab PPE, following lab rules, appropriate use of swarf guard. |
| **Milling** | Pierced/crushed limbs and eye injury | 5 | 2 | Limbs pierced by mill (grievous body harm) | 1 | 5 | 10 | 5 | Standard lab PPE, following lab rules, appropriate use of swarf guard. |
| **Handling of fabric/rubber** | Skin irritation, friction burn if treadmill belt is motion | 2 | 1 | User gets serious friction burn from moving belt | 1 | 4 | 2 | 5 | Standard lab PPE, ensure care is taken when handling such materials, gloves to be worn. |
| **Treadmill buckling under weight** | Added pressure will cause projectile parts to fly out of treadmill harming user and people around the treadmill | 4 | 2 | User falls through treadmill and is the pierced by various parts of it | 1 | 5 | 10 | 5 | Use updated and proved calculations ahead of manufacturing phase |
| **Belt misalignment** | Slip/jam leading to treadmill damage and user injury | 3 | 2 | Belt slip/jam disorients user leading to fall causing severe head trauma/injury | 1 | 4 | 6 | 4 | Use updated and proved calculations ahead of manufacturing phase. |
| **Turning** | Projectile swarf, loss of limbs | 5 | 2 | Swarf projectile hits eye causing loss of sight | 1 | 5 | 10 | 5 | Standard lab PPE following lab rules, appropriate use of swarf guard. |
| **Soldering** | 1st – 3rd degree burns, toxic fumes from soldering | 5 | 2 | Fumes causing nose bleeds, headaches etc. Risk of self-immolation | 1 | 5 | 10 | 5 | Standard lab PPE, use clamps / tweezers to hold soldering material and perform in a well ventilated area. |
| **Heavy objects** | Falling on causing injury | 4 | 2 | Object falls on person causing broken bones, head trauma etc. | 1 | 5 | 8 | 5 | Standard lab PPE, ensure work station is kept clear and ensure safe lifting of objects. |
| **Slips and falls** | Falling in workshop, risk of damaging person/treadmill | 3 | 2 | Person falls and lands leading to grievous body harm | 1 | 5 | 6 | 5 | Standard lab PPE, ensure spillages are cleaned immediately. |

*Table 6: Manufacturing risk assessment table, outlining manufacturing risks and mitigations.*

### Testing risks

Testing risks are concerned with the post-manufacturing process. The most prevalent risk is the assembly of the treadmill. With the use of hinges and T-bars the assembly of the treadmill could go wrong and result in the treadmill breaking. The prototype breaking before the presentation is arguably one of the most detrimental risks to the project.

| Possible risks | Normal Case | | | Worst Case | | | RPN | | Mitigation |
|---|---|---|---|---|---|---|---|---|---|
| | Associated Harms | Severity | Probability | Associated Harms | Probability | Severity | RPN- Normal case | RPN - Worst case | |
| **Short circuiting of electronics** | Electric shock/fire and damage to the treadmill | 5 | 2 | Electric shock causes grievous body harm/death to user | 1 | 5 | 10 | 5 | Standard lab PPE and safety button to deactivate electronic circuit. Also checking the maximum allowance for voltage and current. |
| **Sharp edges on objects** | Piercing/cutting damage | 3 | 2 | Cut by sharp objects leads to loss of a limb | 1 | 5 | 6 | 5 | Standard lab PPE and ensure care is taken when manufacturing parts for handling. |
| **Drilling** | Cut limbs and eye injury | 5 | 2 | Limbs pierced by drill (grievous body harm) | 1 | 5 | 10 | 5 | Standard lab PPE, following lab rules, appropriate use of swarf guard. |
| **Milling** | Pierced/crushed limbs and eye injury | 5 | 2 | Limbs pierced by mill (grievous body harm) | 1 | 5 | 10 | 5 | Standard lab PPE, following lab rules, appropriate use of swarf guard. |
| **Handling of fabric/rubber** | Skin irritation, friction burn if treadmill belt is motion | 2 | 1 | User gets serious friction burn from moving belt | 1 | 4 | 2 | 5 | Standard lab PPE, ensure care is taken when handling such materials, gloves to be worn. |
| **Treadmill buckling under weight** | Added pressure will cause projectile parts to fly out of treadmill harming user and people around the treadmill | 4 | 2 | User falls through treadmill and is the pierced by various parts of it | 1 | 5 | 10 | 5 | Use updated and proved calculations ahead of manufacturing phase |
| **Belt misalignment** | Slip/jam leading to treadmill damage and user injury | 3 | 2 | Belt slip/jam disorients user leading to fall causing severe head trauma/injury | 1 | 4 | 6 | 4 | Use updated and proved calculations ahead of manufacturing phase. |
| **Turning** | Projectile swarf, loss of limbs | 5 | 2 | Swarf projectile hits eye causing loss of sight | 1 | 5 | 10 | 5 | Standard lab PPE following lab rules, appropriate use of swarf guard. |
| **Soldering** | 1st – 3rd degree burns, toxic fumes from soldering | 5 | 2 | Fumes causing nose bleeds, headaches etc. Risk of self-immolation | 1 | 5 | 10 | 5 | Standard lab PPE, use clamps / tweezers to hold soldering material and perform in a well ventilated area. |
| **Heavy objects** | Falling on causing injury | 4 | 2 | Object falls on person causing broken bones, head trauma etc. | 1 | 5 | 8 | 5 | Standard lab PPE, ensure work station is kept clear and ensure safe lifting of objects. |
| **Slips and falls** | Falling in workshop, risk of damaging person/treadmill | 3 | 2 | Person falls and lands leading to grievous body harm | 1 | 5 | 6 | 5 | Standard lab PPE, ensure spillages are cleaned immediately. |

*Table 7: Testing risk assessment table, outlining testing risks and mitigations*

## Project health risks

| Possible risks | Normal Case | | | Worst Case | | | RPN | | Mitigation |
|---|---|---|---|---|---|---|---|---|---|
| | Associated Harms | Severity | Probability | Associated harms | Probability | Severity | RPN- Normal case | RPN - Worst case | |
| **Unavailability of group members** | Work may not be completed on time + increased workload | 4 | 2 | Project is unavailable to be presented at presentation – due to delays | 1 | 5 | 8 | 5 | Depending on members' tasks, have another member capable and ready to do unfinished work. |
| **Missing parts** | Manufacturing will be held up | 5 | 2 | Treadmill unable to be built | 1 | 5 | 10 | 5 | Ordering in advance and check with other suppliers to solve issue. |
| **Going over budget** | Inability to buy essential parts | 3 | 1 | Statement of requirement not met; design may have to be changed late in manufacturing plan | 1 | 4 | 3 | 4 | Updating budget plan throughout the project and stay in close contact with suppliers to know the current price of parts. |
| **Going over time** | Project delay, potential clash with project fair | 4 | 2 | Project is unavailable to be presented at presentation – due to delays | 1 | 5 | 8 | 5 | Refer to and update Gantt chart, as well as working with group to complete tasks in time. |
| **Limited access to facility** | If facility sessions are not planned, delays in build phase | 3 | 3 | Project is unavailable to be presented at presentation – due to delays | 1 | 5 | 9 | 5 | Plan lab sessions in advance and allow changes in availability for follow up lab sessions if necessary. |
| **Miscommunication** | Product delay as members may be confused with task | 2 | 3 | Treadmill built incorrectly causing reduced performance and safety | 1 | 5 | 6 | 5 | Regular group meetings to clear issues up and keep in close contact with group members. |

*Table 8: Project health risk assessment table, outlining project health risks and mitigations*

Project health risks are concerned with project progression, these risks are involved with the streamlining of the project, such as going over time or budget. The most severe harm to project health is the project's delay to the point that the treadmill cannot be presented at the GDM exhibition. Although another detrimental risk is miscommunication which could either delay the project or worst-case scenario, the treadmill is built incorrectly causing reduced performance and safety which poses a threat to the user as well.

The worst-case segments of the risks are used to inform the group about the vast range of harms that could happen throughout the project. With that added knowledge the group can prepare to the best of their ability to mitigate the risks. The worst-case scenarios have also been given appropriate probability and severity ratings, compared to the normal-case scenarios, the worst case has low probability and high severity even still, being aware of the most severe risks is crucial for successful progression in this project.

As shown by the Gannt Chart, choke points are stages on the critical path that could lead to delays in future tasks. Significant choke points have been identified. The most substantial choke point includes the delay in the delivery of parts and materials. If the parts and materials are delayed, the manufacturing processes cannot begin - this delays all future tasks. To counteract this, major leeway on lead times has been accounted for and a contingency plan is in place if the initial manufacturers are delayed. These countermeasures ensure that the choke points will not delay the project.

### Special allowances

Special allowances have been accounted for in the safety plan, as although soldiering is a substantial risk, the ability to outsource soldiering to electronic technicians is possible.

## Compliance with BS-EN Standards

| Number | Title | Description | Method of Compliance | Standard Notes |
|---|---|---|---|---|
| 6.4 | Temper-ature rises | When tested, accessible parts of the treadmill shall not have a temperature greater than 65C. | The components at risk of temperature rise: electronics, belt/boards and bearings<br>The boards are lubricated, and electronic components won't exceed a 65°C temperature. | |
| 6.7 | Stability | The treadmill shall be stable in both training and storage positions when tested | During training, the use of three sets of feet at different points keeps the device stable as well as the use of a steel plate to keep the frames unfolded and hinges open. During storage, the bungee cord can be wrapped around it to maintain stability. | |
| 6.12 | Running surface | Permanent marking in a contrasting colour is required on the running surface to determine if the belt is | This safety requirement will be satisfied by marking the belt using paint to show whether the belt is stationary or moving with painted marks appropriately spaced apart. | The markings on the running surface shall have a length between |

| | | | | |
|---|---|---|---|---|
| | | stationary or moving. At least one marking shall be visible from the top view in any position of the running surface | | 150mm and 350mm and a width between 50mm and 100mm. The space between markings shall not be less than the width of the markings measured in the direction of travel. |
| 6.15 | Folding treadmill | A folding treadmill shall be equipped with a safe locking system to keep it in a folded position where the running surface is designed to be folded up for storage.<br><br>A folding treadmill shall be equipped with a safe locking system to keep it in the useable position when the side handrails are designed to be folded down when stored | This safety requirement is achieved for the folding treadmill by using a steel plate to keep the treadmill in a usable position by locking the hinges in place. The treadmill will be kept in place when not useable using a cord, keeping the treadmill wrapped. Inadvertent release of energy is avoided by having the cables securely wrapped together meaning they will not come undone unless the user does so. | The folding portion shall not be capable of reaching a stable position of equilibrium before being locked. The maximum vertical handling force shall be less than 150N.<br><br>If there is stored energy (compressed gas spring) in the packaged position, a safety device to avoid inadvertent release |

| | | | | |
|---|---|---|---|---|
| | | | | shall be provided |
| 6.16 | Noise | | Noise during the use of the treadmill is reduced as we have opted to use a non-motorized treadmill. | |

## Response to CDR Feedback Presentation

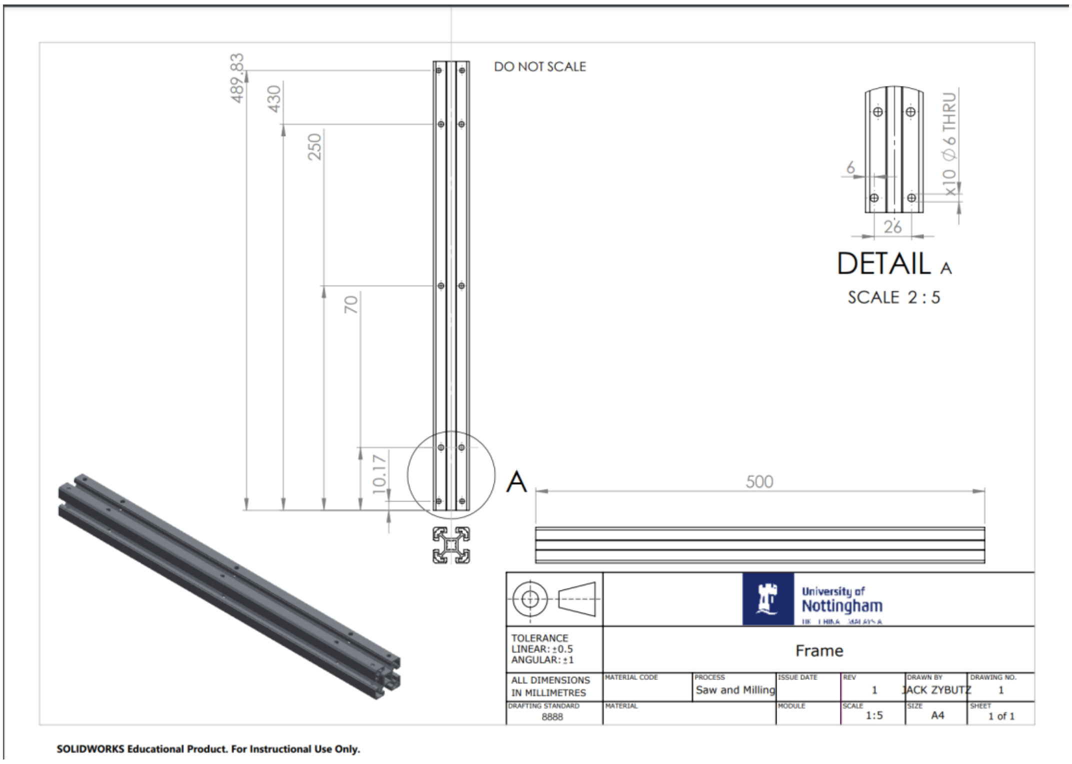
| **Concern** | **Action** | **Notes** |
|---|---|---|
| Update requirements to capture the capability of the machine | The statement of requirements table was updated with new design-focused requirements | See requirements 9 to 12 in table 1 |
| MDF boards not represented in the design | Friction calculations updated | MDF board is available in 25mm thickness, see mechanical budget |
| Belt Alignment and method to ensure the belt stays centred | Crowned Pulley design | See the dynamic bearing shaft assembly drawing |
| 5Kg Weight limit | 'Space' CAD and calculations finalized and included | CAD meets the 5kg weight limit |
| **Statement of requirements** | Missing requirements have been added | |
| **Drawings** | Bearing shaft assembly instructions included<br>Power absorption methods included.<br>Description of interfaces in shear included.<br>Tolerances of shaft bearing, and collars included. | |
| **Calculations** | Friction between boards and belt calculated.<br>Effect of temperature increases on grease, and therefore viscosity, studied and factored in.<br>Cable tension calculations corrected. | |
| **Risk Analysis** | Choke points added to critical path.<br>All aspects, project, technical, health and safety | |

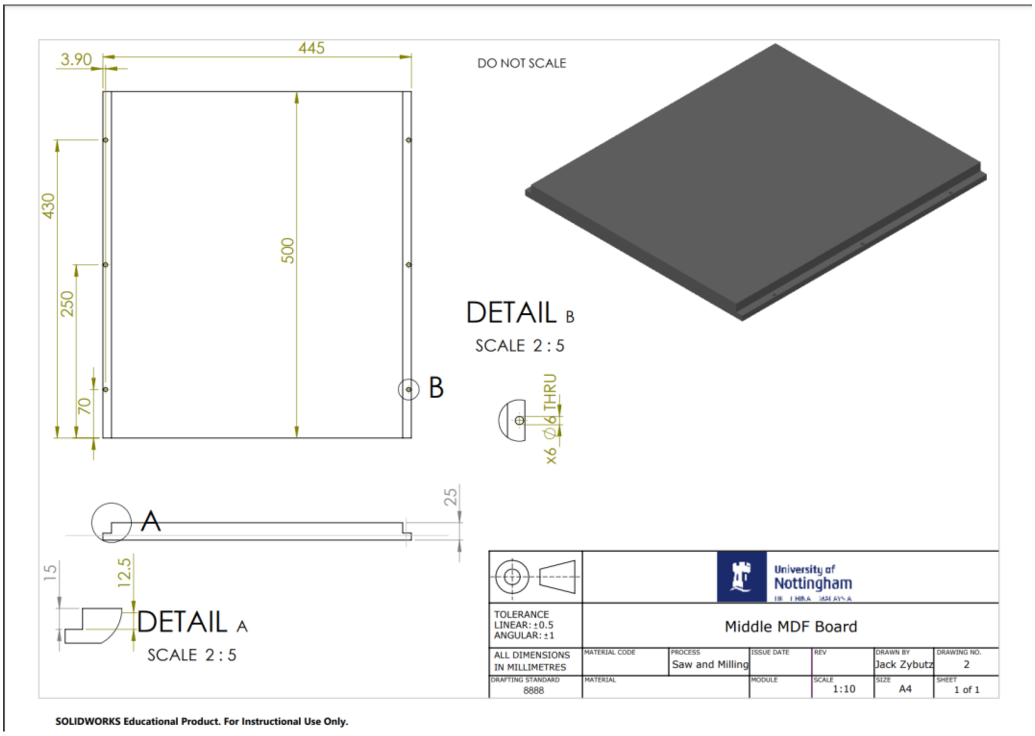
| | | |
|---|---|---|
| | and manufacturing, are covered. | |
| **Project Health** | Added critical path to Gantt Chart | |
| **General** | Updated missing details.<br><br>Crowned roller design for belt alignment | |

# Appendix

## Drawings

### Detail





3.90
445
DO NOT SCALE
430
250
70
500
B
DETAIL B
SCALE 2 : 5
x6 ⌀6 THRU
A
25
15
12.5
DETAIL A
SCALE 2 : 5
University of Nottingham
TOLERANCE
LINEAR: ±0.5
ANGULAR: ±1
Middle MDF Board
ALL DIMENSIONS IN MILLIMETRES
MATERIAL CODE
PROCESS
Saw and Milling
ISSUE DATE
REV
DRAWN BY
Jack Zybutz
DRAWING NO.
2
DRAFTING STANDARD
8888
MATERIAL
MODULE
SCALE
1:10
SIZE
A4
SHEET
1 of 1
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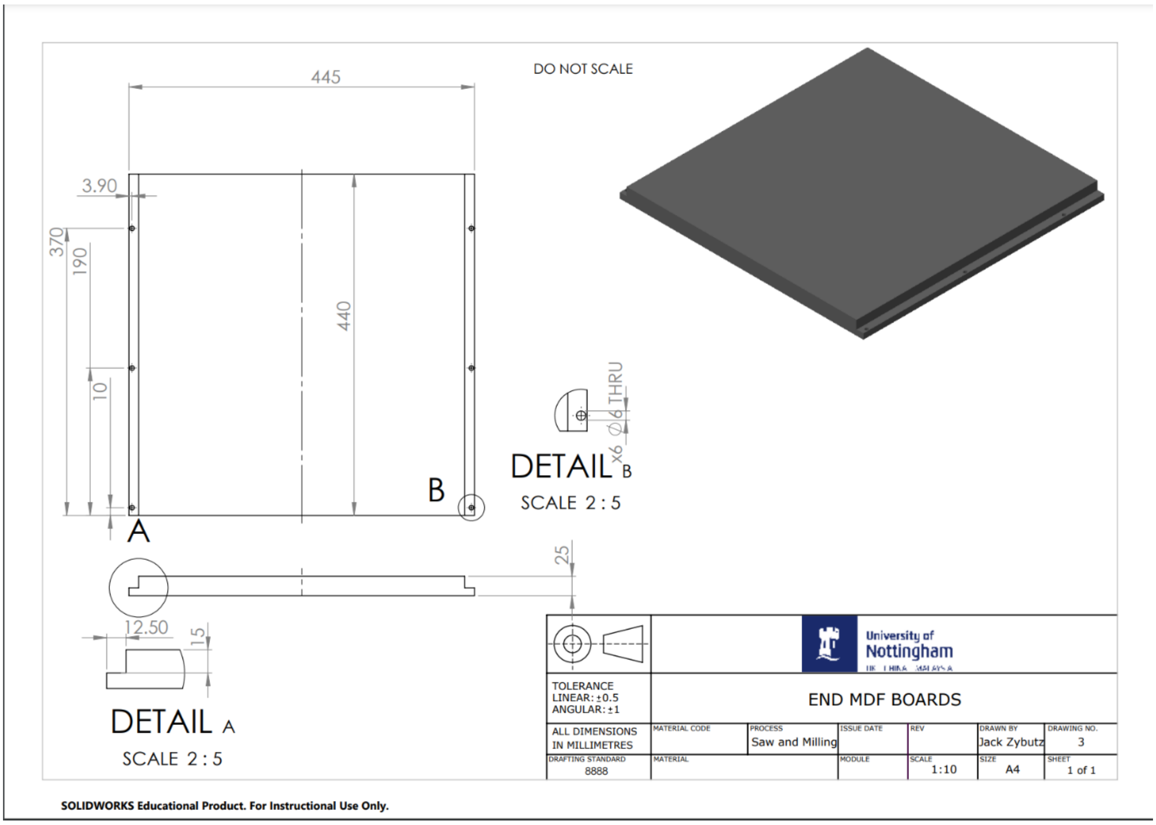
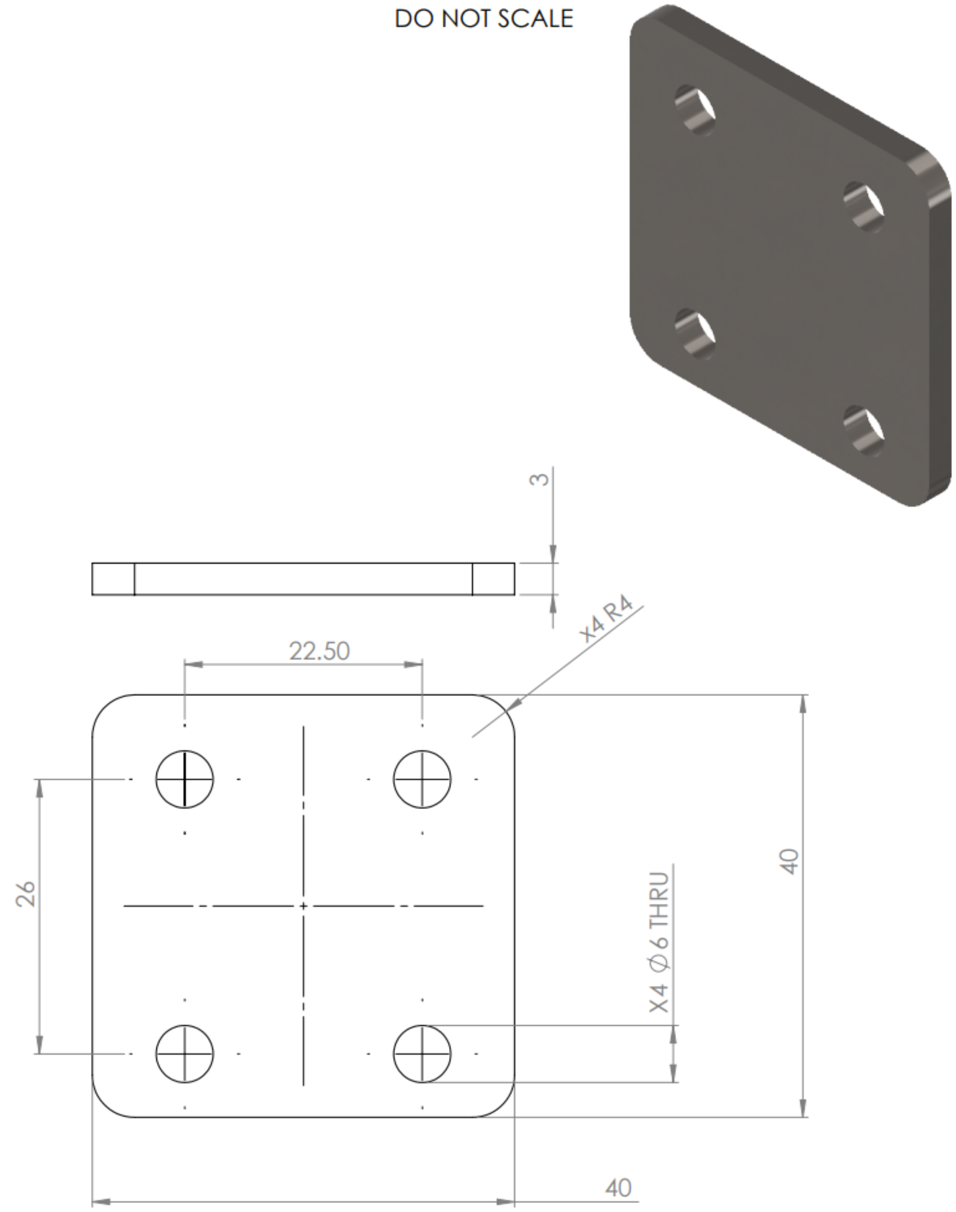


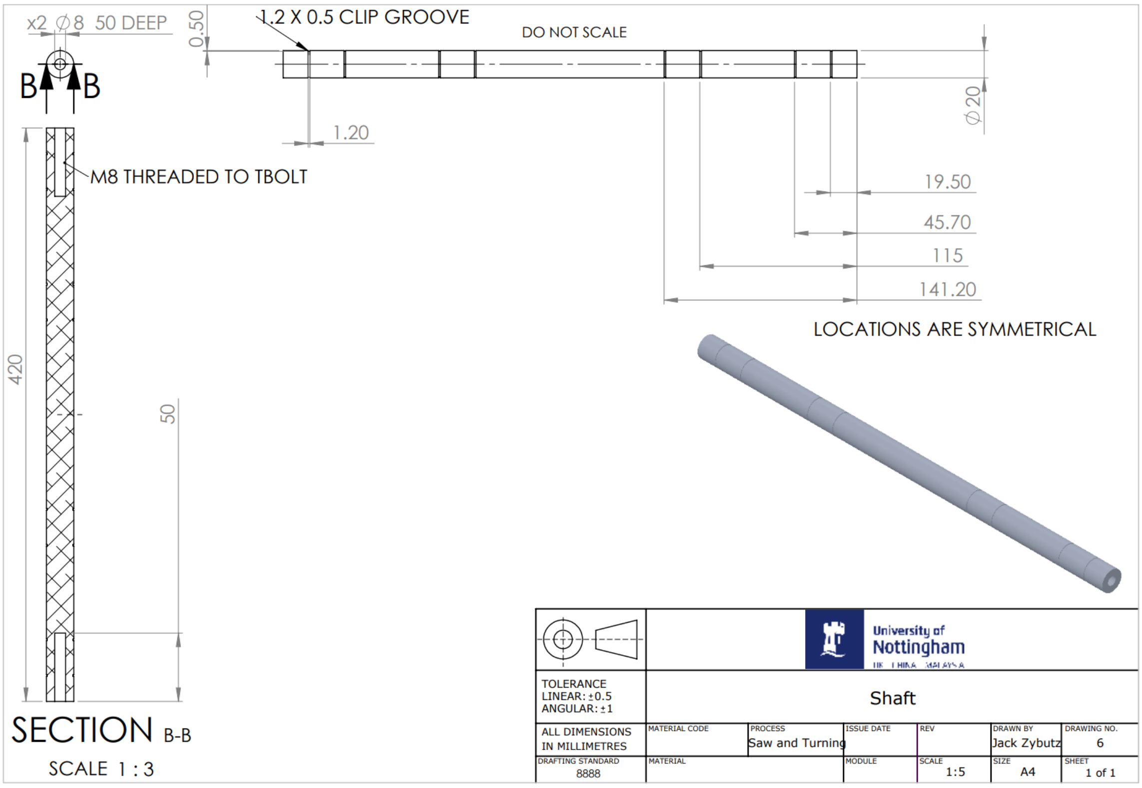
445
DO NOT SCALE
3.90
370
190
10
440
B
A
x6 ⌀6 THRU
DETAIL B
SCALE 2 : 5
25
12.50
15
DETAIL A
SCALE 2 : 5
University of Nottingham
TOLERANCE
LINEAR: ±0.5
ANGULAR: ±1
END MDF BOARDS
ALL DIMENSIONS IN MILLIMETRES
MATERIAL CODE
PROCESS
Saw and Milling
ISSUE DATE
REV
DRAWN BY
Jack Zybutz
DRAWING NO.
3
DRAFTING STANDARD
8888
MATERIAL
MODULE
SCALE
1:10
SIZE
A4
SHEET
1 of 1
SOLIDWORKS Educational Product. For Instructional Use Only.

DO NOT SCALE

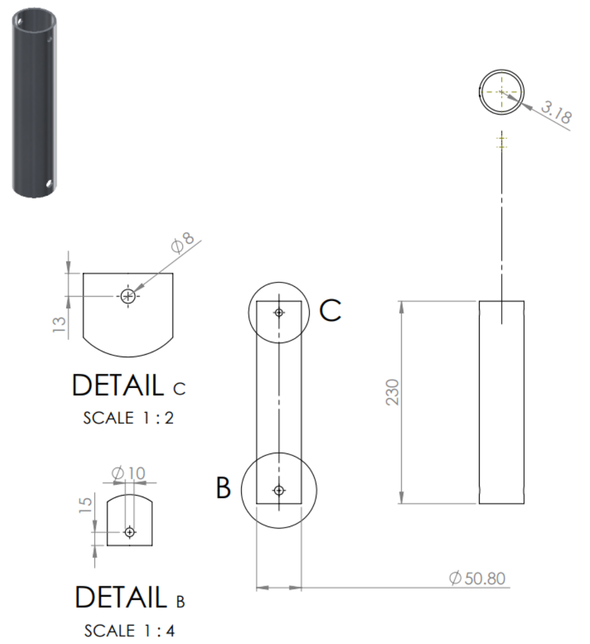



| | |
|---|---|
| | University of Nottingham UK \| CHINA \| MALAYSIA |
| TOLERANCE LINEAR: ±0.5 ANGULAR: ±1 | Steel Plate |

| ALL DIMENSIONS IN MILLIMETRES | MATERIAL CODE | PROCESS | ISSUE DATE | REV | DRAWN BY | DRAWING NO. |
|---|---|---|---|---|---|---|
| | | Pillar Drill and Saw | | | Jack Zybutz | 5 |
| DRAFTING STANDARD 8888 | MATERIAL | | MODULE | SCALE 1:1 | SIZE A4 | SHEET 1 of 1 |


x2 ∅8 50 DEEP
0.50
1.2 X 0.5 CLIP GROOVE
DO NOT SCALE
B
B
1.20
∅20
M8 THREADED TO TBOLT
19.50
45.70
115
141.20
LOCATIONS ARE SYMMETRICAL
420
50
SECTION B-B
SCALE 1 : 3
University of Nottingham
Shaft
TOLERANCE
LINEAR: ±0.5
ANGULAR: ±1
ALL DIMENSIONS IN MILLIMETRES
MATERIAL CODE
PROCESS
Saw and Turning
ISSUE DATE
REV
DRAWN BY
Jack Zybutz
DRAWING NO.
6
DRAFTING STANDARD
8888
MATERIAL
MODULE
SCALE
1:5
SIZE
A4
SHEET
1 of 1

DO NOT SCALE




University of Nottingham

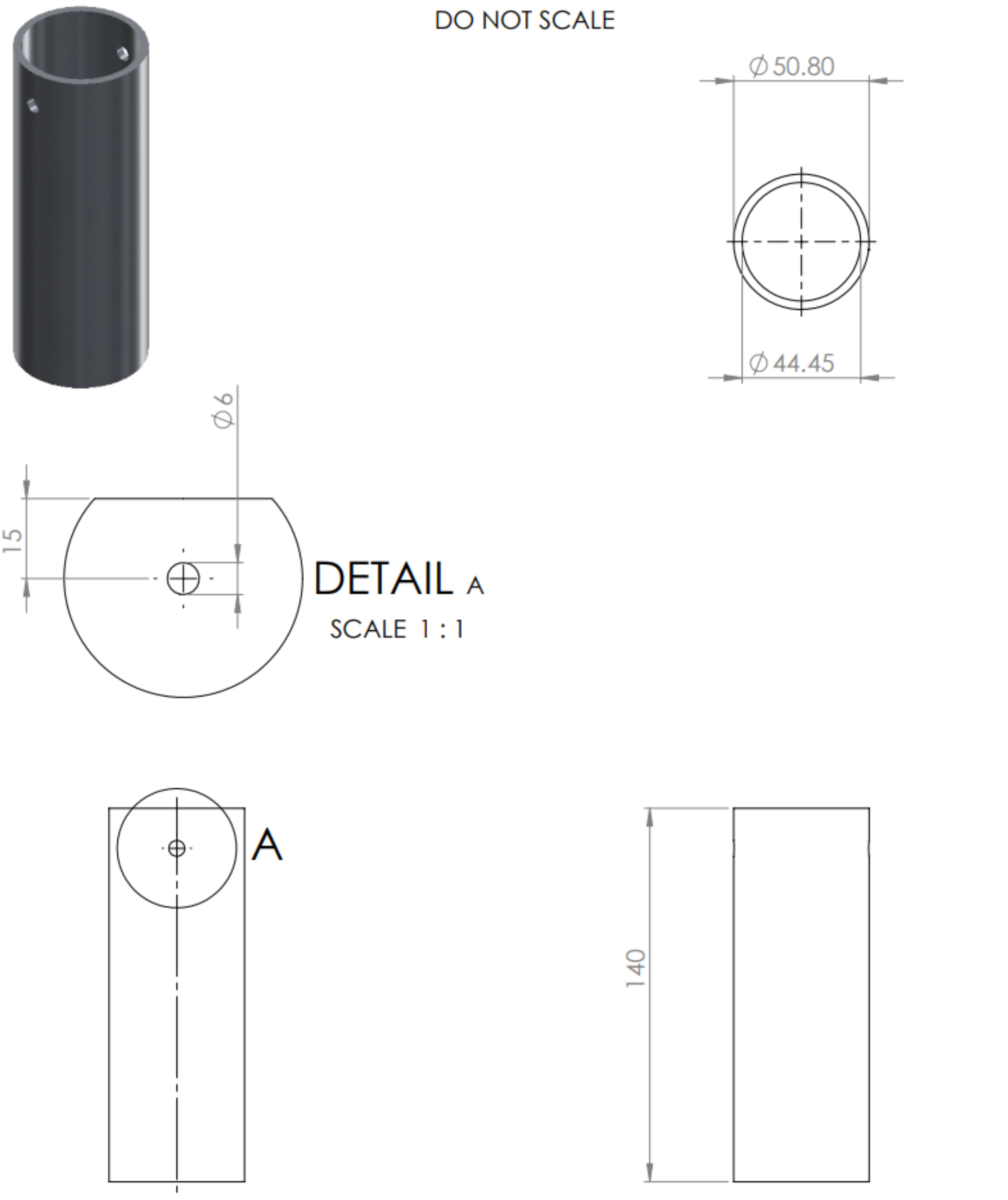
Front Feet

TOLERANCE
LINEAR: ±0.5
ANGULAR: ±1

ALL DIMENSIONS IN MILLIMETRES

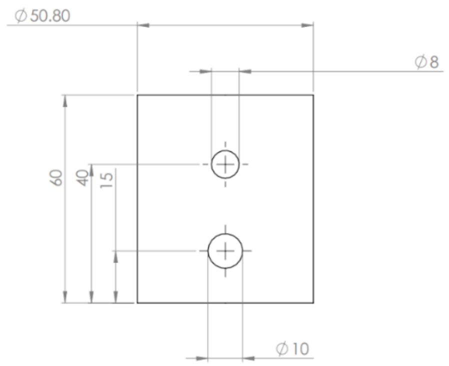
DRAFTING STANDARD: 8888

| MATERIAL CODE | PROCESS | ISSUE DATE | REV | DRAWN BY | DRAWING NO. |
|---|---|---|---|---|---|
| | Milling and Turning | | | Jack Zybutz | 7 |
| MATERIAL | | MODULE | SCALE | SIZE | SHEET |
| | | | 1:20 | A4 | 1 of 1 |



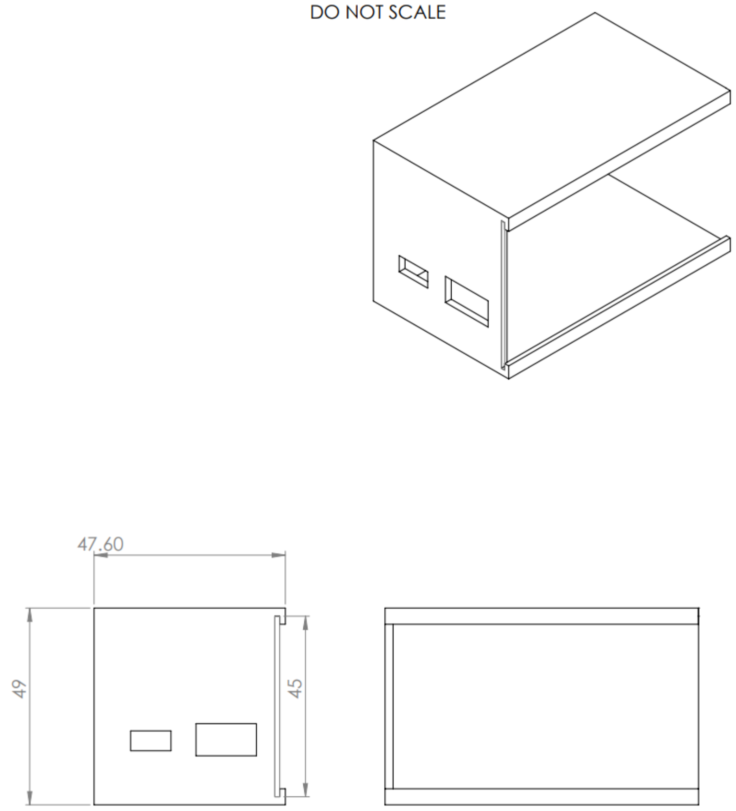

| | | | | | | |
|---|---|---|---|---|---|---|
| | University of Nottingham UK \| CHINA \| MALAYSIA | | | | | |
| TOLERANCE LINEAR: ±0.5 ANGULAR: ±1 | Middle Feet | | | | | |
| ALL DIMENSIONS IN MILLIMETRES | MATERIAL CODE | PROCESS Sawing and Milling | ISSUE DATE | REV | DRAWN BY Jack Zybutz | DRAWING NO. 8 |
| DRAFTING STANDARD 8888 | MATERIAL | | MODULE | SCALE 1:10 | SIZE A4 | SHEET 1 of 1 |

DO NOT SCALE

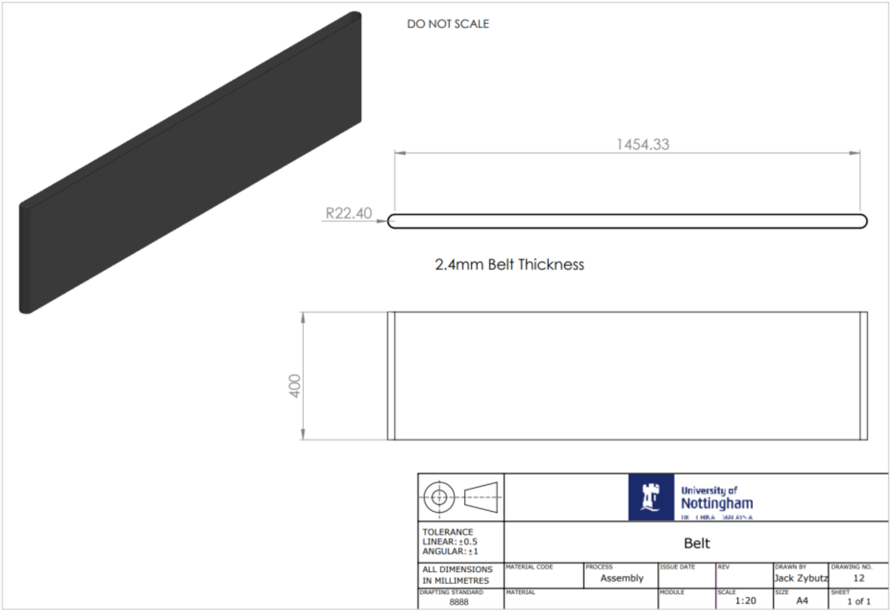



| | | | | | | |
|---|---|---|---|---|---|---|
| TOLERANCE LINEAR: ±0.5 ANGULAR: ±1 | Rear Feet | | | | | |
| ALL DIMENSIONS IN MILLIMETRES | MATERIAL CODE | PROCESS Sawing and Milling | ISSUE DATE | REV | DRAWN BY Jack Zybutz | DRAWING NO. 9 |
| DRAFTING STANDARD 8888 | MATERIAL | | MODULE | SCALE 1:10 | SIZE A4 | SHEET 1 of 1 |

DO NOT SCALE




| | | | | | | |
|---|---|---|---|---|---|---|
| | University of Nottingham UK \| CHINA \| MALAYSIA | | | | | |
| TOLERANCE LINEAR: ±0.5 ANGULAR: ±1 | Electronics Housing | | | | | |
| ALL DIMENSIONS IN MILLIMETRES | MATERIAL CODE | PROCESS 3D Printing | ISSUE DATE | REV | DRAWN BY Jack Zybutz | DRAWING NO. 10 |
| DRAFTING STANDARD 8888 | MATERIAL | | MODULE | SCALE 1:1 | SIZE A4 | SHEET 1 of 1 |

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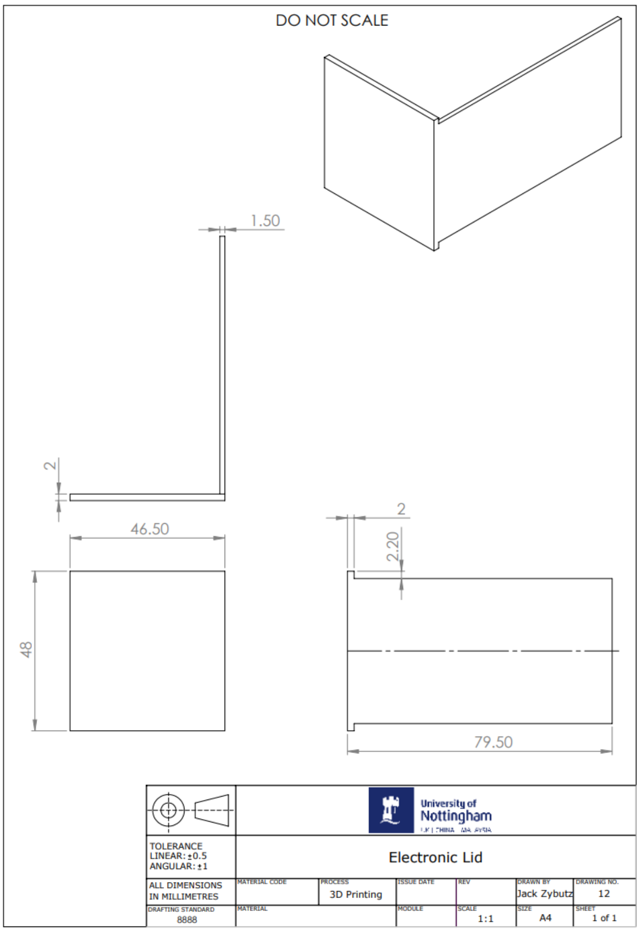
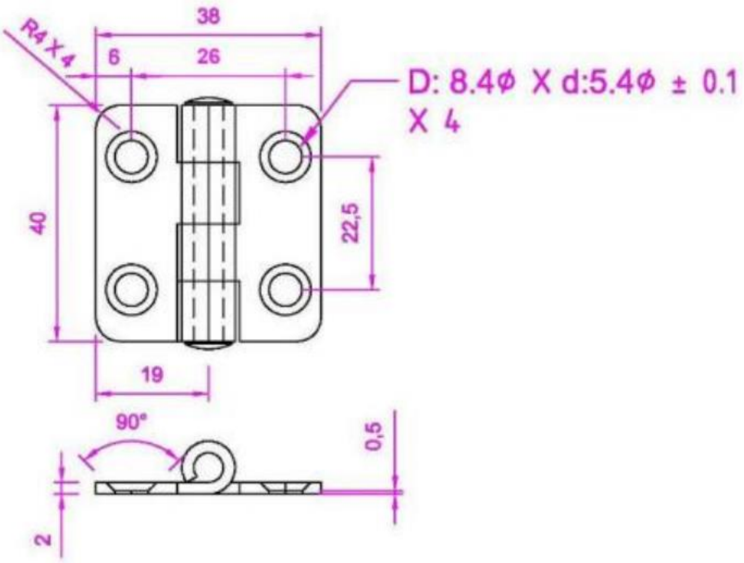
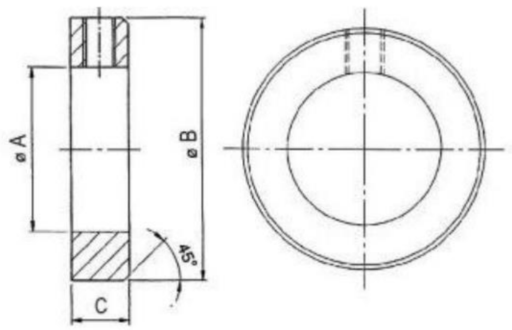
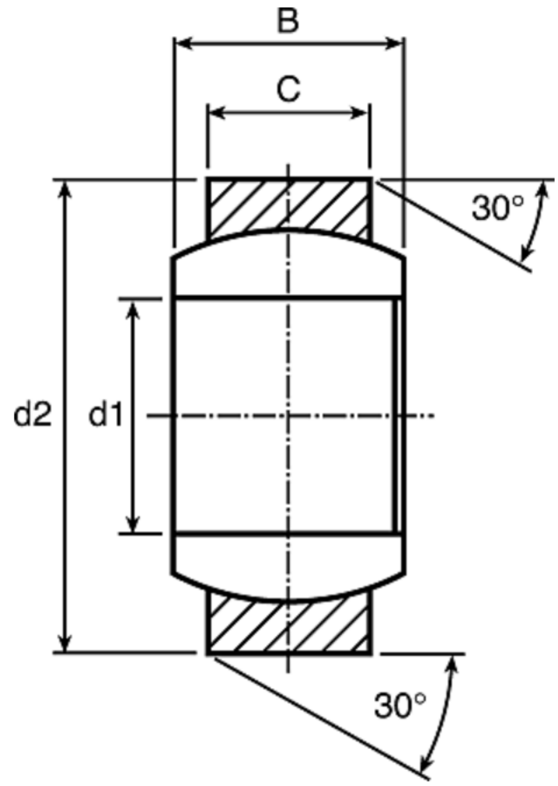



SOLIDWORKS Educational Product. For Instructional Use Only.



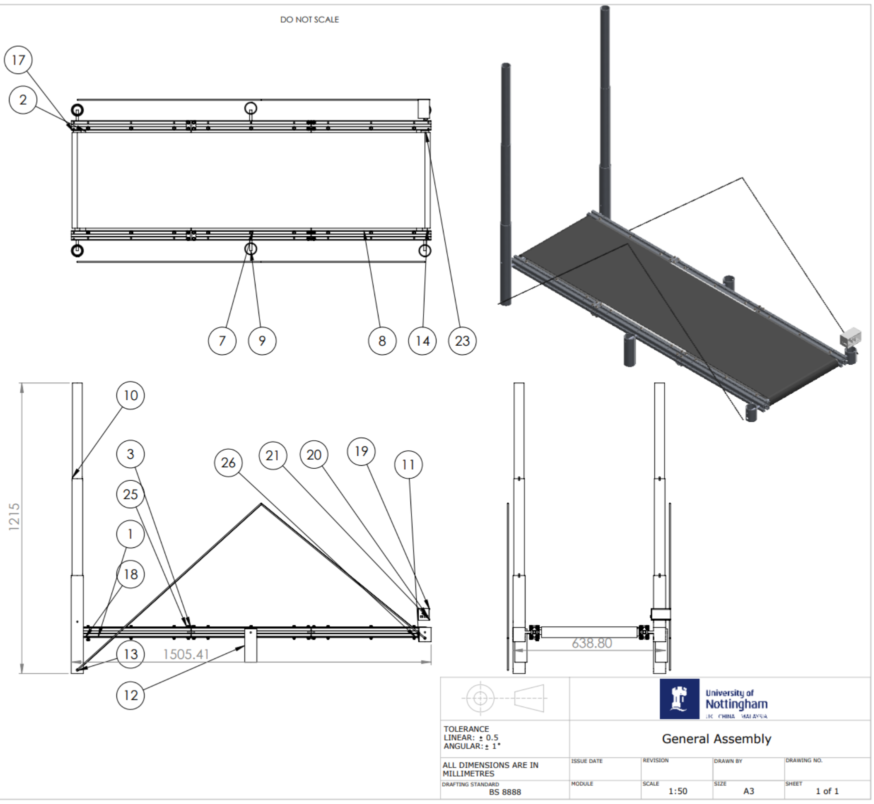

MATERIAL : STAINLESS STEEL 304
TREATMENT : ELECTROLYZED & POLISHED
TOLERANCE : ±0.3 m/m



# General Assembly

| ITEM NO. | PART NUMBER | QTY. |
|---|---|---|
| 1 | Metal X Frame_v6 | 6 |
| 2 | End mdf board | 1 |
| 3 | Hinge | 4 |
| 4 | Steel Plate | 2 |
| 6 | Middle MDF Board | 1 |
| 7 | Low Friction Board | 1 |
| 8 | Main Board^Boards_Unit C_Main Assembly | 1 |
| 9 | TNut^Main Assembly | 10 |
| 10 | Front^Feet_Main Assembly | 1 |
| 11 | Back^Feet_Main Assembly | 1 |
| 12 | Middle^Feet_Main Assembly | 1 |
| 13 | Bungee^Feet_Main Assembly | 2 |
| 14 | Shaft^Viscous Roller Assem_Main Assembly | 2 |
| 15 | kglm-20_01 | 8 |
| 16 | kglm-20_02 | 8 |
| 17 | Collar^Viscous Roller Assem_Main Assembly | 16 |
| 18 | Belt^Main Assembly | 1 |
| 19 | main cover1 | 1 |
| 20 | Main board | 1 |
| 21 | main cover2 | 1 |
| 22 | hall cover | 1 |
| 23 | Copy of Copy of Magnet^Electronics | 1 |
| 25 | BS EN ISO 4162 - M6 x 50 x 50-C | 34 |
| 26 | BS EN ISO - 4161 - M6 - C | 35 |

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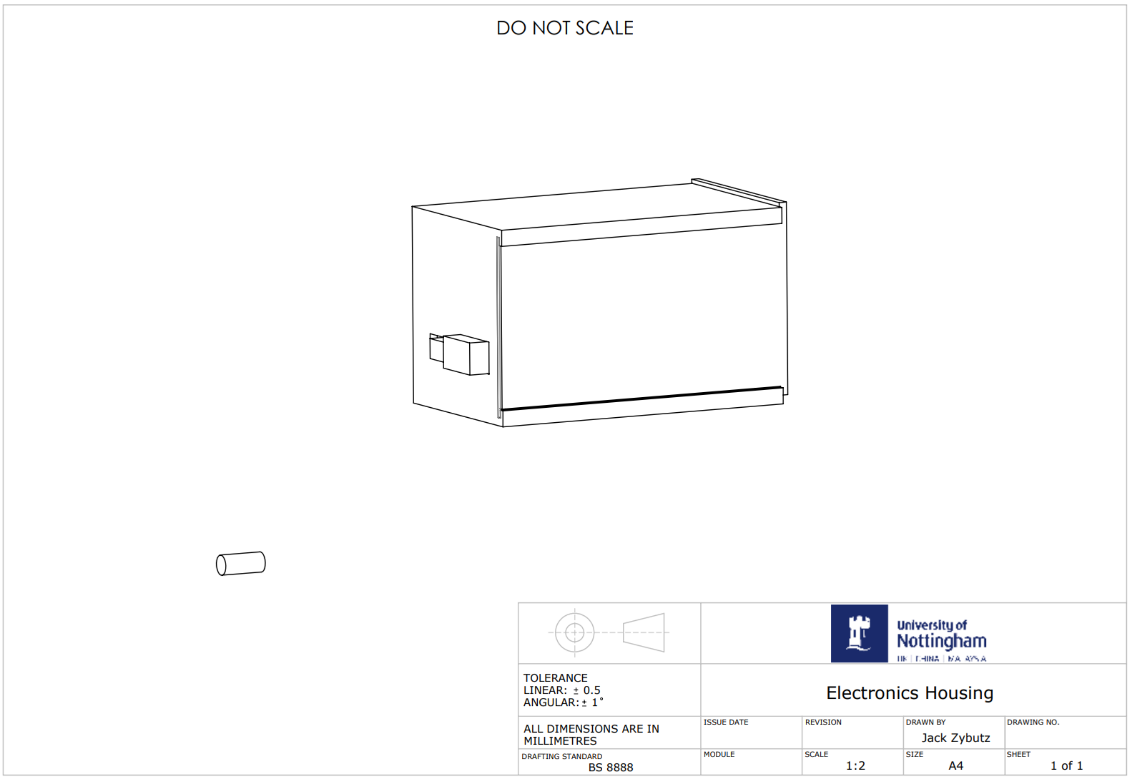


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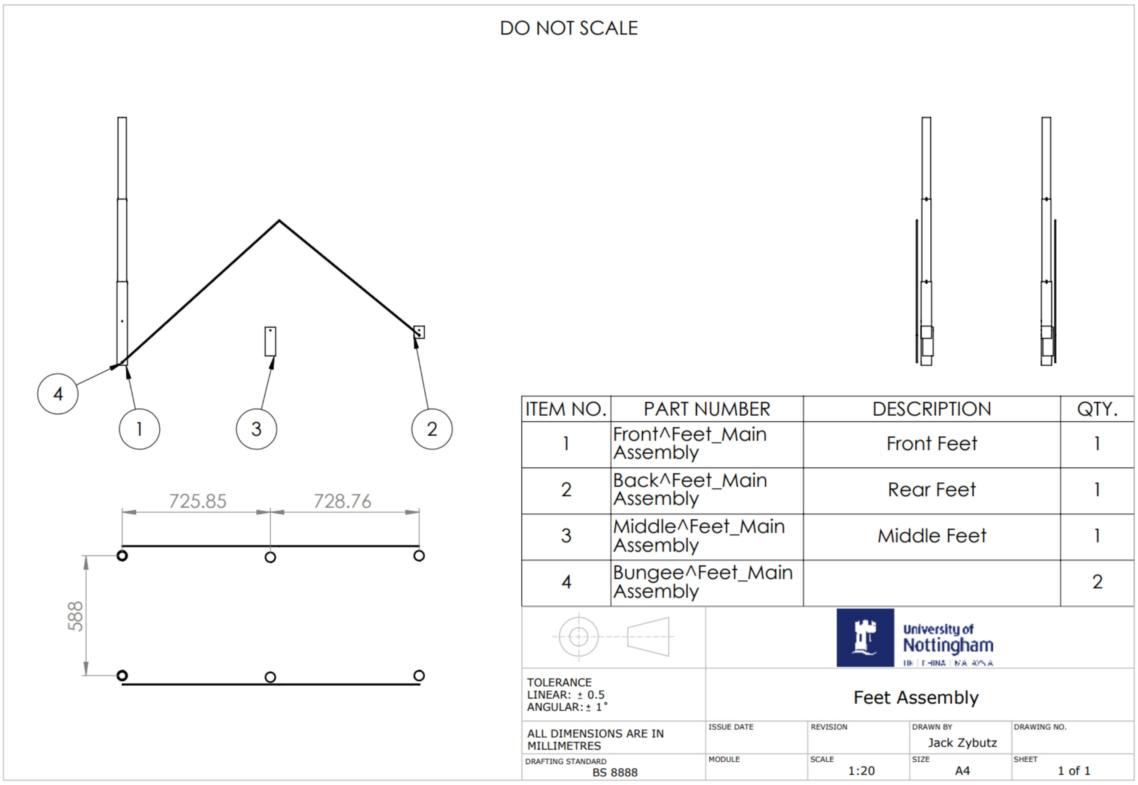


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# Process Sheets

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| 1. | Cut 40x80x3mm metal sheet into 2x 40x40x3mm sheets. | Buzzsaw | | |
| 2. | Drill 4x M6 through holes into plate referring to drawings for positions. | Milling Machine | | |
| 3. | Deburr sharp edges. | | File | |
| 4. | Clean part. | | | |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 5 | 4 | Steel Plate | Stainless Steel | |

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| 1. | Cut 1m aluminium shaft into two 420mm length parts. | Buzzsaw | - | Use rule and pencil to mark cutting points |
| 2. | Drill M4 pilot holes and then M8 holes 50mm deep on each side of the shafts. | Lathe | - | Operate Lathe at lower speeds for high surface finish and accurate dimensions |
| 3. | Deburr sharp edges. | | File | |
| 4. | Clean part. | | | |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 6 | 14 | Bearing Shaft | Aluminium | |

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| 1. | Mark correct lengths on 820mm length (2" dia, 1/4" wall thickness) Aluminium tube, then cut tube down into 2 tubes of 230mm. | Buzzsaw | - | Use rule and pencil to mark cutting points. |
| 2. | Drill M8 through hole for T Nut on both large tubes referring to drawings for positions. | Milling machine | | |
| 3. | Drill M10 through hole for hooks on both large tubes referring to drawings for positions. | Milling machine | | |
| 4. | Deburr sharp edges. | | File | |
| 5. | Clean part. | | | |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 7 | 10 | Front Feet | Aluminium | |

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| 1. | Cut 420mm length 50.8mm x 6.3mm (2" x 1/4" wall) Aluminium Tube into to 2x 140mm length tubes. | Buzz saw | | Mark using pencil and ruler correct length<br>Use remainder of 210 mm length tubing after rear feet cutting meaning the length cut down from is 150mm |
| 2. | Drill M8 through holes referring to drawings for positioning. | Milling Machine | | To allow connection to frame – M8 used for T-Bolt |
| 3. | Deburr sharp edges. | | File | |
| 4. | Clean part. | | | |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 8 | | Middle Feet | Aluminium | |

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| 1. | Cut 420 mm length 50.8mm x 6.3mm (2" x 1/4" wall) Aluminium Tube into to x2 60mm length tubes. | Buzz saw | | Mark using pencil and ruler correct length |
| 2. | Drill 1x M8 through hole for frame connection in each foot, referring to drawings for positioning. | Milling Machine | | M8 hole is for T-Bolts |
| 3. | Drill 1x M10 hole for hooks in each foot, referring to drawings for positioning. | Milling machine | | |
| 4. | Deburr sharp edges | | File | |
| 5. | Clean part | | | |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 9 | 11 | Rear Feet | Aluminium | |

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| **1.** | Roughen the surface of the bearings using abrasive paper to ensure a high friction interface with the belt. | | | |
| **2.** | Of the 8 bearings, sand down 2 of the bearings by 0.622mm on the outside diameter. | | Sandpaper | Make sure bearings have smooth edge. |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 10 | 15/16 | Bearings | Plastic | |

| Operation No | Operation Description | Machine | Special Tools | Notes |
|---|---|---|---|---|
| **1.** | 3d print housing for electronics. | 3d printer | | |
| **2.** | Shave down any excess plastic protruding from the housing's dimensions. | | File | |
| **3.** | Check fit of electronics board | | | |

| Drawing No | Item No | Description | Material | Sheet 1 of 1 |
|---|---|---|---|---|
| 10 | 19/21 | Electronics Housing | PLA | |

## Tolerance Chart

| | ISO SYMBOL | | DESCRIPTION | |
|---|---|---|---|---|
| | Hole Basis | Shaft Basis | | |
| Clearance Fits | H11/c11 | C11/h11 | Loose running fit for wide commercial tolerances or allowances on external members. | More Clearance |
| | H9/d9 | D9/h9 | Free running fit not for use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures. | |
| | H8/f7 | F8/h7 | Close running fit for running on accurate machines and for accurate location at moderate speeds and journal pressures. | |
| | H7/g6 | G7/h6 | Sliding fit not intended to run freely, but to move and turn freely and locate accurately. | |
| | H7/h6 | H7/h6 | Locational clearance fit provides snug fit for locating stationary parts; but can be freely assembled and disassembled. | |
| Transition Fits | H7/k6 | K7/h6 | Locational transition fit for accurate location, a compromise between clearance and interference. | |
| | H7/n6 | N7/h6 | Locational transition fit for more accurate location where greater interference is permissible. | |
| Interference Fits | H7/p6[1] | P7/h6 | Locational interference fit for parts requiring rigidity and alignment with prime accuracy of location but without special bore pressure requirements. | |
| | H7/s6 | S7/h6 | Medium drive fit for ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron. | |
| | H7/u6 | U7/h6 | Force fit suitable for parts which can be highly stressed or for shrink fits where the heavy pressing forces required are impractical. | More Interference |

## References


[1] https://www.nasa.gov/image-feature/exercising-on-the-t2-treadmill

[2] https://www.techbriefs.com/component/content/article/tb/pub/briefs/bio-medical/39434

[3] NILSSON, J. and THORSTENSSON, A. (1989), Ground reaction forces at different speeds of human walking and running. Acta Physiologica Scandinavica, 136: 217-227. https://doi.org/10.1111/j.1748-1716.1989.tb08655.x

[4] https://mechanicalc.com/calculators/mohrs-circle/

[5] https://marathonhandbook.com/average-stride-length/

[6] https://shop.newgatesimms.com/product/tribosyn-320-yellow/

[7]https://www.researchgate.net/publication/355865271_DETERMINING_THE_COEFFICIENT_OF_FRICTION_OF_WOOD-BASED_MATERALS_FOR_FURNITURE_PANELS_IN_THE_ASPECT_OF_MODELLING_THEIR_SHREDDING_PROCESS#:~:text=The%20highest%20values%20of%20the,equal%20respectively%3A%200.77%20and%200.68

[8] https://link.springer.com/article/10.1007/s10010-022-00589-9#:~:text=At%20low%20average%20rolling%20speeds,is%20highest%20at%20low%20speeds

[9] http://personal.cityu.edu.hk/meachan/Online%20Anthropometry/Chapter2/Ch2-5.htm#:~:text=Hip%20height&text=Definition%3A,lateral%20surface%20of%20the%20hip

[10] https://www.researchgate.net/figure/10th-50th-and-90th-mass-and-height-percentiles-for-male-and-female-adults-for-Caucasian_tbl1_51180593#:~:text=The%20size%20of%20each%20body,the%20weight%20is%2078%20kg

[11] https://www.eng-tips.com/viewthread.cfm?qid=342518