Webswinging Robot

Third Year Individual Project – Final Report

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Contents

1. Abstract

Wall climbing robots has been used for broad range of applications such as inspection and window cleaning. They tend to be bulky and heavy, a new adhesion technology called electroadhesion technology will be investigated robot locomotion. 2D and 3D Comsol electrostatic simulations based on Maxwell stress tensor will be developed for the pad optimization on dielectric materials. A comparison of different pad manufacturing techniques will be done. A new manufacturing technique based on UV light imaging will be proposed. A detailed procedure of how pad coating is done will be developed. The pad will then be tested in safety interlock setup. Force analysis on the robot will then be developed and a robot design will be proposed.

2. Glossary

HV High Voltage

PCB Printed Circuit Board

2D 2-Dimensions

3D 3-Dimensions

UV Ultra Violet.

ELA Electroadhesive

3. Introduction

Robots importance in human life is getting important, from inspection robots to landmine detection and removal [15]. An important characteristic of the robot is the locomotion technique used. This specifies how the robot can move and tackle obstacles. Conventional locomotion techniques such as droned, wheeled and legged robots lack the ability to work in certain environments as was analysed in the progress report. Which was the motivation for using different locomotion technique.

Many robot designs have been inspired from nature such as legged robots for instance which are inspired by human. The progress analysed Webswinging robots. Which are inspired from spiders. The robot uses robes and hooks to attach to objects and tackle obstacles. This robot lacks the ability to move in areas where fragile objects exist. Such as a room with mirrors or glass. Also, it is hard for the robot to work in an area where human exist. Therefore, the goal of the project was shifted from Webswinging robots to wall climbing robot.

Wall climbing robots provide an extra skill the robot can use while moving, which is it is ability to only use ground surfaces but also vertical surfaces. If the ground has a big gap. Legged and wheeled robots can get completely stuck. At the same time wall climbing robot can adhere to the wall avoid the gap and then move back to the ground.

There are different adhesion techniques the robot can use to adhere to the wall. Such as suction cups, dry adhesion, magnetic adhesion and electroadhesion. These were analysed in the progress report in details. electroadhesion was chosen the adhesion technique for this project. This was because of it is ability to work on almost all surfaces such as conductive (aluminium) and non-conductive (brick) surfaces. Rough (wood) and smooth (glass) surfaces. Regular, irregular and dusty surfaces. electroadhesion also uses very low power, in the order of μW which is a great advantage over ordinary adhesive technologies such as suction cups. electroadhesion has relatively fast and easy controllability. And finally, electroadhesion provides quite operation.

3.1. Aims

The general aim of this project is to have a robot that can climb the wall. Which will give it an additional locomotion skill to tackle obstacles, but what can the robot do if it is able to move up the wall?

Wall climbing robots have been used for window cleaning, inspection and urban reconnaissance [7]. However more tasks can be done which were not thought of before. Such as having a wall climbing robot which can paint the wall. Although human can do these tasks, it’s hard to apply complex designs, and if possible, it will take significantly longer time compared to the robot. Also, when it comes to high outdoor buildings it becomes risky for human to do it. Imagine having a full building that is painted with any design needed.

3.2. Objectives

The main part for the robot is the electroadhesive pad which is required for the adhesion to the wall. If better pad is used, higher adhesion force will be generated and therefore smaller and heavier robot can be used. In other words, the better the pad the easier it is to design a robot which can easily climb the wall. Therefore, optimization of the pad is needed.

Most of the literatures used electrostatic simulations for optimizing the pad parameters. Where all the pad parameters are fixed and only one parameter is changed. In order to analysis the effect of this parameter on the force generated. Although literatures did simulations for different pad parameters, they contradict in important parameters [2]. Also, not all parameters have been simulated such as the electrode thickness, coating thickness, coating dielectric constant and coating thickness. Therefore, Comsol electrostatic simulation will be used to acknowledge what is given by the literatures and provide information for what was not done before.

Also, it was found that literatures don’t only contradict with each other’s, some literatures either don’t have experimental results [16] or their experimental and theoretical results don’t agree. Therefore, an experimental testing will be done to analyse the agreement between theoretical and experimental results. Because of the high voltage used for the pad. Safety interlock setup was used for testing the pad.

Finally, an analysis of the forces on the robot will be done to know how big the robot will be if the pad is integrated to it. As will be shown the analysis cannot be done on it is own therefore the robot will be designed as will be shown in section 8.

After designing the robot, it should then be manufactured and tested on vertical surfaces.

4. Theoretical Development

Electroadhesion is the fact of producing an electrostatic force electrostatic force in material, by applying high voltage in the electroadhesive pad more than 1 kV. The glory about electroadhesion is that it works in both conductive and non-conductive materials.

The force generated in each material is based on completely different approach. For conductive substrates the charges are able to move and align them self-based on the voltage applied in the pad. Attraction between the charge generated in the pad and opposite charges in the substrate cause force that result in the substrate stick to the pad. In dielectric material because the charges are not able to move, the force occurs because of the polarization in the pad [2].

Electroadhesion is a complicated phenomenon with over 33 variables affecting the force generated, some of these variables are based on atmospheric parameters which are very hard to control such as temperature and humidity [2]. Other variables such as pad parameters can be easily controlled, therefore a model will be used to optimize the pad parameters in order to use these parameters in the pad design.

Literatures used different methods for optimizing the parameters for the pad such as [1] which used the average electric field in the substrate for optimizing the width and space between the electrodes. Although the electric field is an important factor which affects the force, it’s not the only factor. Either a vector product of electric field with polarization has to be done to get the electrostatic force, or Maxwell stress tensor equation where the direction of the electric field needed to be taken in to consideration.

[2] used 2D Comsol Multiphysics Electrostatic model to calculate the adhesion pressure of the pad based on the average polarization in the dielectric substrate, however the method of how the force is calculated wasn’t mentioned.

[3] used the capacitance of the pad for optimizing the pad geometry. Capacitance is the ability pad to have charge for a given voltage which is important for conductive

substrates. Since charge carriers in the substrate can be attracted forming a layer of charge near the surface which is what forms the force. In the case of dielectric substrates, the charge carriers are locked in the atom as was mentioned before. The value of capacitance will correspond to the force from charges that are already near the surface.

[4] and [7] and [11] used Maxwell stress tensor for the force calculation. This is the best way since it calculates pressure at different faces in the substrate, which is what is needed to be optimized. Also, the equation is derived from Lorentz force law shown in equation 4.1. So, it's relating the microscopic force inside of the material to the macroscopic force generated on the dielectric substrate.

$$F = q(E + v \times B) \qquad (4.1)$$

Where: F is the force on a charge in the material, q is the electrical charge, E is the electric field experienced by q, v, is the velocity of the charge, B is the magnetic field experienced by q.

Equation 4.1 is the bases of Maxwell stress tensor. When the dielectric substrate experiences an electric field, the substrate will be polarized depending on the polarization type the atom structure will change. If dielectric polarization is considered for instance, electron clouds around the atom will shift which will be captured by equation 4.1 and therefore by Maxwell stress tensor.

Because the force in dielectric material is mainly based on polarization [2], Maxwell stress tensor was used for the model.

4.1. Simulation Procedures

Comsol Multiphysics was used for the modelling because it has the ability to compute electric field in independent directions. Which is needed for Maxwell stress tensor equation as will be shown by equation 4.3. Comsol also has the ability to calculate the maximum value in specific domain of the geometry which was needed for dielectric breakdown expectations.

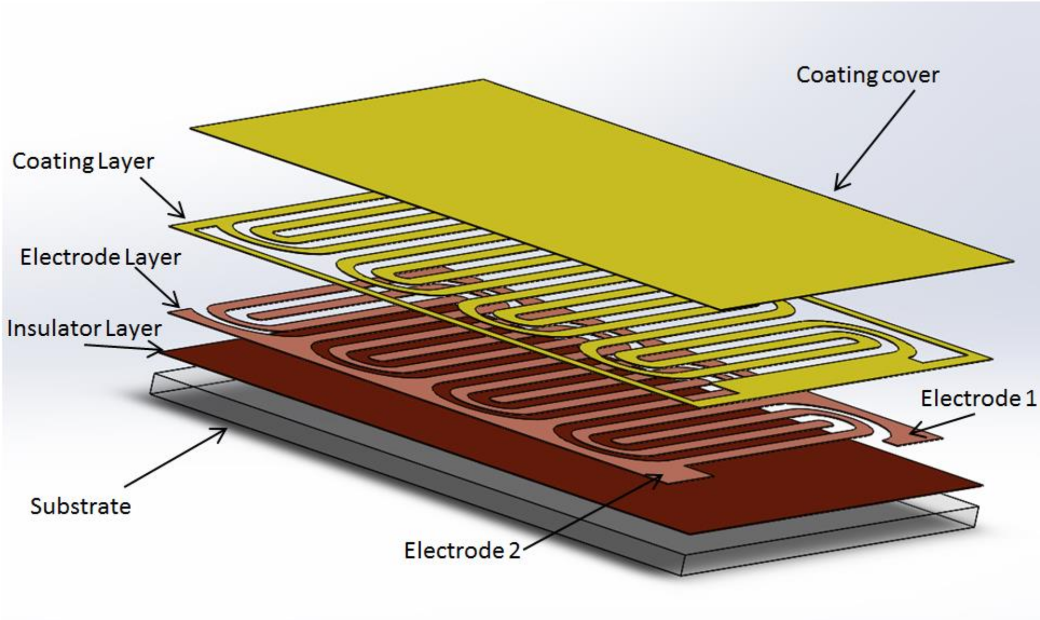


Figure 1: Electrodhesive pad Geometry.

Because of the symmetry of the geometry, SolidWorks was used for the Electrode layer. “Linear sketch pattern” function can be used where only 2 electrodes can be drawn and the function will replicate them for the specified number of electrodes. This electrode layer was then used to generate coating layer, by adding a rectangle around the electrode layer (to fill the areas between the electrodes). These two layers were then added to an assembly and imported to Comsol. The substrate, insulator and coating cover layers were then added in Comsol. These layers were done in Comsol for easier controllability of their thicknesses. The final geometry is shown Figure 1. The structure of the pad will be explained in detail in section 5.1.

Table 1

Layer	Substrate	Insulator	Electrode	Coating layer	Coating cover
Material	Glass	Polyamide	Copper	Polyurethane	Polyurethane
Thickness (μm)	1000	25.4	25.4	25.4	25.4
Relative permittivity	4.2	3.4	1	3.6	3.6

The thicknesses of the layers were chosen as shown in Table 1. For all of the layers except the substrate, the values reflect the parameters for pad 6, which will be tested in section 6.2.7. This pad was chosen because it generates significant forces unlike the pads before it. Although the thickness of the substrate used in the test was 6 mm, the substrate was chosen as 1 mm in the model. This is because when 6 mm substrate is used in the model the results are relatively low. This will be justified in section 4.2.1. The electrode width was chosen as 5 mm and the gap between the electrodes were chosen as 5 mm, again this is to reflect the values for pad 6. For the cad model see appendix 12.

After adding the geometry, the materials were then added as shown in Table 1. The pad materials were chosen to reflect the physical pads, justification of why these materials were used will be shown in section 5.1 [2] and [3] used glass as a sample for dielectric substrates. So, the substrate material was chosen as glass as a starting point. The values for the relative permittivity of the insulator and coating layers were obtained from the datasheets [5] and [6].

After adding the materials an electrostatic physics was used, where 7500 V was applied to electrode 1, electrode 2 was grounded. The back face of the substrate was also grounded, similar to what [2] did.

The mesh was then generated, this will reflect the accuracy of the simulation. Finer mesh will give more accurate results, on the other hand more computation time. Extremely fine mesh was specified to the boundary between the substrate and the insulator layer. Fine mesh was chosen for the remaining layers. Ideally finer mesh should be specified for the substrate, because the pressure is calculated in the substrate. When finer mesh is applied to the substrate, the simulation didn't converge. Therefore, only fine mesh was used for the substrate. Less fine mesh in the substrate shouldn't affect the accuracy significantly because most of the stress occurs at boundary between the substrate and the pad, and this was generated as extremely fine. After the mesh is generated, stationary study was then added, and the simulation was computed.

As was mentioned before Maxwell stress tensor will be used for the electrostatic stress calculation.

$$\sigma_{ij} = \varepsilon_0 E_i E_j + \frac{1}{\mu_0} B_i B_j - \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{1}{\mu_0} B^2\right) \delta_{ij} \quad (4.2)$$

Where: σ_{ij} is the stress acting on face i in direction j, ε_0 is the permittivity of vacuum, E_i is the component of the electric field in direction i, E_j is the component of the electric field in direction j. μ_0 is the permeability of vacuum, B_j is the component of the magnetic field in direction j, E is the magnitude of electric field, B is the magnitude of magnetic field, δ_{ij} is Kronecker's delta

Equation 4.2 is Maxwell stress tensor general equation, used for electromagnetic forces calculations. In the case of electroadhesion, high dc voltage is applied with very small fluctuations, therefore the magnetic term will be neglected leaving only the electrostatic term shown in equation 4.3. Neglecting the magnetic term was done by [4].

$$\sigma_{ij} = \varepsilon_0 E_i E_j - \frac{1}{2}\varepsilon_0 E^2 \delta_{ij} \quad (4.3)$$

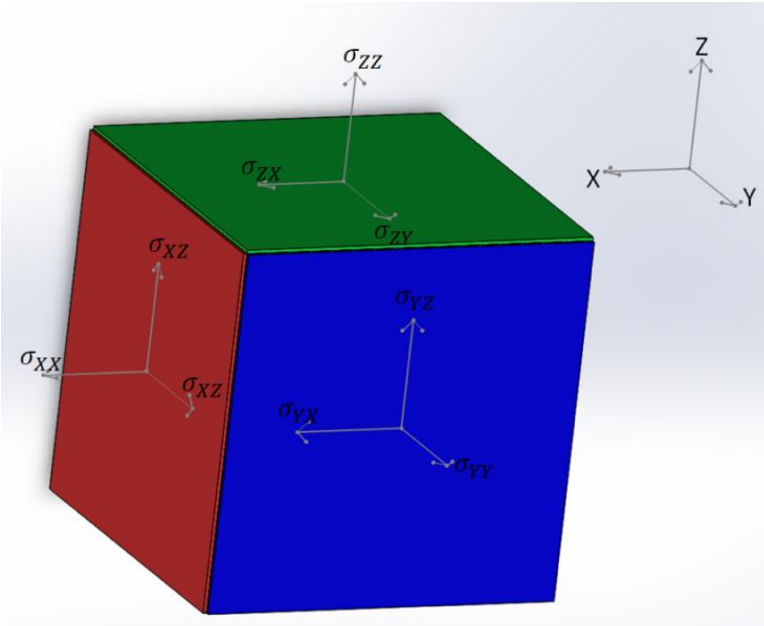


Figure 2: Cube for Maxwell stress tensor Explanation

Equation 4.3 in 3D will give a 3× 3 matrix, where each term in the matrix correspond to one the stresses shown in Figure 2. Consider the cube shown in Figure 2 to be the substrate shown in Figure 1, and the green face to be the boundary between the substrate and the pad. The force for electroadhesion is mainly because of the values in the Z axis. σ_{YZ} and σ_{xZ} can be neglected because these faces aren't in contact with the pad. σ_{ZZ} is the pressure between the substrate and the pad, this term will be used for the calculations. Therefore equation 4.3 will be as shown in equation 4.4.

Because i = j, δ_{ZZ} will be equal to 1.

$$\sigma_{ZZ} = \varepsilon_0 E_Z E_Z - \frac{1}{2}\varepsilon_0 E^2 \text{.....................} \quad (4.4)$$

Equation 3.4 is the equation used to plot Maxwell stress in the dielectric substrate. This will give the spatial pressure in the substrate as shown in appendix 2.

The aim of the simulation is to change the pad parameters and analyse the influence of each parameter on the force generated. The values plotted gives vector quantitates at each point in space. There are two methods which can be used to change this simulation results to scalar quantities. In order to compare each parameter effect easily. The first method is to integrate the pressure at the boundary between the insulator layer and the substrate which will give the force generate. The second method is take the average pressure in the substrate. If boundary integration method was used the force generated will be resulting from only the values at the boundary between the pad and the substrate. This will not consider any force away from the boundary. Therefore, surface average method was used, in order to capture the effect in all of the substrate. This is similar to what [2] did.

4.2. Factors affecting Electroadhesion

4.2.1. Thickness of the wall

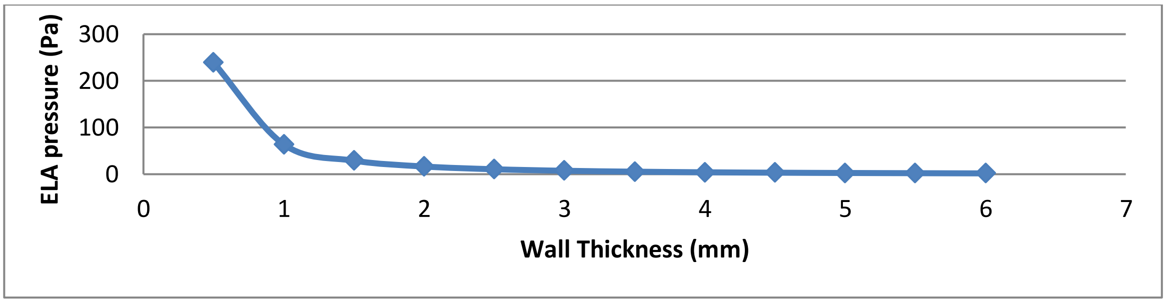


Figure 3: wall thickness influence on Electroadhesive pressure

Figure 3 shows that pressure is a steep function of the wall thickness, however as will be shown in section 6.2.7. This is not correct because at 6 mm the simulation is showing a pressure very close to 0 Pa and in reality, the pad generates a pressure of 86.8 Pa.

This occurs because pressure was calculated by taking the average pressure in the substrate, most of the pressure is occurring close to the boundary between the pad and the wall. Because electric field is inversely proportional to the distance square. When the wall thickness is increased this will increase the volume in which the values are calculate with small increase in the pressure. Therefore, when the average is calculated in the whole substrate smaller values were shown. 1 mm substrate was used for the rest of the simulation because it's the most reflective to the experimental values.

4.2.2. Relative permittivity influence on the pressure

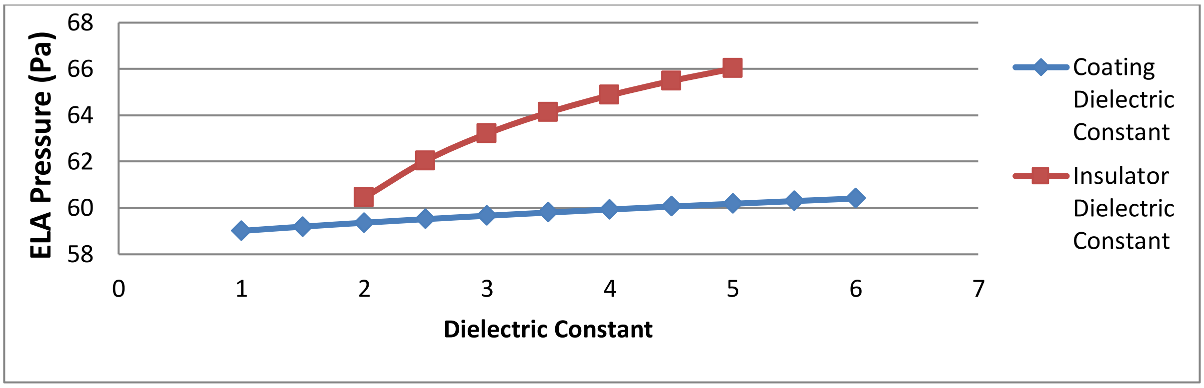


Figure 4: Influence of relative permittivity of different layer on the pressure generated

Figure 4 shows an increase in the pressure as the insulator relative permittivity is increased which is similar to what [2], [4] and [7] provided. This is because the higher the relative permittivity of the insulator layer the higher the electric field in the insulator layer. which will cause an increase of the average electric field at the boundary between the substrate and the insulator layer. causing higher pressure in the substrate. However, it should be noted that an increase from 2 to 5 in relative permittivity showed relative increase of only 9% in the pressure value. In real life because of friction between the substrate and the pad there will be a small air gap which will minimise the effect of relative permittivity even more. Because at the boundary in some areas there will be air layer not an insulator layer, at these areas the relative permittivity will always be 1. Figure 4 also showed that the higher the relative permittivity of the coating the higher the average pressure obtained which was not provided by the literature, but again the effect is small.

4.2.3. Thickness of the layers influence on pressure and electric field

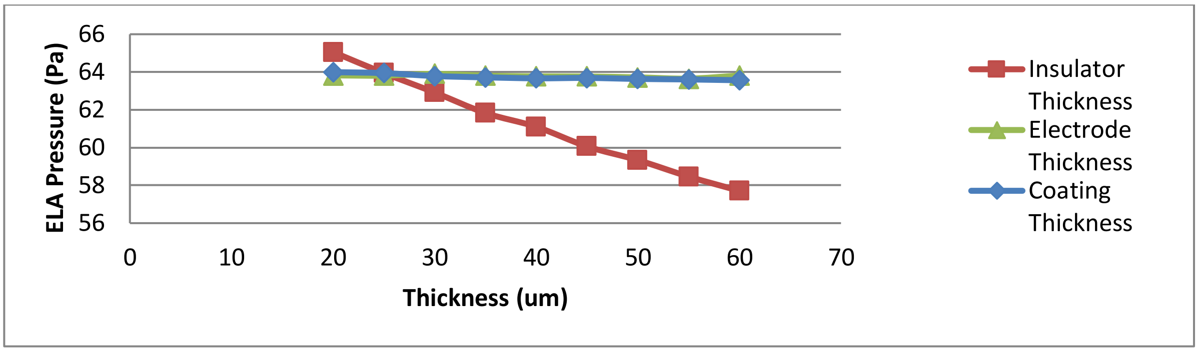


Figure 5: Influence of increasing the thickness of each layer on the pressure generated in the substrate

Figure 5 showed that the smaller the insulator thickness the higher the pressure generated which agrees with [2], [4] and [7] This is because electric field is inversely proportional to the distance square. The smaller the thickness of the insulator layer, the closer the substrate will be to the pad and therefore the higher the electric field which will provide higher pressure from equation 4.4. Figure 5 also showed that the electrode and the coating thicknesses don't cause effect on the pressure generated. This was not provided by the reference.

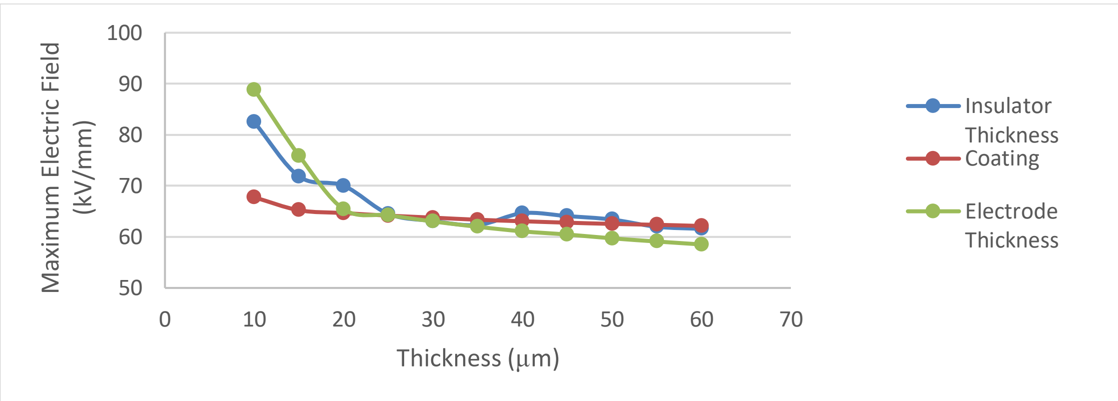


Figure 6: Influence of each layer thickness on the maximum Electric Field in the insulator layer

The force generated depends on the voltage applied which was provided by [2], [4] and [7] However, the higher the voltage applied the higher the risk of breakdown in the insulator and the coating layers. If breakdown occurred this will stop the pad from functioning. The literatures say that the smaller the thickness of the insulator layer the higher the risk of breakdown. However, this wasn't proved theoretically. Also, the literatures give no information about the electrode and the coating thicknesses influence on the electric field. Therefore, a simulation had to be done to analyse the steepness of each of these trends.

The purpose of the simulation is to calculate the magnitude of the maximum electric field in the insulator layer. If this value exceeded the dielectric strength of the material, then dielectric breakdown will occur. Electric field in simulations is strongly dependent on the mesh generated. In 3D it takes significantly more time to compute the values if finer mesh is generated. In 2D it takes less time because there's one dimension the simulation doesn't need to calculate the values in. Therefore, the model for electric field was done in 2D to be able to generate extremely fine mesh which will be significantly more accurate than the 3D simulation. In this simulation the only difference between the 3D and 2D simulations is the geometry used. The geometry used in the 2D simulation is shown in appendix 3, this is the similar to the geometry used by [2], [4] and [7], however it reflects the physical pad used in this project. The result of the simulation is shown in Figure 6.

The trend for the insulator thickness showed that the smaller the thickness of the insulator the higher the electric field, it showed different trend at 40 μm insulator thickness. This can be because of the error in the simulation itself. However overall the figure shows that the smaller that thickness of the insulator the higher the maximum electric field in the insulator. This acknowledge what was said by the literatures. If Figure 5 and Figure 6 are combined the optimum insulator thickness will be 25 μm. This will give the lowest electric field to pressure ratio which what is needed. The figure is show in appendix 4.

The model also showed that the thicker the electrode layer the smaller the maximum electric field in the insulator layer. This is because the thinner the electrode the sharper it's, which will cause very high electric field at a specific point which can cause dielectric breakdown. Because the electrode thickness doesn't affect the force generated as was shown in Figure 5, it's better that the electrode is chosen to be as thick as possible to reduce the risk of breakdown. The simulation also showed that the thicker the coating the lower the maximum electric field, this will be useful while spraying the pad as will be shown in section 5.1.3, especially because it's hard to accurately control the thickness of the coating.

4.2.4. Electrode width

The electrode width is an important variable for the pad design increasing the electrode width will increase the electrode layer area. This will increase the number of polarized charges in the substrate and therefore the force generated [4]. The force of electroadhesion in dielectric materials is mainly because of the interdigitated electrode designs, where there are large number of alternation between the HV electrode and the ground. When the electrode width is increased, the number of boundaries (number of electrodes) will reduce, which will reduce the alternation between the High voltage electrode and the ground, and therefore reducing the total force generated.

The literatures contradict for the trend of the force generated against electrode width. [1] showed that the optimum value is 3 mm, [4] and [7] showed that the smaller electrode the higher the force. [2] showed that the trend depends on the substrate thickness. [2] showed that there’s an optimum value for the electrode width for substrates with thicknesses between 1.8 mm and 2.2 mm. This optimum value was 1.8 mm. For substrates with thickness more than 2.2 mm, [2] showed theoretically that the smaller the thickness the higher the pressure. For substrates with thickness less than 1.8 mm, [2] showed theoretically that the bigger the electrode width the higher the pressure.

When the literature review was done there was many routes that can be taken to simulate the pad, one of them was to simulate the pad in 3D using the capacitance values as [3] did. Therefore 10 pads were designed in SolidWorks to simulate the effect of the electrode width in 3D. However, as will be shown in 6, the simulation isn’t very accurate in providing the trend for the electrode width. To save time the electrode width and gap between electrodes simulations were done in 2D. Because in 2D only 1 model is needed, and the electrode width can be changed in the same model. However, in 3D if 10 values are to be plotted 10 models will be needed. The only new difference from 3D to 2D will be the equation used. In 2D the equation 3.4 was used for pressure plotting, the y axis is pointing up.

$$\frac{\varepsilon_0}{2}\left[E_y^2 - E_x^2\right] \qquad (4.4)$$

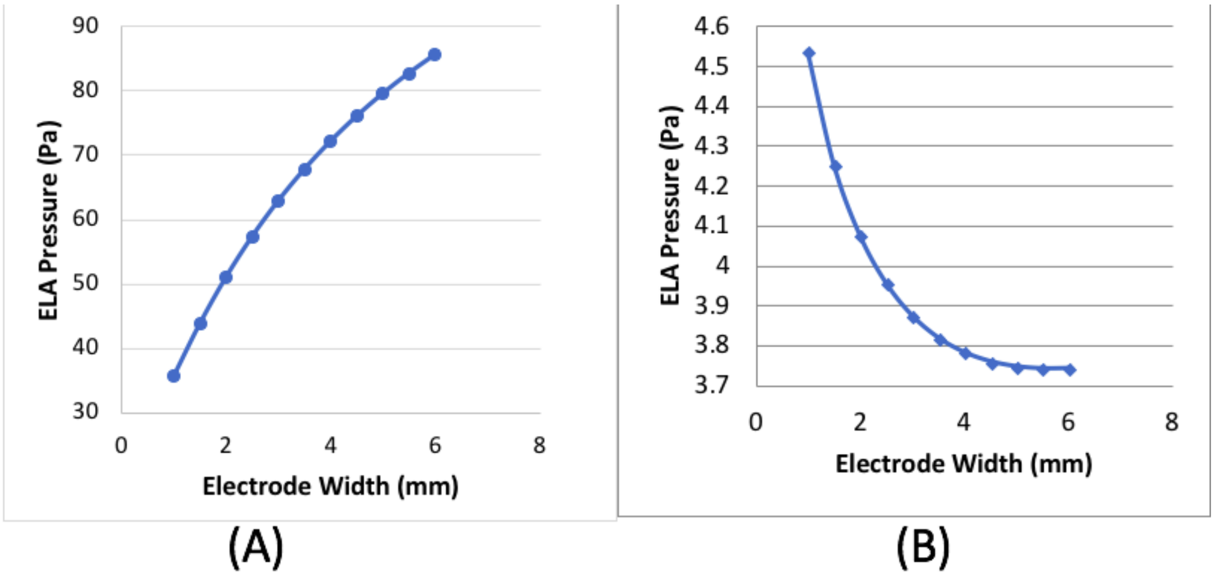


Figure 7: Influence of electrode width on ELA pressure for different substrate thicknesses. (A) 1 mm substrate (B) 6 mm substrate

As was shown by [2] for optimizing the electrode width the substrate thickness has to be taken into consideration, the pad will be tested using 6 mm substrate, so this value was plotted, 1 mm substrate thickness was plotted as well since it was used in previous simulations. The result is shown in Figure 7. This agrees with [2]. The pad will be tested on 6 mm substrate, therefore the electrode width should be as small as possible.

4.2.5. Gap between Electrode

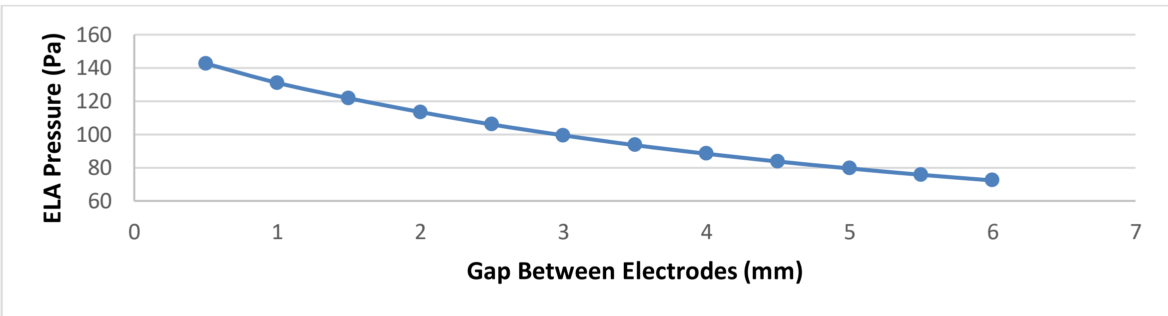


Figure 8: Influence of gap between electrodes on the pressure generated.

If the gap between the electrodes is reduced. Both the effective electrode area and the number of electrodes will increase for a given pad area. Therefore, the overall pressure will increase as shown in Figure 8. However, when the gap between the electrodes is reduced the probability of dielectric breakdown occurance will increase so the gap should not be reduced indefinitely.

5. Pad Manufacturing

5.1. Parameters used

5.1.1. Insulator Layer

As was shown in Figure 1, the pad should consist of three layers the first one from the bottom is the insulator layer, this is the layer which will be touching the substrate. It should be flexible to conform around the substrate in case it is irregular or rough. Polymers are commonly used for this layer especially Polyamide [7], [4], [2] and Polyester [3]. Polyester has dielectric strength of 310 kV/mm and dielectric constant of 3.2 [3]. Polyamide has dielectric strength of 303 kV/mm and dielectric constant of 3.4 [6]. Polyamide was chosen since it has higher dielectric constant which means higher force as was shown in section 4.2.2, especially because the difference in dielectric strength is very small. The thickness will be 25.4 μm since it's very close to the optimum value 25 μm as mentioned in section 4.2.3.

5.1.2. Electrode Layer

The second layer is the electrode layer which has to be conductive. Usually this layer is made of aluminium [8] or copper [3], [2]. Since they are good conductors, flexible and commercially available with the structure needed. There was access to a sheet which had polyamide as the insulator and copper adhered on both of it is sides. Although the thicker the electrode the better as was shown in section 4.2.3, the thickness used was 25.4 μm because of the materials available.

5.1.3. Coating Layer

The third layer is the coating, this layer is applied for two reasons. The first one is to provide dielectric medium for the electric field applied which should increase the force. Section 4.2.2 showed that the higher the relative permittivity of the coating the higher the force generated will be.

The second reason why the coating is applied, is to increase the breakdown voltage, since the higher the voltage applied to the pad, the higher the force generated. The breakdown voltage in the coating is affected by two parameters. First one is the dielectric strength of the coating and the second one is the bonding of the coating to the insulator and electrode layers.

If no coating is applied the coating can be considered as air. If polyurethane is considered as the coating for instance, which has dielectric breakdown of 60 kV/mm [7] as compared to 3 kV/mm for air. This is a significant difference which can cause significant increase in the breakdown voltage as will be shown in section 6. therefore, the coating has to be done and cannot be skipped.

The most popular material used for this layer is Polyurethane this was used by [2] and [3]. As was mentioned before this material has high dielectric strength (60 kV/mm) and a dielectric constant of 3.6. It’s a hazardous spray which is a disadvantage since this provide limitations if the pad is to be manufactured at home.

Silicon acetoxy was used only by [8]. The big advantage of this material is that it’s gel which is commercially available, so it should be easier to use over Polyurethane. it has a dielectric strength of 300 kV/mm and dielectric constant of 3.1 [8].

The bonding to the material defines how good the coating can stick to the material, this is a complicated area to look at and it was not investigated in this project because of the time required. The bonding to the material might be the reason why most of the literatures prefer polyurethane over Silicon.

Although the dielectric breakdown for Silicon is much higher than polyurethane as will be shown in section 6, the pad doesn’t suffer from dielectric breakdown it’s suffering from surface flash over. In other words, breakdown occurs through air which means that 60 kV/mm is high enough. Also, Polyurethane has a dielectric constant of 3.6 which is higher than dielectric constant for silicon 3.1. This means that at the same voltage a pad coated with Polyurethane will provide higher force than a pad coated with Silicon. Therefore, Polyurethane will be used for the coating material.

Having a perfect coating with no air bubbles is essential to reduce the probability of breakdown occurrence. since air has a dielectric breakdown of 3 KV/mm which is much lower the coating breakdown voltage. Perfect coating is very hard to achieve. There are techniques which can be used to reduce the probability of having trapped air bubbles such as using a vacuum oven. Instructions for how to use the vacuum oven is shown in section 5.3.3.

5.2. Different manufacturing techniques being used

5.2.1. Direct image using wax and Xerox solid-ink printer

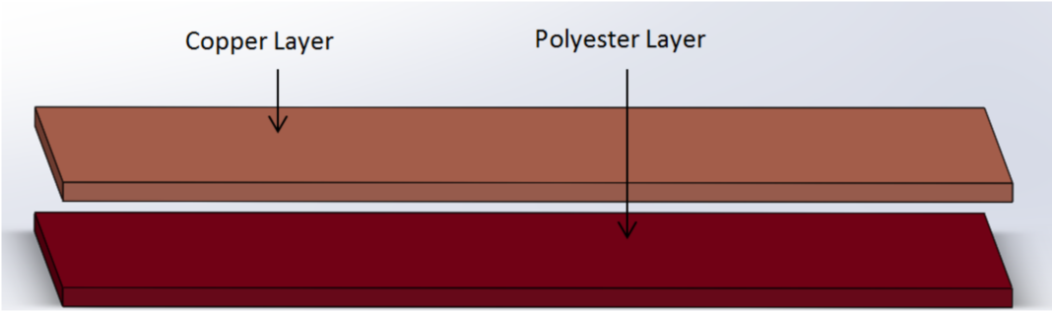


Figure 9: Structure of the material used by [3]

[3] Used a copper laminate with a structure similar to the one shown in Figure 9. The insulator layer material was polyester. And the electrode layer was copper. The process is aiming to provide an electrode geometry similar to the one provided in Figure 1 excluding the coating layer. The process starts by cutting the laminate into A4 size pieces to be able to fit the pads in the printer; sandpaper is then used to remove sharp edges in the material. Iso-Propyl Alcohol and acetone were then used to clean the pad and allow the wax to stick to it.

The electrode geometry was then designed using SolidWorks. The design is then to be printed on the copper laminate, using Xerox solid-ink printer. This will apply wax in the areas where the copper is to be kept. No wax will be applied to the areas where the copper is to be etched away. This is evaluated based on the design.

The pad is then placed in a tank which contains ferric chloride. This step will etch away the areas which don't have wax. Water is then used to clean the pad from any ferric chloride which was not removed. The wax was also removed using label removal. The polyurethane coating should then be applied as will be shown in section 5.3.3.

This method is relatively cheap if the tools required, like the solid ink printer are available. This method doesn't provide the flexibility of changing the pad size since the pad size is fixed to A4 size. It was not possible to use this method since there was no access to solid-ink printer.

5.2.2. Manufacturing of an electroadhesive pad without machines

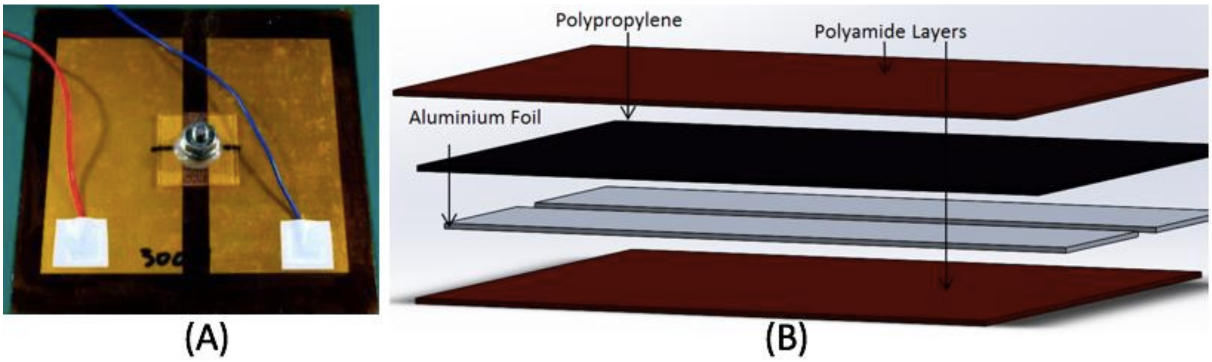


Figure 10: Electroadhesive pad done by [9]: (A) Physical pad, (B) Structure of the pad

The structure of the pad is simple and was done using conductive electrodes in between non-conductive plates. [9] manufacturing process starts by cutting an aluminium foil into rectangles and glue into 200 μm of polypropylene sheet as shown in Figure 10. 75 μm thick polyamide sheet is then used as the insulator layer (layer attached to the wall). Another layer of polyamide was used on the back side of the polypropylene sheet to provide symmetry for the pad.

This is what was done by [9], however technically the pad can be sprayed using the coating before gluing the electrode layer to the bottom polyamide layer.

This is the cheapest technique for having an electroadhesive pad, there's no need to buy machines like the UV light exposure machine, the laminator, the Xerox solid-ink printer or 3D printers. The size of the pad can be much bigger than the rest of the methods. Also, the conductive layer can be cylindrical wire as an example which will avoid sharp points which will reduce risk of dielectric breakdown.

As was mentioned in section 4.2.4, the smaller the gap between the electrode the higher the force generated. If the gap is to be 1 mm as an example it's going to be very hard to perfectly align the electrodes by hand. Probably impossible to do around 40 electrodes glued next to each other with no human error introduced. if any two electrodes touched short, circuit will occur. Even if they are closer together (less than 1mm) this can cause breakdown to occur at a voltage less than the breakdown voltage achieved by other manufacturing methods.

5.2.3. Pad manufacturing Based on SLA Rabid Prototyping

This manufacturing technique is slightly different from the previous ones, it was used by [1] It's based on having non-conductive mold which sets the internal shape of the pad. The conductive electrodes are then added which will take the shape defined by the mold.

The mold has three layers made of non-conductive silicon; these layers are the base, core and, cover layers. The base layer is the one touching the substrate; this is equivalent to the insulator layer shown in Figure 1.

The core provides channels for the conductive electrodes. These channels define the geometry of the electrode, its dimensions, and the gap between them. The core layer is manufactured based on SLA rabid prototyping process. The electrodes are made of conductive silicone which was used to fill the gaps provided by the core as shown in Figure 11. To fully enclose the electrodes a final layer of non-conductive silicon was added as the cover layer as shown in Figure 11.

To allow the base to be as flat as possible an extra cover is added to the base while the electrodes are curing, after curing this layer was removed.

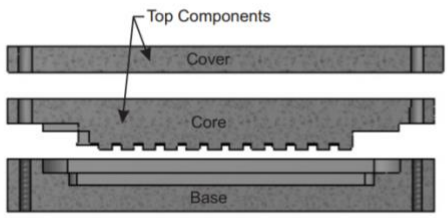


Figure 11: cross-section of the Pad used by [1]

There is an important advantage for this technique as compared to the others, the core which is what sets the shape of the electrode is done based on 3D design which is really useful, as was mentioned in section 4.2.3, the sharpness of the electrodes directly affects the electric field in the insulator and coating layers. for 2D technique shown in sections 5.2.1 and the method used in this paper. The electrodes are rectangular in shape which have very sharp points near the edges. This increases the risk of breakdown. If the electrodes are going to be manufactured in 3D the electrodes can be cylindrical in shape this will reduce the electric field in the insulator and coating layers and higher voltages can be reached before breakdown. This will provide higher forces.

This manufacturing technique doesn't need coating layers unlike the other methods. since the dielectric medium is set by the core layer. The problem with this technique is that it requires SLA rapid prototyping which is some form of 3D printing. Therefore, it's expensive. Because the materials are flexible. The 3D printer available was not able print the core. Therefore, this method was not used in this project.

5.3. Manufacturing technique used

After analysing the advantages and disadvantages of methods already in use. The only method which can be used is the one that does not require a machine. because other techniques require tools that there is no access to. As was mentioned before misalignment of the electrodes can cause short circuit, and it is hard to accurately align the electrodes which will be hard to compare the experimental results to the theoretical ones. Therefore, a new manufacturing method will be proposed which is very similar to the one used in section 5.2.1. Traditionally this method is used for flexible PCB designs.

5.3.1. Design of an Electroadhesive Pad

Figure 12: Pad 5 Altium design

The worm comb design will be used for this project which was proposed by [3] as the best design, for more explanation see appendix 5. The design of the pad is shown in Figure 12.

The pad had to be designed in Altium Designer. This will be used by the plotter machine to generate the negative. The negative will be used in printing the design on the pad. The worm comb design with 5 mm electrode width and 5 mm gap between the electrodes will be shown as an example for how the design was made, the rest of the pad were done using the same procedures.

Unlike other PCBs this design doesn't need a schematic diagram however using a simple schematic will guarantee that the tracks are never closer than the minimum distance required. The clearance is set as 5 mm to make sure no tracks are closer than this value. A schematic was done with only 2 nets. HV and ground.

Rectangle blocks were used as the copper tracks and attached the HV net, arcs were used at the end of the tracks arcs to have the worm comb shape. As shown Figure 12.

The same steps were done for the next track and arc however it will be attached to the ground net. When there are 4 tracks and two arcs this is the design of the pad and it just need to be repeated for a specific number to achieve the length required for the pad. The pad shown in the figure needed just 4 tracks.

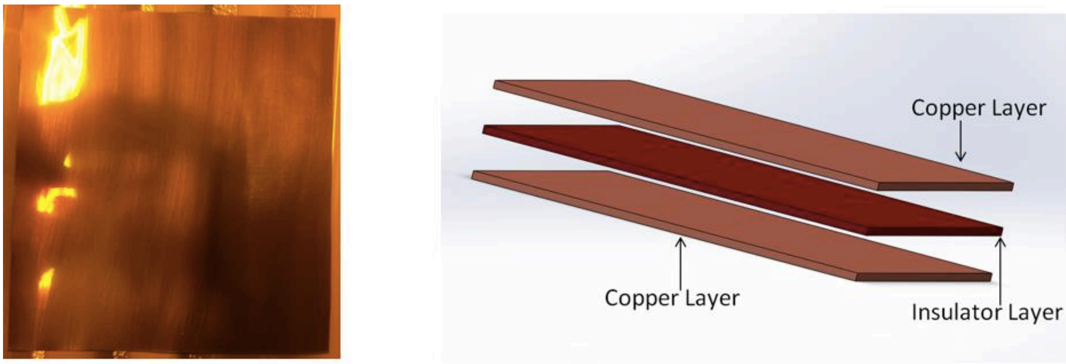
There's no clear way in Altium to repeat the same blocks more than one time. So, the blocks were copied and pasted but when pasted. Paste special was used to keep the nets for the blocks. This was done more than one time until the required dimension was achieved.

Polygon pour was used for the side electrodes where. One polygon was attached to the HV net and the other was attached to the ground net. In the properties of the polygon it was chosen to pour over the same net. This will merge the tracks of the same net and the side electrodes.

For the worm comb design there are two tracks of the same net one that is connected directly to the side electrode and the one that is connected through the arc. The polygon was extended to even further to cross the arcs and reduce the sharpness of the tracks that aren't connected directly to the side electrode.

Finally, two copper blocks were added for connections. This was done for the pads were the width of the tracks is small. For this pad the side electrodes are big enough for connections therefore these blocks were not added.

5.3.2. Printing the design using UV light imaging



(A) (B)

Figure 13: (A) Material used front face view, (B) The structure of the sheet in (A).

The material used was supplied from (DuPont, UK). The material used is shown in Figure 13(A). In the context of this paper this material will be referred to as the pad. The pad consists of an insulator layer made of polyamide with 2 copper layers adhered to it as shown in Figure 13(B).

The first step was to laminate the pad with a photo resistive film from the top and the bottom. The photo resistive film is transparent which is not visible in pictures. The photo resistive film is the layer on the pad where the image (circuit design) will be applied to.

(A) (B) (C)

Figure 14: (A) Pad with the negative on the top (B) UV light Exposure unit. (C) Pad after UV light is applied.

The negative mentioned before which is generated by the plotter machine is placed on the pad as shown in Figure 14(A). The UV exposure unit shown in Figure 14(B) applies UV light to the top and bottom layers of the pad with negative on top of it. The exposed areas of the copper will be hardened which will not be etched in the next steps. The black areas will not be affected by the UV light. Because the copper layer in the bottom isn’t needed for an electroadhesive pad. A layer was used below the pad to stop the light from being exposed to the bottom of the pad. The result of applying the UV light is shown in Figure 14(C).

The UV machine sucks air from its borders to make the pad and the negative film are as close to each other’s as possible. This is done so that the light does not diverge because of the creases in the material. If it did this can merge two tracks together. In an electroadhesive pad this will cause a short circuit and therefore a failure in the pad.

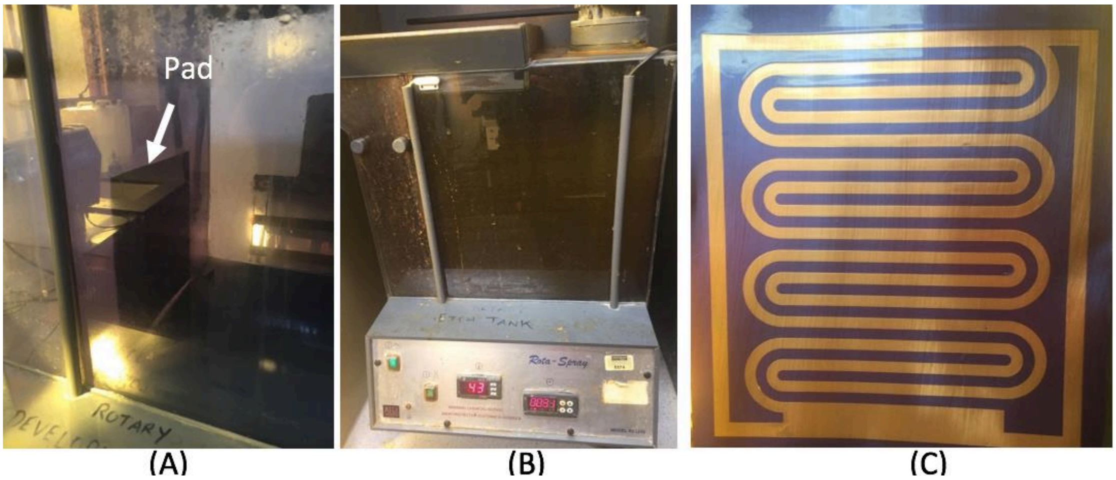
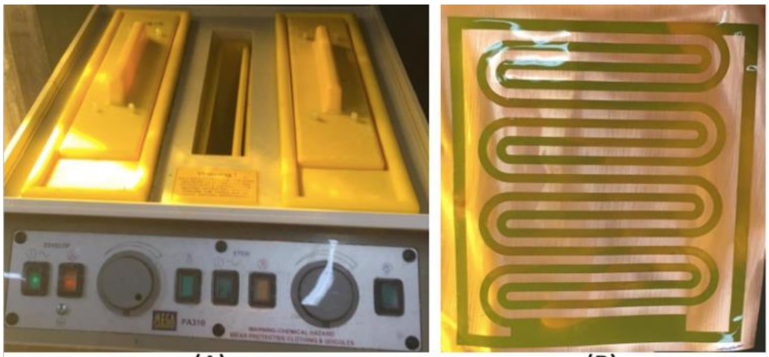


Figure 15: (A) Developing solution tank (B), Etching tank, (C) Etching resuly

The next step is to put the pad on the side of a developing solution tanks as shown in Figure 15(A). The developing solution will be spinning in the tank. This should be done for both sides of the pad. This step softens the areas that were not exposed to UV light so that it’s easier to remove them when the pad is placed in the etching tank. The pad is then placed in the etching tank where ferric chloride is spinning in the tank in a similar manner to the developing solution tank. Note that the pad is inside the tank in Figure 15(B), however it is hard to see it because ferric chloride is spinning. The result of this step is shown in Figure 15(C) where the UV light effect is obvious on the photo resistive film applied in the first step.



(A) (B)

Figure 16: (A) Tank for removing the laminate, (B) Final result

The photo resistive film was then removed by placing the pad in the tank as shown in Figure 16(A), then using water to remove the film. This is done for both sides of the pad. The pad was then left to dry. The final result of this process is shown in Figure 16(B). The result of this process is the insulator and electrode layer from Figure 1.

Manufacturing the pad using this method is cheap if the tools required are available, which is the case for this project.

There are limitations for the size of the pad manufactured using these techniques. As was discussed before the UV exposure unit sucks the air from the borders, the bigger the pad the higher the possibility that the force on the pad from on one edge is higher than from the opposite edge. This will cause creases in the material which can lead to failure of the pad. Also, after putting the pad in Ferric chloride, the pad is very flexible, similar to a wet paper, which increases the risk of the pad to be cut if the pad is bigger.

The size of the pad is an important factor since the purpose of this project is to investigating wall climbing robots using electroadhesion for locomotion. Where the best design is the tracked robot design which requires relatively long pad 1.3965 m as will be shown in 8.3. This manufacturing technique cannot do a single pad which is that long. Not only because of the risk of breakdown but also because the height of the etching tank, laminator and exposure unit is less than the required length.

5.3.3. Spraying the pad using Polyurethane

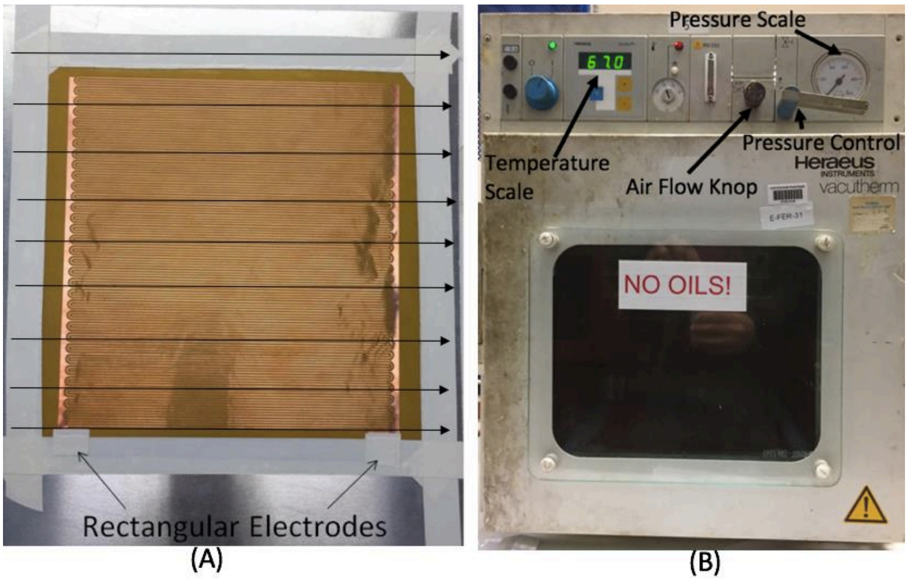


Figure 17: (A) Pad Before spray (B) Vacuum oven used

The pad was sprayed in the fume cupboard for ventilation. For the risk assessment see appendix 17. For a pad sprayed in wrong procedures see appendix 16. To keep the pad as flat as possible, the pad was placed on an aluminium sheet as shown in Figure 17(A). 4 pieces of tape were used on the corners to make fix the pad on the base. The sides of the pad were covered by tape to prevent the spray from leaking to the back of the pad. By making pressure on the pad using a book the air below the pad was removed while putting the side tape pieces. Again, this is done to make the pad as flat as possible. The rectangle electrodes shown in Figure 17(A). were covered by tape to be able to make connection to the pad after having the coating.

The pad was sprayed from left to right in one direction as the arrows are pointing in Figure 17(A). Since the pad has a width of 195 mm this was approximated to 200 mm. The pad was sprayed for around 2 seconds to have speed of around100 mm/s as specified by the [7]. This was repeated vertically until all the pad is covered, in other words each arrow in the figure takes 2 seconds. The pad was then left for 3 minutes for the spray to be more defined. This will make some areas where there's no spray these areas will be filled when another layer is sprayed. This was done 4 times to make sure the whole pad is covered. The number 4 doesn't represent scientific background, however the simulation showed that the thicker the coating the lower the maximum electric field in both the insulator and the coating layers, so it's better to make it thicker to reduce the risk of breakdown.

The pad was then put in the vacuum oven shown in Figure 17(B), for 90 minutes at around 80°. This is one of the recommended drying time in the datasheet. The air flow knop must be put vertically to avoid air from getting in to the oven, the pressure control hand was then put in the horizontal position as shown in Figure 17(B) this will allow the pressure in the oven to change. The pump was then turned on which will suck the air inside the oven until 0 Pa Pressure is achieved (vacuum). The pump is not shown in the figures. The temperature of the oven will increase gradually till 80℃ is achieved. The time is then started. After 90 minutes the pad is taken out of the oven and left for 24 hours before testing.

6. Experimental Results

6.1. Experimental Setup

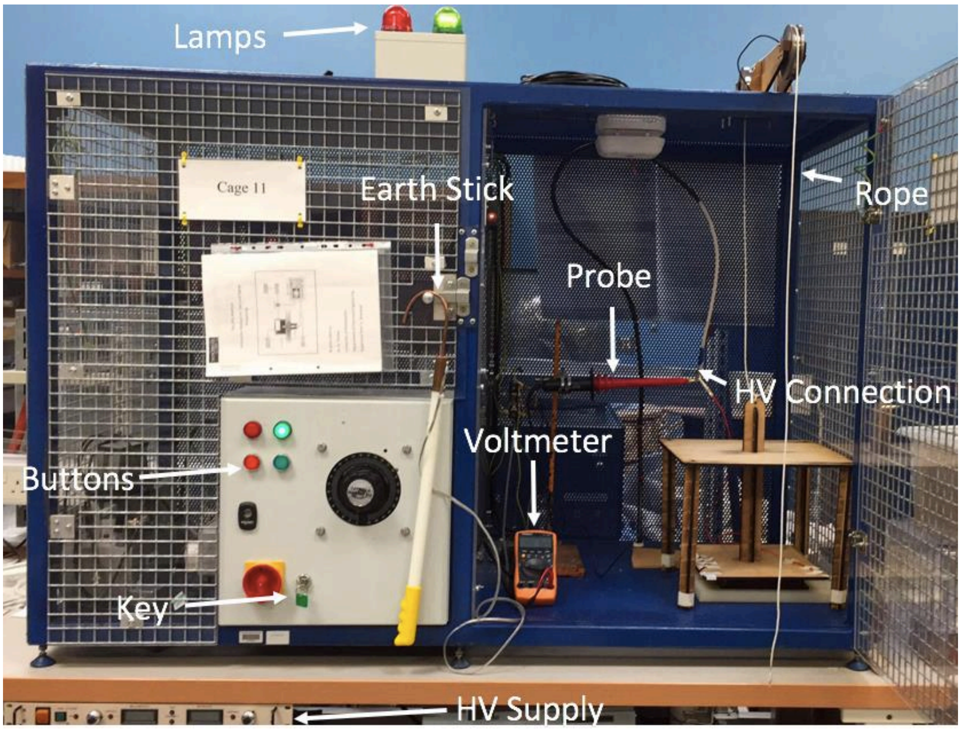


Figure 18: Safety interlock system

[2] and [3] used an expensive 6 axis force/torque sensor for the quantifying the force generated. This sensor is more expensive than the budget used in this project. Therefore, an indirect force measurement was used to quantify the force generated. Because of the high voltage applied to the pad a safety interlock system was used. the setup is shown in shown in Figure 18. Although the front face of the cage is completely closed, the top and bottom of the cage had 5 mm holes. A rope was

passed through these holes to safely move the pad from outside the cage. The components needed for the cage were designed using SolidWorks, to save time and cost.

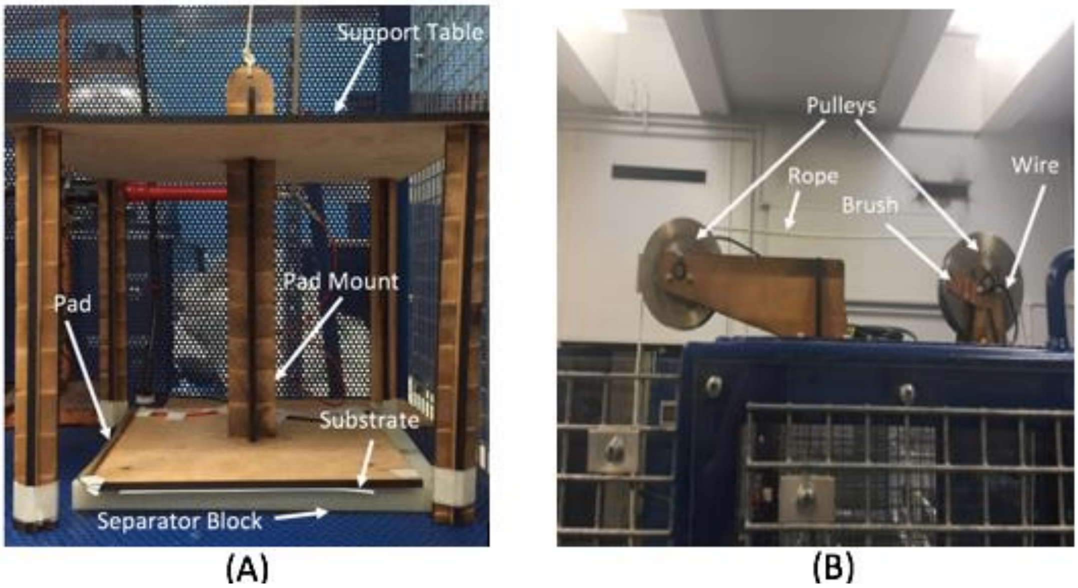


Figure 19: (A) Pad mount and Support table (B) Side View of the pulleys

Two pulleys were manufactured as shown Figure 19(B), to allow the experimenter to move the pad mount shown in Figure 19(A) from outside the cage. High voltage supplies are susceptible to charge build up. Any unexpected dust or paint on the robe can cause charge build up on the robe and then the experimenter. This can lead to an electric shock to the experimenter if the pulley material was nonconductive.

To avoid this, the pulleys were manufactured to be conductive as a safety precaution. The pulleys were earthed. If charge build up occurred on the robe, current will flow from the pulley to earth without any risk to the experimenter. Metallic brushes were used to make a connection between the rotating pulley and the stationary earth wire as shown in Figure 19(B).

The pad mount and the support table were made out of nonconductive material (wood). To make sure the person doing the experiment completely isolated from the voltage applied inside the cage. The pad mount was used for the attachment of the pad, and the support table was used to keep the pad mount horizontal and therefore keeping the pad horizontal as shown in Figure 19(A).

Because the base of the cage is grounded. If the substrate was placed directly on the base there was going to be a high vertical electric field at the HV electrode which might cause dielectric breakdown in the insulator layer. Therefore, a separator block was used as shown in Figure 19(A). This is a non-conductive block which will the will raise the substrate from the earthed base.

The experiment starts by turning the interlock system on using the Key shown in Figure 18. The green is button is then pressed to supply power to the HV supply. If at any time the cage door is opened. A proximity sensor will switch off the power to the high voltage supply. The voltage is then increased to the required voltage.

The experimenter then pulls the robe from outside the cage to check wither the pad lifted the substrate or not. The substrate in the beginning of the test will be a sheet of paper to proof that there is a force. If the pad generated a force the next step is to quantify this force.

Wood was chosen as the substrate material because some indoor walls are made of wood. The thickness of the substrate is one of the variables that affects the force, Ideally the thickness of the substrate should be the same. In order to change the mass being lifted without changing the thickness, a weight lifter block was designed in SolidWorks see appendix 15, the physical block is shown in Figure 20. If the weight is to be increased more material of known mass will be added inside of the weight lifter. The thickness of the material in contact will be always be 6 mm as shown in Figure 20(B).

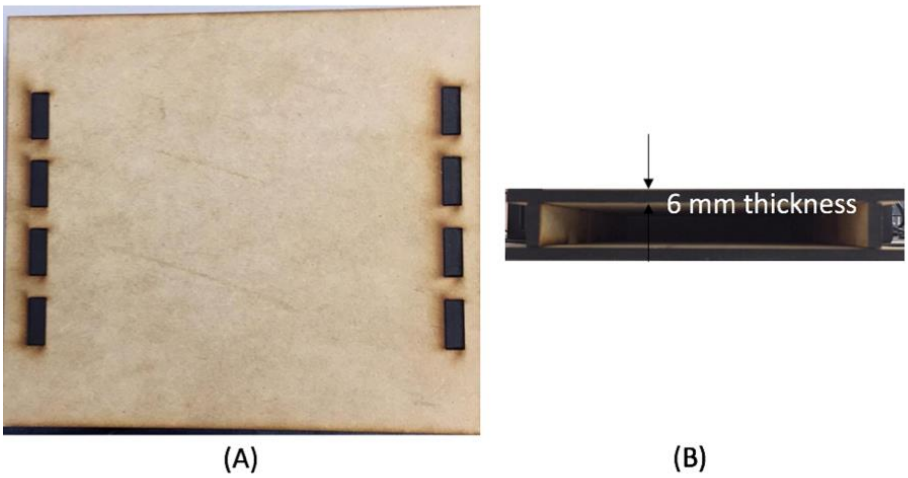


Figure 20: Weight lifter block: (A) Top View (B) Front View

After finishing the experiment, the voltage is returned to 0V, the red button is pressed, the cage is opened, and the earth stick is placed on the high voltage electrode, this insure that if there are any charges which didn't decay it goes to earth. To be able to measure the voltage supplied to the pad a probe was used as a potential divider. Because the voltmeter used isn't rated for that high voltage.

6.2. Experimental Testing

An important outcome of this project is to know how easy to manufacture an electroadhesive pad. Each step used adds time and cost to the manufacturing process. Therefore, some steps are going to be skipped to have a controlled measurement, in order to know the significance of each step in the breakdown voltage and the forces that can be generated.

6.2.1. Pad 1 Test

In this test the coating was removed to know wither or not any force can be achieved without it. The pad being tested is shown in appendix 6. The coating will effectively be air.

$$\text{Breakdown Voltage} = \text{Dielectric Strength} \times \text{Distance} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.1)$$

Section 4.2.4 and 4.2.5, showed that the both the electrode width and the gap between the electrodes should be as small as possible for higher forces. Both of them were set to 0.4 mm because this is the smallest value that can be done with confidence with the manufacturing method used. From equation 6.2 the breakdown voltage if air is used is 1200V. For safety the voltage was limited to 800V.

In the beginning of the experiment the pad was touching the substrate, the substrate in this test was a sheet of paper. The pad mount mentioned in section 6.1 was making pressure on the pad which reduced the thickness of the air layer between electrodes in the pad. The voltage was increased to 800 V and wait for about 60 seconds for charge to build up. The Rope was then pulled to check if the pad lifted the paper.

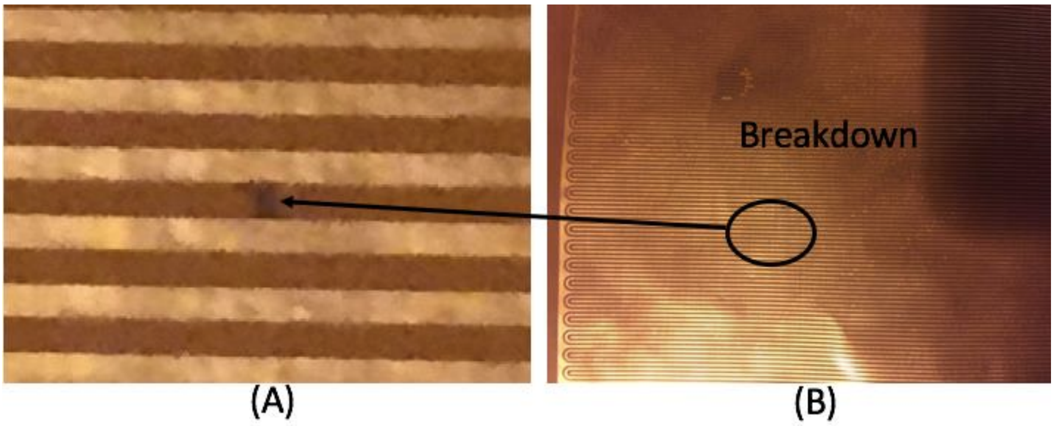


Figure 21: (A) Close up on the Breakdown in the material (B) Breakdown in the material

The edges of the paper were bend which showed that there's an attraction force between the paper and the pad. After around 3 seconds, surface flash over occurred which caused breakdown in the polyamide layer as shown in Figure 21.

The reasons why breakdown didn't occur instantaneously after 800 V was applied is that in the beginning there was very thin air layer because of the pressure from the pad mount. When the pad mount was lifted up and there was no pressure, air increased between the electrodes which caused flash over and then caused permanent breakdown in the insulator layer as shown in the figure.

The fact that breakdown occurred at 800V instead of 1200V showed that the simple calculation in equation 6.1 isn't enough, because the geometry the of the pad is an important factor which was not taken into consideration in the equation. This means that simulation has to be done to show the effect of the geometry on the Electric field.

Also, the equation is mainly done for air calculation, in other words if there are two points in air which have potential difference between them. Which is not the case for this pad. Since there's a surface (insulator layer) for the current to flow. Also, the gap between the electrodes was 0.4 mm which is less than 1 mm. The dielectric properties of materials change below 1 mm [2]. Therefore, the next pads to be designed will have at least 1mm gap between the electrodes to be sure about the properties of the material.

6.2.2. Pad 2

Electric field simulation for pad 2

The parameters used for this simulation is same as in Table 1, however the electrode width is 0.4 mm and the gap between the electrodes is 1 mm which are the parameters for the pad to be tested. The purpose of the simulation is to expect the voltage limit that should be applied. Therefore, the maximum electric field in the coating layer and the maximum electric field in the insulator layer were plotted for different voltages. For the electric field distribution in the surface see appendix 7.

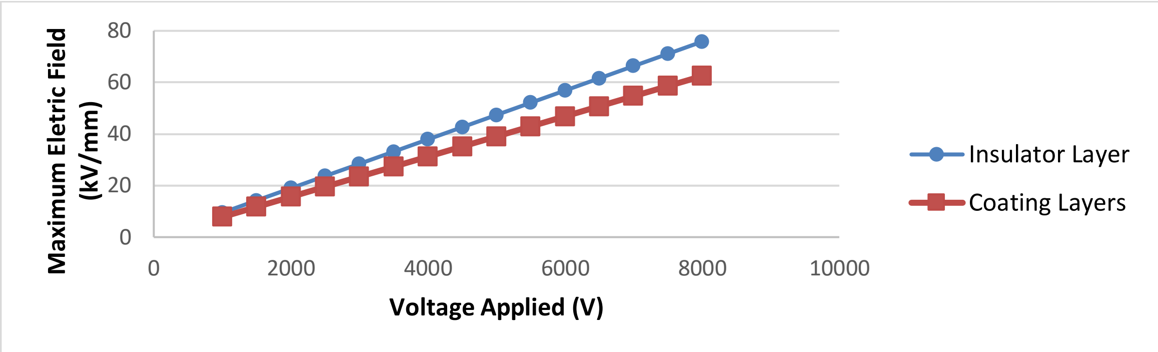


Figure 22: Influence of increasing the voltage on the maximum electric field in different layers

The maximum Electric field in the insulator layer at 8000 V was 71.3 kV/mm, according to the data sheet the dielectric strength is 303 kV/mm for 25.4 μm thickness in AC conditions with no information for the DC conditions, however the DC dielectric strength is higher than the AC values. Which means that that pad theoretically can safely operate at 8 KV without breakdown in the insulator layer. The dielectric strength of the polyurethane layer is 60 kV/mm. From Figure 22 the maxumum electric field in the polyurethane layer at 8 kV is 62.5 kV/mm, according to the simulaton breakdown will occur at 62.5 kV/mm. therefore the voltage should be limited to 7500 V.

Pad 2 Test

As was shown in section 5.2.2 the pad can be done at home. For some coating materials Silicon acetoxy for instance the coating can be done at home. The only step that might not be easily done at home is the usage of vacuum oven to remove air bubbles in the coating. The purpose of this test is to know wither or not any forces can be obtained if the coating was done, and the pad is left to dry for 24 hours at room temperature instead of using the vacuum oven.

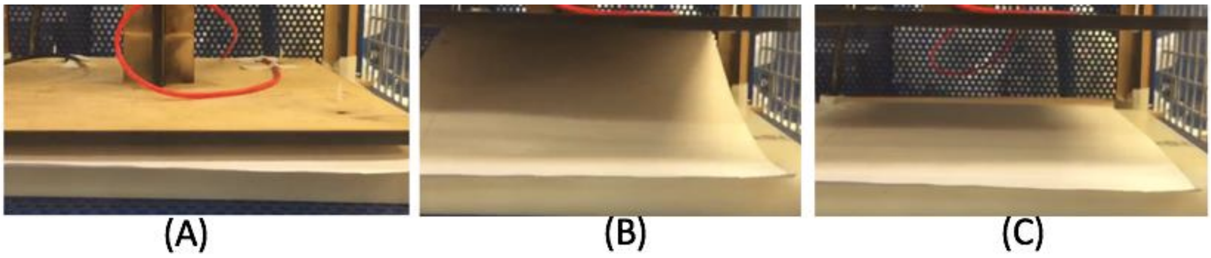


Figure 23: (A) Setup before the test (B) Pad raising a paper (C) Pad falling after 1 second

The pad tested is shown in appendix 8. Same setup for pad 1 was used. The voltage was increased till 1.5 kV waited for 1 minute, the pad was then raised, and it did show a force which raised the paper as shown in Figure 23(B) however the force was not high enough to completely lift the paper and it fall as shown in Figure 23(c).

The voltage was increased and at 2.1kV there was the sound of flash over occurred, the pad was below the pad mount, so it was very hard to see where this happened from outside the cage.

The fact that it didn’t show mark on the pad says that flash over happens in air, which is because of the air bubbles trapped between the coating. Also, air is a self-healing material which means that after breakdown in air the pad will still be able to work till the breakdown voltage (2.1kV) which is what is happening. If breakdown happed in the polyurethane layer or the polyamide this was going to make a permanent short circuit and voltage cannot be applied below the 2.1kV. Although this showed a proof of concept of electroadhesion, the force isn’t high enough for this to be in cooperated into any application. This shows that the vacuum oven step cannot be neglected.

6.2.3. Pad 3 Test

By adding the coating and then using the vacuum oven theoretically the pad should be very close to [2] and [3]. However, since some steps are not very clear how to do like spraying the pad, these steps can cause the pad to fail. To avoid wasting the material and save cost small size pads of the same parameters as pad 2 was used.

because of the symmetry of the pad this should have the same breakdown or flash over voltage. Vacuum oven was used this time.

The purpose of this test is to see what is the maximum voltage that can be applied to the pad without breakdown so that when voltage is applied to the big pad the voltage is limited so that breakdown doesn't occur. The same spraying technique used in section 5.3.3 was used for this pad. The pad being tested is shown in appendix 9.

The voltage was increased for this pad till flash over occurs and it occurred at 3.9 kV. and again, it was breaking down through air, because no mark was found, and it was going up to the flash over voltage even after flash over occurred once. which means that even when vacuum oven is used air bubbles aren't totally removed.

This means that the simulation will never provide the correct flashover voltage, because it's very hard to know how big the air inside the coating is and add it in the simulation. To check wither or not air bubbles exist the pad was looked at under the microscope.

6.2.4. Using the microscope to detect any air bubbles

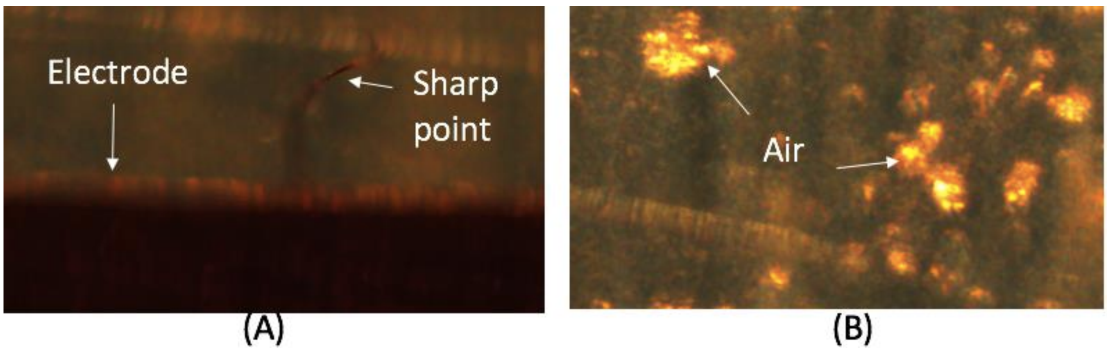


Figure 24: Pad under the microscope, (A) Very sharp point, (B) Air in the coating

A microscope was used to check if the air bubbles can be detected. The pad looked at with bright light below it, if there's air trapped the brightness will change which is the case as shown in Figure 24(B). Also, very sharp points on the border of the electrodes were found as shown in Figure 24(B). This means that the copper isn't etched 100 % accurately according to the design. This is a significant issue since electric field increase according to how sharp the conductor is, sharper points lead to higher electric field. This means that breakdown will never be expected accurately from the simulations. Therefore, the dielectric breakdown will only be analysed experimentally in the next sections.

6.2.5. Pad 4 Test

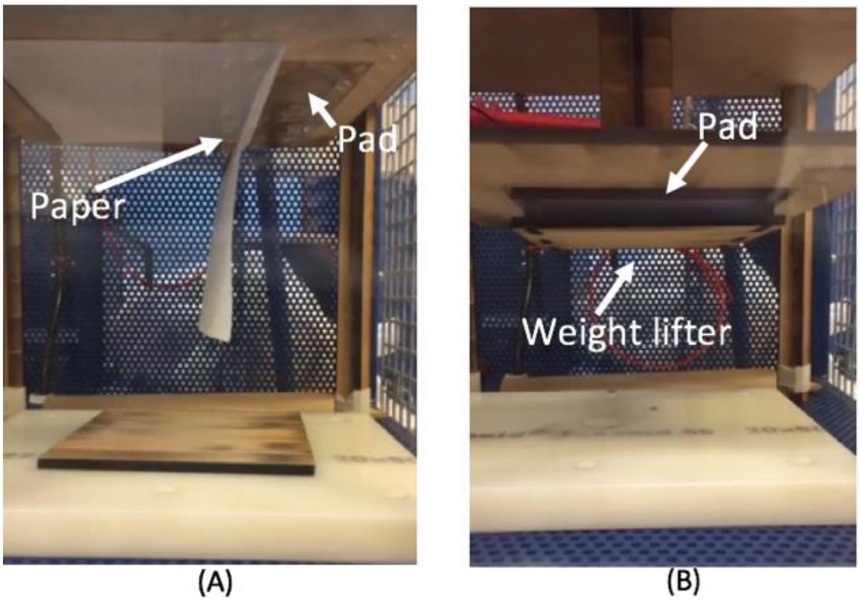


Figure 25: (A) Pad fully 4 raising a paper, (B) Pad 6 raising weight lifter

After knowing the flash over voltage for the small sample shown for pad 4, Pad 5 was designed with the same geometry, but bigger size to quantify the force. The maximum voltage that was applied is 3.8kV to avoid surface flash over which occurred to the smaller sample. The voltage was increased until the pad fully raised the paper, and this occurred at 2.5 kV as shown in Figure 25(A). The paper wasn't making contact with the entire pad.

This however is not the maximum voltage that can be applied to the pad which means higher force can be generated out of the pad at higher voltages. 239, 147 and 97 grams samples were tried at the maximum voltage however the pad could not lift them. This means a pressure less than 42 Pa. From the model the Pressure should be in the range of 80 Pa. This means that the simulation doesn't agree with experimental results this might be because of the uncontrolled measurements such as temperature and humidity [1].

Although the simulation showed that the smaller the electrode width the higher the force generated, this however isn't confirmed by all the literatures and almost all of them contradicts in this area. Therefore, the width of the electrode was increased to see wither the forcers are two low because of the uncontrolled variables or it's because of the pad parameters. Also, it should be noted that the maximum voltage that can be applied before flashover is low relative to the some of the literatures which might be the reason why the forces are relatively low so the gap between the electrodes was increased as well.

6.2.6. Pad 5 Test

A sample of the big size pad was designed to know the maximum voltage that can be applied to the pad 5 mm was chosen as the electrode width. The gap between the electrodes was chosen as 5 mm. The same coating procedures were used as shown in 5.3.3.

The pad being tested is shown in appendix 11. The voltage was increased from 0V until flashover happened at 7.9KV. Bigger pad was then manufactured to quantify the force generated.

6.2.7. Pad 6 Test

Pad 6 is shown in appendix 12. The pad was able to lift the paper at 2 KV, A flat piece of wood was then tried. The pad raised the wood sheet of 96 grams at 3480 V. The weight lifter which had a mass of 239 grams and an area of 150×150 mm^2 was then tried, the pad raised it as shown in Figure 25(B) at 7.7 KV. This means a pad of 180 $\times$ $150\ \mathrm{mm}^2$ area can provide a force of 2.34N. This gives a pressure of 86.8 Pa which is enough to make a robot of reasonable area.

It should be noted that pad 6 lift 96 grams at 3480 V. Pad 4 could not lift this mass at the same voltage. This means that the trend provided by the simulation is not correct. Especially because the gap in pad 6 was increased to 5 mm, which should reduce the force (agreed by all the literatures) and the model. However, the force is increased experimentally. The trend resulted from the simulation done in this paper is the same as [7] and [2]for 6 mm substrates. This means that something is missing in simulations in general.

6.2.8. Pad 7 Test (Scalability of the pad)

The previous pad had an area of $27000\ mm^2$ the area needed for the robot depends on many parameters however it's at least 10 times more than this area as will be shown in section 8.2. The purpose of this test is to know the scalability of the force, if the area is multiplied by a factor is the same pressure going to be obtained or not. The pad was scaled to be 250 mm × 250 mm which is shown in appendix 13. This is the maximum size that can be fit in the vacuum oven, taken into consideration the size of the base for the pad and the tape needed to fix it.

The pad was able to lift a weight lifter that is 180 mm × 175 mm, and mass of 387 grams. The weight lifter was smaller than the pad, when flat sheet of wood that is 250mm × 250mm same dimensions as the pad was tried, the pad couldn't lift it. This might be because the side electrodes aren't providing as big force as the middle part of the pad. Also, when the area is increased the probability that there are parts which aren't making contact is higher. From this the maximum pressure was calculated using the smaller area substrate which had a mass of 387 grams, the full pad area (250mm × 250mm) was used for the calculation. So, the maximum pressure that can be provided by this pad is 60.7 Pa, which is still enough to use it for the robot.

7. Analysis for the agreement between simulation experiment results

The pressure was calculated by taking the surface average in the substrate. This was done because integrating the pressure at the boundary will just give the force at the borders with no consideration to the inside of the substrate. As was mentioned before increasing the thickness of the substrate will reduce the average pressure significantly so the wall was set to 1 mm which will calculate pressure at the boundary and the inside of the material as well. Similar to what [2] did.

The force in dielectric materials is mostly dependent on polarization, there are different types of polarization. electric polarization, ionic polarization dipolar polarization and space charge polarization [2]. Comsol is showing only the dielectric polarization this is because electric field is in the same direction as the polarization. There's another way to calculate the force which is by doing vector cross product of electric field and polarization. If this is done the result will be 0 which isn't true, so it has to mean that not all polarization types are shown by Comsol. And this might be a reason why the theoretical results are less than the experimental results.

Also, it should be noted that the model will never accurately reflect the experimental result since the simulation assumes linear, homogeneous and isotropic material which never exist in reality, there's always a tiny air gap between the substrate and the pad due to the surface roughness, even when this is accounted for in the simulation it's virtually impossible to expect it correct. Usually there's air bubbles that are trapped inside of the coating which isn't accounted for in the simulation. The simulation also assumes a flat pad which is hard to be done experimentally because of the flexibility of the material. Finally, the simulation itself has errors because it's calculating differential equations at specific points. The closer these points together the better the simulation will reflect reality however it's never the true value.

In the future it's suggested that electroadhesion against electrode width is done experimentally, under controlled measurements. All the variables need to be controlled such as temperature and humidity which was hard to be controlled in the scope of this project. To be sure wither the inconsistency is because of the uncontrolled measurements or because of the simulation.

[2] Says that the experimental results are controlled however the method of how the force is calculated wasn't mentioned. Although the simulation and the experimental results for [2] agree, the simulation parameters didn't reflect the experimented pad parameters. The literature used unrealistic dielectric relative permittivity 11.7 and in his experimental results used polyester which has a maximum relative permittivity of 4.5. The voltage used in the simulation ($\pm$ 6 kV) is way higher than the one used in the experiment ($\pm$2 kV).

Usually small electrostatic forces occur at small voltages and in most of the models this force occur in the same material which is not the case for electroadhesion. This might be the reason why the values theoretically the pressure obtained was less than experimentally. Because Comsol is expecting the electrostatic force to happen in the pad, not in the substrate. This might be solved by using Multiphysics in Comsol. Where the mechanical stress is calculated, and electrostatic stress is calculated, and their effect is combined. This was not used for the simulation because most of the literatures simulate the pad in very similar way to how was done in this project. In the future it is suggested to use Multiphysics. Where one physics is the electrostatic one used before and the other physics is structural mechanics one.

8. Robot using Electroadhesion for locomotion

8.1.1. Robot Design Literature review

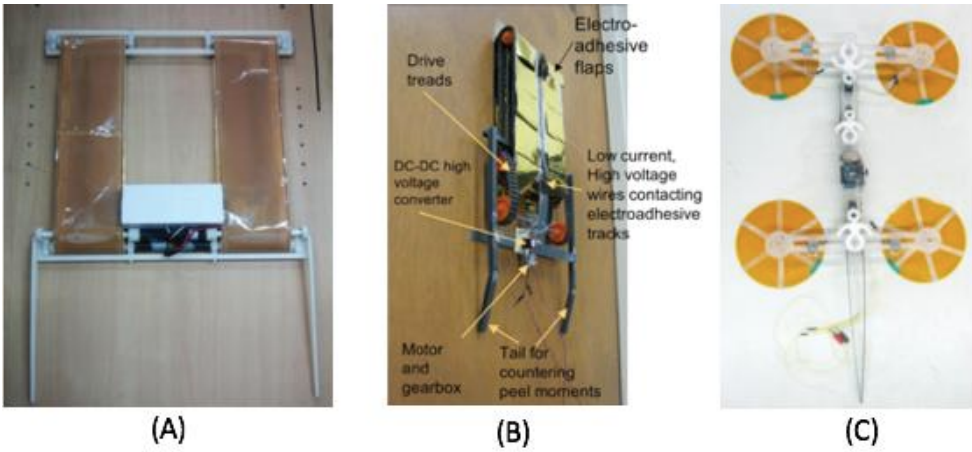


Figure 26: Different wall climbing robot designs, (A) single pad double tracked robot [11] (B) Multiple pads double sheet robot [10], (C) Gecko inspired design using electroadhesion [12].

The tracked robots are very common for wall climbing robots using Electroadhesion it was used by [11], [12], [9] and [8], since the bigger the area touching the wall the bigger the force would be. The principle is simple, by having a big pad which generates a force normal to the wall the robot can support itself statically on the wall, a high torque motor s then used to allow the robot to slide up the wall. The design is shown in Figure 26(A) and (B).

The big advantage for this design is that approximately half the area of the pad is touching the wall at any given time which gives it relatively high contact area. Also, if the robot has single track design which is shown in Figure 26(B). When the robot is placed perfectly vertical with respect to the ground the robot will move straight up with centre of mass moving in one direction. This is important since changing in the robot centre of mass can cause moments which may lead the robot to fall.

Tracked robot is simple to be modified for rotation, the robot shown in Figure 26(A) has the ability to rotate with a radius more than or equal to 0.5 m simply by adding another track.

The problem with this design is that’s hard to make a supply connection for the robot since the track is moving and the supply is stationary. Also, as was shown section

5.3, it's not possible to make a single pad that is very big with the fabrication technique for this project. More than one pad can be fabricated and integrated to make the belt for the robot. This is similar to what the robot shown in Figure 26(B) uses, for this specific robot its using unipolar supply where the pad is excited by just one polarity. The robot shown in the figure has two pads next to each other's one pad is connected to HV and the other is grounded. so, it was simpler for [10] to make connection by just having a commutator touching the outside face of the pad. For tracked robot it is relatively harder to make ground to wall transition, which provide limitations if the robot is to work in an area with no human to place it on the wall.

Gecko inspired robot design shown in Figure 26(C) is a design which can be used as well. The robot has 4 Electroadhesive pads for the attachment to the wall. This robot requires relatively high number of motors. The robot shown in the figure has 7 motors, 4 for lifting each leg independently, 1 for the two front legs swing, 1 for the two rear leg swing and 1 for waist swing which is used to allow the robot to rotate. The number of motors adds extra weight to the robot which is a huge disadvantage since the force generated needs to be significantly bigger to allow the robot to climb the wall securely.

Some motors can be removed for example the 4 which lifts the legs. This can be done if more than one supply is used where each supply will be turned on while attaching and off while detaching however this will massively increase the price of the robot since each supply is around 150 GBP. Another solution might be a tristate buffer, however no buffer was found for such high voltage used by the robot (>3KV).

2 diagonal legs need to be attached to the wall at any time to stop the robot from rotating clockwise or anticlockwise with respect to the wall. The other two legs can be used for moving the robot up the wall. This means that ½ of the maximum force is provided during transfer phase. This can be increased to a maximum of ¾ if only one leg is used for transferring the robot. However, this will scarify climbing speed.

The robot centre of mass is moving away from the wall. This provide extra complexity on the control of the robot and increase the risk of the robot falling while the detachment process. This design can be easily modified to make ground to wall transition, by adding another degree of freedom in the waist.

Tracked robots have significantly higher contact area the gecko one. This is because the bigger the pad for the gecko design the higher torque which will be needed for the detachment process and therefore the higher the mass of the motors and then the robot. This means that tracked robot have higher contact area, easier to control, once put on the wall they will not fall. Which are the reasons why this design was chosen for this project.

If tracked robot will be used for this project, slightly different modifications will be made since interdigitated pad design was used for this project. The is because it provides significantly higher forces on dielectric substrates. If tracked robot is to be used a belt of non-conductive material will need to be done and then the pads adhered to it. An adhesive copper which is commercially available can be used for the connection of all the pads together. Bearing can then be used to connect the stationary supply copper adhered to all of the pads.

8.2. Robot Force analysis

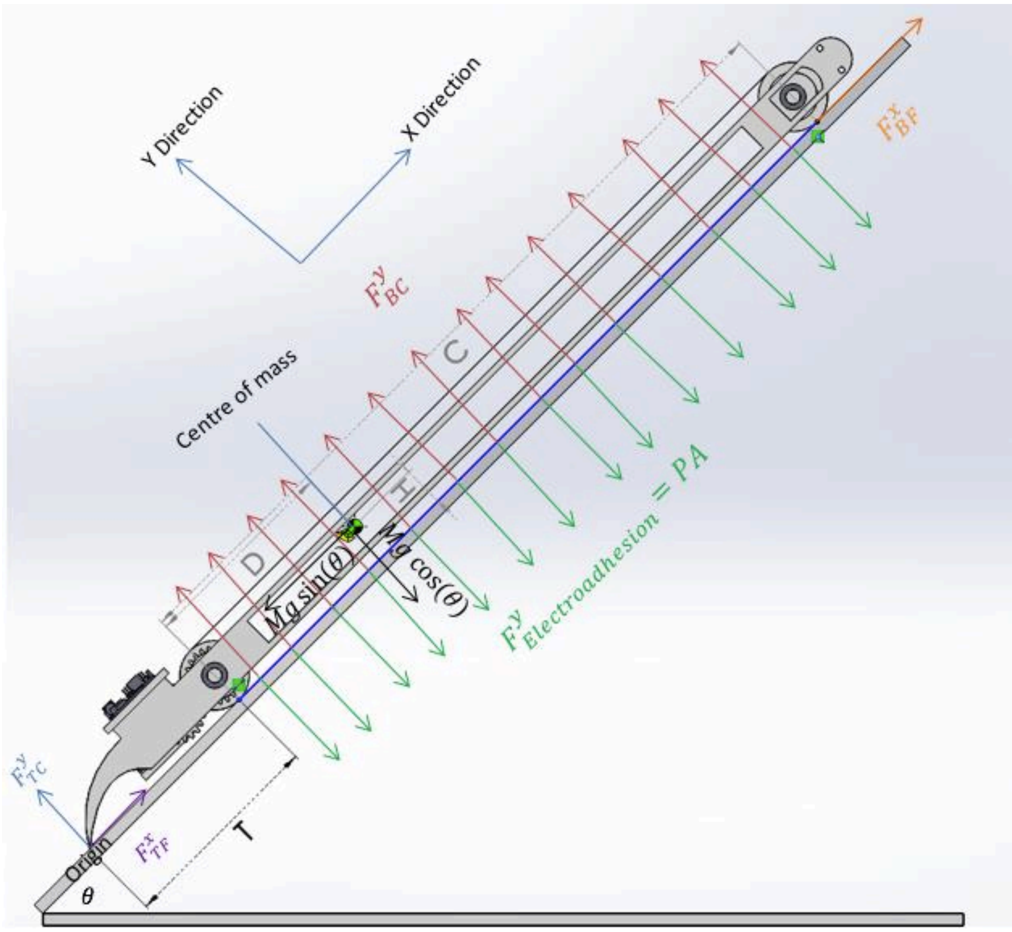


Figure 27: Forces analysis on the Robot

Because of the symmetry of the robot in the Z direction which is into the page, the forces analysis was simplified in to 2D model as shown in Figure 27. The model shows the forces when the robot is holding statically on a surface with an angle θ to the horizontal. The blue line in the picture which has a length C represent the contact between the belt (Pads) and the wall, in 3D the contact area will $W \times C$ where W is the belt width in the Z axis (not shown in the figure) this is the area which contribute to the electroadhesive pressure. It's assumed that the pressure of the belt will be the same as the pressure of the pad given in section 6.2.8 (6.7) Pa.

F_{BC}^{y} is overall normal contact force cause by the belt in the y direction however it will be distributed across the length C. F_{BF}^{x} is the friction force caused by the belt which is equal to μF_{BC}^{y} where μ is the coefficient of friction between the wall and the belt. The material which will be touching the wall will be polyamide which is the insulator layer of the pad. Because of previous experiments and the accessible materials, the material of the wall will be wood. Coefficient of friction between these materials wasn't found online, therefore the it was measured by adding weight on the pad and find the horizontal force required to move the pad.

F_{TC}^{y} is the normal contact force by the tail this is used to reduce the peeling moments, F_{TF}^{x} is the friction force caused by the tail, because the contact area is negligible, F_{TF}^{x} will be neglected in the calculations, T is the length of the tail from the last point where there is force generated by the belt.

$Mg\sin(\theta)$ is the component of the weight in the X direction, $Mg\cos(\theta)$ is the component of the weight in direction Y. D is the distance from the last point where there is force generated by the belt and the centre of mass of the robot. H is the height of the centre of mass of the robot calculated from the wall. g is the gravitational force.

F_{BC}^{y} can be obtained by equating the forces in the X direction. As shown in equation 8.1.

$$F_{BC}^{y} = \frac{Mg\sin(\theta)}{\mu} \quad (8.1)$$

Equation 8.2 was calculated by equating the forces in the Y direction and using equation 8.1 for F_{BC}^{y}. This gives the normal contact force because of the tail of the robot. It's multiplied by 2 because there's two tails. Only one is shown in Figure 27.

$$2F_{TC}^{y} = PA - \frac{Mg\sin(\theta)}{\mu} + Mg\cos(\theta) \qquad (8.2)$$

By equating moments at distance T from the origin shown in Figure 27, equation 8.3 can be obtained, because F_{BC}^{y} and PA are distributed across the line C. the moment calculation for these forces will be a line integral as shown in equation 8.3.

Clockwise Moment

$$\int_0^C PA\,dx + (D \times Mg\cos(\theta)) + T \times (PA - \frac{Mg\sin(\theta)}{\mu} + Mg\cos(\theta)) = \int_0^C \frac{Mg\sin(\theta))}{\mu}dx + H \times Mg\sin(\theta) \qquad (8.3)$$

If the robot is able to climb vertical surfaces it will be able to climb surfaces at an angle less than 90°. Therefore, the robot will be designed for vertical surfaces so that it can work in both situations. By setting $\theta = 90°$ and simplifying equation 8.3, an equation for the required contact area can be shown obtained as shown by equation 8.4.

$$A = Mg\frac{(T+C+(\mu\times H))}{P\times\mu\times(C+T)} \qquad (8.4)$$

It is very hard to know exactly the area needed before designing the robot because the area required will depend on the mass of the robot, and H will depend on the alignment of the components in the Y direction. An estimate of these values has to be done and after all the values are known, it will then be verified wither or not the area was big enough.

The length of the cage is around 1 m. If T is chosen to be 100 mm and the distance from the front roller to the front of the robot is chosen to be 100 mm. And the robot is willing to climb 100 mm inside the cage, this leaves 700 mm for the length C, which is the length of the belt touching the wall. There was a previous design which had C equal to 670 mm, which is very close 700 mm, so C was chosen to be 670 mm to avoid totally changing the previous design.

If the robot height is 70 mm the centre of mass will be approximately in the middle, which means that H can be estimated as 35 mm. μ was measured as specified before which is equal to 0.434. the mass of the robot was estimated as 1.25 Kg, using equation 8.5 the width of the belt needed which is in the z axis (not shown in figure) can be estimated.

W = Mg$\frac{(T+C+(\mu\times H))}{C\times P\times\mu\times(C+T)}$………………………………………..………………………....(8.5)

When the values were put in the equation W was found to be equal to 708.5 mm. the width of the cage is approximately 850 mm, to leave safety margin the width was chosen to be 800 mm.

8.3. Robot Design

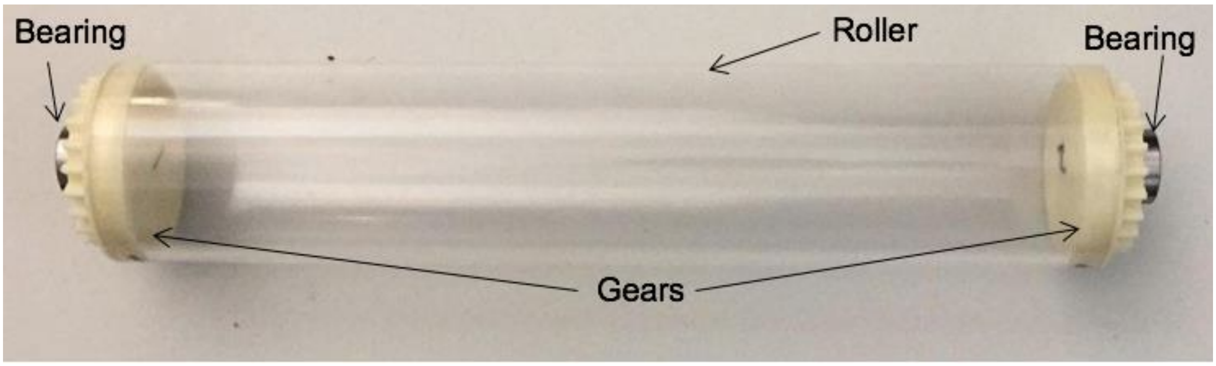


Figure 28: Top view of physical rear pulley

The rear pulley is the part where which will drive the belt, and this part will be driven by a gear attached to the motor. The gears which will be attached to the roller had to be done in 3D. therefore there are two options either to 3D print the gears with the roller as one part, or to 3D print just the gears as shown in Figure 28.

If only the gears are 3D printed this will reduce the cost because less material will be used. Other than reducing the cost, the rear pulley was designed to be hollow to reduce the mass. The part is closed from the outside and hollow from the inside, if it is 3D printed there was a probability that the 3D printer fails to make it hollow. Therefore, only the gears were 3D printed and then glued to acrylic roller which was hollow from inside.

Bearing will be used to attach the rear puller to the side bar as shown in Figure 28 and Figure 29 . This will make the rollers rotate freely. In SolidWorks the material for the gears was chosen as ABS (material used for 3D printing) the density was 1020 kg/m^3. The roller material was chosen as acrylic with density 1020 kg/m^3. The bearing mass was specified as 6 grams which is the mass of the bearing that was planned to be used.

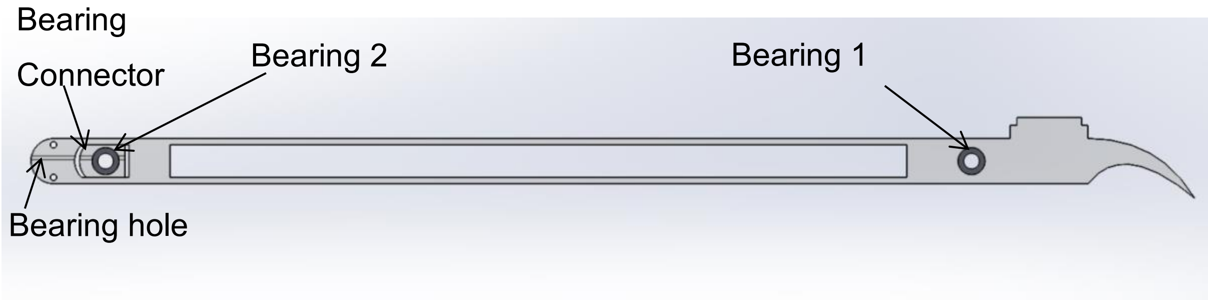


Figure 29: 2D view of the side bar

The side bar is the part which will be holding the rear and front pulley from the sides. Bearing 1 will be connected to the rear pulley from the inside and to the side bar from outside. Bearing 2 will be connected to the front pulley from inside and to the bearing connector from the outside. The purpose of the bearing connector is to allow the front pulley to slide for a small distance horizontally to stretch the belt. This can be done using a screw which will go through the bearing hole in the side bar shown in Figure 29 then through the bearing connector. From the other side a screw and a nut can be used to stretch the belt. The side bar will be made out of acrylic because it has a high strength to density ratio, it’s relatively strong and light weight at the same time. As shown in Figure 29, a part of the side bar was removed to reduce the weight.

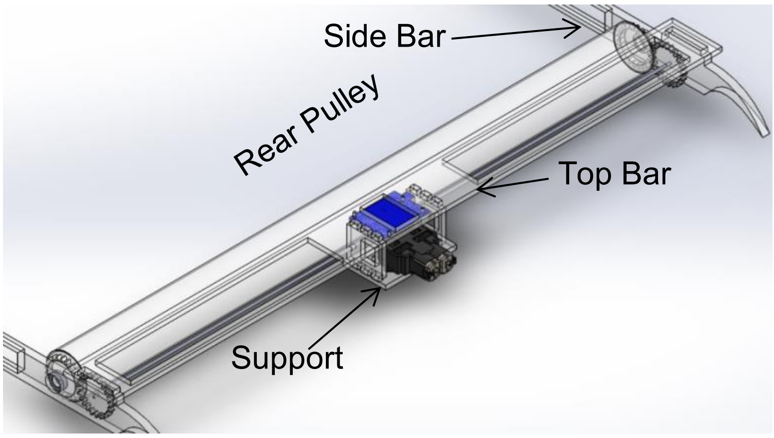


Figure 30: Isometric view showing the rear of the robot

A twin motor was chosen for driving the robot, due to it is high gear ratio (288) and low mass (60 grams with the gears). An Arduino was chosen as the microcontroller and Arduino motor shield will be used as the motor drive board, these two had a mass of 61 grams. They will be placed upside down to make the centre of mass of the robot as close to the wall as possible. The top bar material will be acrylic due to it is strength to density ratio as mentioned before and it will be laser cut. Holes were made in the top bar to reduce the mass. A support part was made for the motor with the motor positioned, so that the motor gears are placed correctly with respect to the rear pulley gear. The material for the support part will be acrylic and it will be laser cut as well.

The mass of the belt was calculated as 32.3 grams. The mass of the copper and spray were neglected. The mass of the screws and wires which will be used were neglected as well. For more realistic design the distance T was specified as 82.5 mm to keep the length of the robot equal to 900 mm to fit in the cage. After the mass of all parts were added in SolidWorks, the new robot parameters were evaluated in SolidWordks as shown in table 1. equation 8.4 was calculated again.

Table 1

Parameter	Mass (grams)	H (mm)	C (mm)	T (mm)	P (Pa)	u	A (mm^2)
Value	1391.22	33.6	670	82.5	60.7	0.434	536000

The area needed for this robot is 528100 mm^2 which mean that the area used by the robot is more than what is needed, and the robot will be able to hold statically on the wall. Dynamically the robot should be able to climb the wall as well because the centre of mass isn't moving from the wall which is the only parameter needed from equation 8.4. For the full robot design and the CAD models see appendix 14.

9. Conclusion and future development

The model provided trends which were used as guidelines for designing the pad and choosing the materials and dimensions of the pad. However, for some pad parameters such as the electrode width, which is a very important parameter, the simulation wasn't able to provide correct trend for it. In the future this can be solved by using Multiphysics simulation in Comsol where the mechanical stress and electrostatic stress are calculated separated. The first physics will be the electrostatic physics used before and the second one will be structural mechanics physics.

After looking at the pad under the microscope very sharp edges where found. This provide limitations on the maximum voltage the pad can operate at. For better pad manufacturing it is suggested that the pad is 3D printed as suggested in section 5.2.3, the electrodes can then be cylindrical. This will enhance the pad, however the pad already manufactured provides pressure which can be used for a wall climbing robot.

Unfortunately, the pad was not able to go above 800 V when the coating layer was not done, this resulted in no force being generated. 46% percentage increase in the flashover voltage was found, when vacuum oven was used as compared to when it was not used. Also surface flash over was occurring not dielectric breakdown. This is because of the air trapped inside of the coating, which was seen under the microscope. it is suggested that the spraying techniques is changed. For accurate knowledge of how this can be done, it’s suggested to look at how polyurethane is bonding to the insulator and electrode layers. This is chemical engineering.

The pulley system served the objective of quantifying the force generated. Which was used to calculate the contact area required by the robot. However, the alignment of the substrate with respect to the pad affects the force generated. This affected the repeatability and accuracy of the results since human error was introduced. For accurate measurement of the force 6 axis force/torque sensor should be used same as [2] and [3].

Finally, all of the objectives were achieved except the manufacturing and testing of the robot, which were not done because of timing issues. Therefore, the next step is to manufacture the robot based on the design suggested in section 8.3. The robot was designed based on the size of the cage, using the same principal for testing the pad, the robot can be tested in the cag. Vertical surface can be added to the cage using the same principal for the pulleys.

10. References

[1] Ruffatto D, III, Shah J, Spenko M. Optimization of Electrostatic Adhesives for Robotic Climbing and Manipulation. ASME. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Volume 4: 36th Mechanisms and Robotics Conference, Parts A and B ():1143-1152. doi:10.1115/DETC2012-71384.

[2] J Guo, T Bamber, M Chamberlain, L Justham, M Jackson, Optimization and experimental verification of coplanar interdigital electroadhesives, journal: Journal of Physics D: Applied Physics, volume: 49, number: 41, pages: 415304, year: 2016 url: http://stacks.iop.org/0022-3727/49/i=41/a=415304

[3] GUO, J. ...et al., 2016. Geometric optimisation of electroadhesive actuators based on 3D electrostatic simulation and its experimental verification. IFAC-PapersOnLine, 49(21), pp. 309-315.

[4] Jiu-Bing Mao, Lan Qin, Wan-Xiong Zhang, Li Xie and Yong Wang Eur. “Modeling and analysis of electrostatic adhesion force for climbing robot on dielectric wall materials” Phys. J. Appl. Phys., 69 1 (2015) 11003 DOI

[5] Electrolube, “PUC400 - Coating, Conformal Coating, Polyurethane, Aerosol, 400 ml”, 1898441 Datasheet, URL: http://www.farnell.com/datasheets/2332383.pdf?_ga=2.208972498.1504389933.1524926185-2120380693.1524926185

[6] DuPont, “DuPont™ Pyralux® AP flexible circuit materials“, AP 8515R Datasheet, June 2012, URL: http://www.dupont.com/content/dam/dupont/products-and-services/electronic-and-electrical-materials/flexible-rigid-flex-circuit-materials/documents/PyraluxAPclad_DataSheet.pdf

[7] Liu, Rong & Chen, Rui & Shen, Hua & Zhang, Rong. (2013). Wall Climbing Robot Using Electrostatic Adhesion Force Generated by Flexible Interdigital Electrodes. International Journal of Advanced Robotic Systems. 10. 1. 10.5772/54634.

[8] Dhongadi, M., Nellur, N., Shetty, N. and Sapare, P. (2011). SURVEILLANCE ROBOT. Bachelor of Engineering in Electronics and Communication. B. V. Bhoomaraddi College of Engineering and Technology.

[9] A. Yamamoto, T. Nakashima and T. Higuchi, "Wall Climbing Mechanisms Using Electrostatic Attraction Generated by Flexible Electrodes," 2007 International Symposium on Micro-NanoMechatronics and Human Science, Nagoya, 2007, pp. 389-394. doi: 10.1109/MHS.2007.4420886, URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4420886&isnumber=4420811

[10] H. Prahlad, R. Pelrine, S. Stanford, J. Marlow and R. Kornbluh, "Electroadhesive robots—wall climbing robots enabled by a novel, robust, and electrically controllable adhesion technology," 2008 IEEE International Conference on Robotics and Automation, Pasadena, CA, 2008, pp. 3028-3033. doi: 10.1109/ROBOT.2008.4543670type=t, URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4543670&isnumber=4543169

[11] R. Chen, R. Liu and H. Shen, "Modeling and analysis of electric field and electrostatic adhesion force generated by interdigital electrodes for wall climbing robots," 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, 2013, pp. 2327-2332. doi: 10.1109/IROS.2013.6696682 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6696682&isnumber=6696319

[12] R. Chen, R. Liu, J. Chen and J. Zhang, "A gecko inspired wall-climbing robot based on electrostatic adhesion mechanism," 2013 IEEE International Conference on Robotics and Biomimetics (ROBIO), Shenzhen, 2013, pp. 396-401. doi: 10.1109/ROBIO.2013.6739491 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6739491&isnumber=6739425

[13] grabcad. (2018). Tamiya Twin Motor Gearbox. [online] Available at: https://grabcad.com/library/tamiya-twin-motor-gearbox [Accessed 2 Apr. 2018].

[14] grabcad. (2018). Tamiya Twin Motor Gearbox. [online] Available at: https://grabcad.com/library/tamiya-twin-motor-gearbox [Accessed 2 Apr. 2018].

[15] P. Debenest, E.F. Fukushima, S. Hirose “Gryphon-I - buggy robot for field applications on uneven terrain” [online] 5-7 Aug. 2002 available: http://ieeexplore.ieee.org/document/1195204/

[16] Xie Li, Zhang Zhixiang, Qin Lan. (2016) Research on a wall climbing robot based

on electrostatic adhesion. 2016 10th International Conference on Sensing Technology (ICST), pages 1-6.

11. Appendices

11.1. Appendix 1 – Progress Report

Project Title

Third Year Individual Project – Progress Report

5/11/2017

Nour Elghazawy

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Supervisor: Dr. Simon Watson

Contents

1. Introduction

In the late 1950's and early 1960's robots started to be used in industrial automation, where they assisted factory operators [1]. At that time people were thinking to have robots to help human, by reducing the number of employees needed to do a certain task, or doing it in faster way in order to improve efficiency or reduce the cost. Robots not just have the ability to help human, they can even replace them. Single Chinese factory replaced 90% of its employees with robots which increased the production to 250% [3]. The real challenge is to have robots that can do tasks that can't be done by human. Now there are robots which can stop a bomb from explosion, go the edge of a volcano [1], detect and remove landmine [2].

Figure 1 Industrial plant [6]

For robots to be able to do tasks human cannot do, they must have the capability of moving in their working environments. It's aimed to have robots that can move in small confined places as shown in figure 1. Different technologies have been developed to allow robots to move, one of these technologies drones which fly to move from one place to the other however some places restrict their usage [4]. There are also legged and wheeled robots which aren't restricted to fly in some places, however they get stuck in some environments [7]. If the robot isn't able to move in its working area, it certainly cannot do its task. Hence drones cannot be used neither wheeled nor legged robots by their own.

2. Aims and Objectives

The aim is to have a robot that can work in narrow industrial area like confined corridors with a lot of pipes and gaps.

- Review about adhesive technologies
- Developing and fabricating an Electroadhesive pad in the university
- Testing Electroadhesive technology
- Simulating different robots designs
- Designing robot using SolidWorks
- Integrating Electroadhesive technology on the robot

3. Common Locomotion Technologies

Figure 2 Legged Robot Falling [8]

Wheeled robots have the ability to move using wheels driven by a normal motor, they are easy to be controlled and have high speed. There disadvantages are that they get stuck in piped areas or areas which have gaps, they also struggle climbing the stairs. Legged or humanoid robots are often able to climb the stairs they can cross small gaps easily. Legged robots tend to be slow and are very complicated to balance, trivial obstacles can cause them to fall specially when the surface is not even or flat as shown in figure 2.

Although drones have the ability to overcome the disadvantages of wheeled and legged robots as they have high speed and it’s not very hard to balance them. They lack the ability to navigate in narrow confined places [7], and it’s hard to control them. An alternative method of locomotion needs to be used to enhance the movement of robots.

Many methods can be developed to enhance the movement of robots one of them is having a webswinging robot that uses computer vision to find a target. After finding the target, the robots should fire a rope or a material that can stick to surfaces using Electroadhesion or suction sups for example. Calculations will be needed to know when to detach the robot from the rope to move from one place to the other.

Webswinging might be good way to improve the movement of robots, however there are some problems of using this mechanism. One of the problems is that there are not many resources for this technology as compared to other technologies, which will make it harder to be implemented. Also it’s hard to split the problem, it’s not possible to have two different robots each of them does one thing described above, then integrate the two robots into one. The last problem which is a major issue is that this robot might be restricted to some places similar to drones. It’s hard for it work with human or moving objects in general, as the rope produced might bombard with the human.

One of the methods human use to tackle obstacles is jumping, there are robots already developed which can jump buildings [9], this can't be done by human. Animals like geckos use adhesion to move on the wall, this one more functionality enables it to escape from human. Wall climbing robots already exists [10]. As a long term aim these two robots should be integrate into one. It's means it's easy to find the starting point, and climbing robots will be investigated first. Although jumping robot might be restricted to some places, this is not going to be the case for this robot, since it doesn't depend solely on Jumping.

4. Adhesive Technologies

4.1. Electroadhesion

Electroadhesion is a technology which allows two different objects to be attracted to each other's using electrostatic force. It's the same idea of rubbing a balloon against human hair and sticking it to a wall, where the charges in the balloon get attracted to their opposite charges in the wall. Electroadhesion allow a substrate to be attracted to the pad when voltage is induced in the electrodes embedded in the pad. This allows easy control of the adhesion mechanism [13].

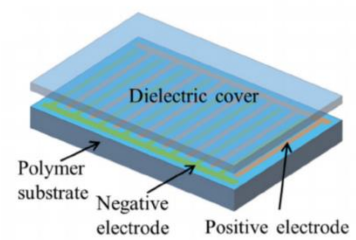


Figure 3 Electroadhesive Pad [11]

Electroadhesive pads consist of positive and negative electrodes with dielectric on the outside for insulation (figure 3), also to improve the electric field when voltage is applied. When electrodes are energized, holes are attracted to the negative electrode, and electrons are attracted to the positive electrode which induces electric field [12]. This induces an attraction force between the pad and the substrate. The voltage applied is usually around 4.5 kV [13].

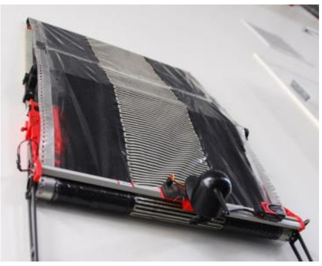


Figure 4 Robot Using Electroadhesion [15]

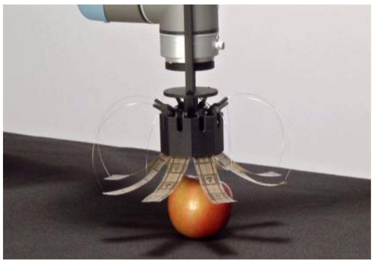


Figure 5 Electroadhesion Grippers [15]


Figure 6 drone using Electroadhesion [15]

Electroadhesion are being investigated to be used in various applications. Figure 4 shows a Wall climbing robot based on Electroadhesive pad. Figure 5 shows an electrostatic gripper which uses Electroadhesion to confine to the object, this is very useful since it can adhere to curved objects. This will be useful when the robot need to adhere to curved pipes. Figure 6 is showing drone using Electroadhesive pads to hold stock and deliver it to houses.

The forces developed from Electroadhesion are big enough to support a robot. The estimated normal force for Electroadhesion on wood is 1.375 $c\mathrm{m}^2$ [7] which mean a force of 34.375 N for a 5cm×5cm pad. If the robot is 2.5 Kg and it's assumed it's a point mass (approximately 25 N) theoretically the force generated should be able to support the robot. As the robot isn't point mass then the force developed needs to be increased. This can be done by either increasing the area of the pad or having more than one pad to support the robot a reasonable safety factory will be considered as well.

4.2. Vacuum suction

There are two ways of generating forces using by vacuum suction. One of them is to have a propeller that generates thrust force that can balance the robot gravitational force so that the object (robot) can move on the wall [17] as if it's moving on the ground (figure 7). Although this theoretically can lead to successful climbing this is not what happens practically, the robot often slips on the wall and it's hard to be controlled. Also if the thrust force is very high the robot isn't going to be able to move easily on the surface. It's hard to make transitions from ground to the wall and human often needs to place the robot on the wall. It's aimed that the robot can navigate area without the need of any human, so this is a significant drawback.

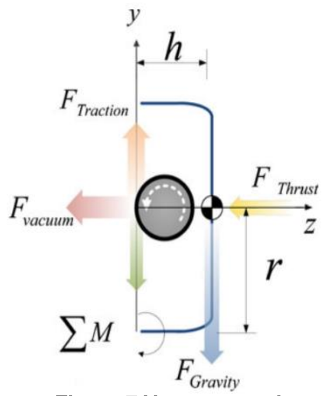


Figure 7 Vacuum suction based robot [16]

Another way commonly used to produces forces using vacuum suction is pressure differential. Which is to have a cup that is made of a flexible material like rubber, in order to have a good seal when the lip make contact with the target surface [18]. The seal can be done passively by just pushing the cup to the surface which is good as it doesn't consume power. In robotic application it's very hard to control the robot using passive suction cups. The robot shown in figure 8 is using passive suction which limited its movement to just one degree of freedom. Some substrates the cup isn't going give force needed for the application.

Figure 8 Suction Cup Robot [19]

Vacuum pump is often needed to remove the air between the cup and the surface [12]. This mechanism produces relatively bigger forces if compared to passive suction, which provide a good control if used in robotics. Vacuum pumps are bit bulky and produce huge noise. Robots using vacuum pumps consume a lot of power, which limits its working duration, and have a relatively higher weight because of the more batteries need to power it.

4.3. Gecko Inspired Adhesion

Geckos have an exceptional ability to stick to any surface either vertical or inverted surface like the ceiling, they can also climb wet or dry, smooth or rough surfaces [20].

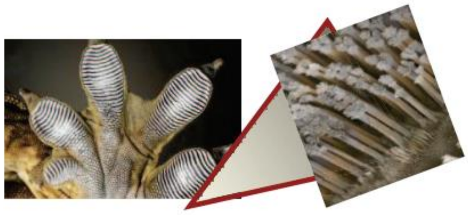


Figure 9 Close Look at Gecko Feet [17]

Figure 9 shows a close look at gecko feet. Geckos have protein micro hair 100 microns long and 5 microns in diameter in each of their toes. Geckos have roughly 500000 hairs per foot. Their hair splits at ends into nanofibers (spatula), cup-like suction structures which increase the contact surface area. Furthermore each gecko has about billion spatulas in its toes, which enables it to make great contact area with the surface [20]. The two front feet for a Tokay gecko can support up to 20.1 N of force parallel to the target surface for a 227 pad area, this is 40 times the force needed to support its weight [12].

Scientists were trying to develop adhesion mechanisms, similar to dry adhesion used by geckos to develop adhesion close to that done by geckos. Previous mechanisms such as flat polymer always had the problem that the adhesion is limited to smooth flat surfaces until FIBRILLAR adhesion was developed which are an “Arrays of fibers with diameters between 28 μm and 57 μm and a height of 114 μm” [18]. The key thing about this mechanism is the spaces between the fibres which allow it to make larger contact area with surface than flat adhesion as shown in figure 10. This allowed gecko inspired adhesion to have the ability to adhere to some uneven surfaces and improved it’s stickiness to rough surfaces. Gecko inspired adhesion still lack the ability to climb dusty surfaces as it loses its stickiness if exposed to dust.

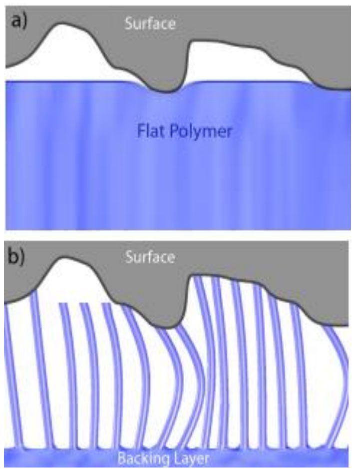


Figure 10 (a) flat (b) FIBRILLAR [18]

5. Adhesive Technologies Comparison

Table I: Comparing adhesive technologies based upon [7] and [10]

Technology	Force/ Area (N/Cm2)	Power Consumption	Surfaces the Technology can work on	Safety of the environment it's working in	Can be used on Dusty Surfaces	Controllability
Electroadhesion [7]	Good (From 0.2 to 2)	Excellent (~0.02mW/N)	Excellent	Excellent	Excellent	Excellent
Vacuum Suction [17]	Excellent	Bad (Up to 450 Watts)	Good	Excellent	Bad	Good
Dry Adhesion (Gecko Feet) [17]	Good	Excellent (Passive)	Bad	Excellent	Bad	Bad
Claws, Microspines	Excellent	Excellent	Bad	Bad	Excellent	Bad
Chemical Adhesion	Excellent	Excellent	Excellent	Good	Bad	Bad
Magnetic Adhesion	Excellent	Excellent (Passive)	Bad	Good	Excellent	Bad

There is wide range of adhesive technologies, some of them have extreme drawbacks which will lead to eliminating them. Chemical adhesion is an adhesive force produced when chemical bond is generated, once the bond is generated it can't be used again. This is a massive drawback since it's aimed that the robot climbs the wall more than once [21]. There are robots which uses Microspines to generate forces by penetrating in to penetrate in the surface [22]. Although they can climb rough surfaces and the forces they produce are relatively high, they can't climb smooth surfaces. They can damage the substrate they adhere to, which will ruin the environment it's working in, this is enough to exclude it. Although magnetic adhesion produces relatively high forces, the range of surfaces it can work on is extremely limited, as it can only work on ferromagnetic surfaces. From this the last 3 technologies can be eliminated.

Vacuum suction has the highest force generated if compare to Electroadhesion and Gecko inspired adhesion. It requires time to adhere to the surface, since it has to suck the vacuum in the cup. If compared to other technologies robots using vacuum suction are relatively slow [7]. Any gap in the seal will cause the adhesion mechanism to fail, which doesn't allow it to adhere to cracked surfaces [7] Vacuum suction produces noise and cause the robots to be bulky because of the vacuum pumps.

One big benefit about gecko inspired adhesion is that it requires almost no time to attach to the surface, which allows for no delay locomotion as compared to Vacuum Suction and Electroadhesion [7]. Gecko inspired adhesion climbs on smooth surfaces very well, they don't need power to adhere to the substrate but they need power to peel the robot from the surface which gives it an advantage over Vacuum Suction. Gecko inspired adhesion adheres to fewer surfaces than Electroadhesion. Recently it had the ability to climb some rough surfaces such as wood, but it still struggle to climb some rough surfaces [23]. This is a major drawback since it will limit the areas which the robot will be able to work in.

Electroadhesion can work on most of the materials like silicon, silicon dioxide, wood, dry wall, glass, concrete and plastics. It can adhere to rough and smooth substrate [24], it has fast responses, easy to control it, it's energy efficient , and it doesn't produce noise if compared to vacuum suction [7], the only drawback if compared to vacuum suction and gecko inspired adhesion, is that Electroadhesion has relatively lower forces. It was proven in previous sections that theoretically Electroadhesion provide enough forces. This is the best adhesion technology for wall climbing robots.

6. Tracked Robot using Electroadhesion

Tracked robots are popular for the use of with Electroadhesion, since the force increases significantly with the surface area. This robot showed in figure 11 weights 220 g including the batteries and control. It has the ability to climb wide range of surfaces with speed up to 15 cm/s [7]. Unlike most wall climbing robots this robot uses belt which is driving Electroadhesive pads, this technique allows the pads to take the shape of the surface, which allow it to work on rough and uneven surfaces.

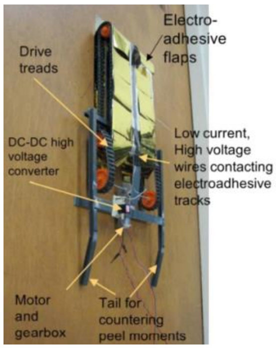


Figure 11 Tracked robot Electroadhesion [7]

Tracked robot uses Electroadhesive pads as flaps (figure 12). This increases the contact surface area without actually increasing the size of the robot itself, hence reduces the weight. This can be a good idea for the design of the robot. This robot didn't have the ability to rotate, however if the robot is separated into two sides each side has a separate track theoretically it should rotate easily.

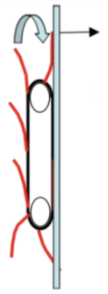


Figure 12 Pads used as flaps [7]

7. W-Climbot Robot

W-Climbot has five degrees of freedom it is made of five joint modules and two suction modules as shown in figure 13. Each suction cup module has three suction cups [24]. It uses Bellow cups to be able to adhere on tilted surfaces. The Length of the robot when it's fully extended is 1.3m and its weight is 15.8 Kg [25]. W- Climbot has a small vacuum pump which can generate pressure around 25 kPa in the suction module in seconds [25].

Figure 13 W-Climbot Robot [24]

One of the challenges for wall climbing robots is to adjust the robot arm to be close and perpendicular to the target surface. This is needed for vacuum suction to insure good vacuum absorption. It's also vital for Electroadhesion, since electrostatic forces decreases tremendously with the square of the distance [12].

This robot uses visual feedback to monitor the climbing process. Tactile senor was used to detect the contact with the surface. Ultrasonic sensors were implemented to detect how far the end effector is from the target surface. These sensors will be needed when Electroadhesion is used to give a visual idea of the environment.

The mechanism of using the sensors to give an idea of the environment allow the time used to securely put the robot arm on a surface to be reduced from 3 minutes if just teleoperation was used to 30s if the sensors were used to assist teleoperation. This shows that feedback sensors have to be used even when Electroadhesion is used to improve the speed of the attachment [25].

The design of the robot is impressive. It can make transitions easily from ground to wall and from wall to ceiling. Also there's a special advantage about this design is that it can be improved to allow the robot move through holes, which most of the normal wall climbing robots can't do. Similar design can be integrated in a wheeled robot which will increase its speed and allow it to tackle a lot of obstacles. Even if

Electroadhesion will be used the pad should be spilt in to more than one pad to avoid tilting caused by the deformation of the pads.

8. Waalbot II

Waalbot II weights 85 gram with a length of 95.6 mm, it consumes average power of 2.4 W, it has two foots for the actuation each one has triangular leg with three adhesive pads, each leg has 2 degrees of freedom to enable the robot to maintain contact with the surface. It's using Polyurethane FIBRILLAR footpads inspired from dry adhesion used by geckos [23]. Waalbot II has a foam layer between leg and the adhesive pad which reduces the probability of misalignment between the leg and the target surface.

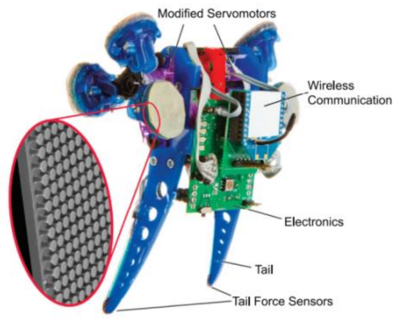


Figure 14 Waalbot II [23]

Waalbot II has the ability to climb vertical surfaces at speed approximately equal to 5 cm/s. It has the ability of climbing vertical smooth surfaces carrying an extra weight of 100g. It doesn't just climb smooth surfaces it can also climb non-smooth surfaces with a high surface roughness like rough wood. It can also move on vertical and inverted surfaces of any orientation.

When the robot is moving poor synchronisation between the two foots produce a torque which imbalances the robot and make it fall from one side, this happens when there's no tail. Adding two tails one on each side which are aligned with the centres of rotation of each foot, causes the resulting torque not to be transferred to the other side [23]. Although having tail on the robot might look like it's adding more weight, this proves that a tail might be needed to have motion as expected. This means that a tail might be needed if the body of the robot is going to be split into two bodies. It's also a good idea to have foam layer when Electroadhesion is used, to reduce the misalignments and absorb the reaction forces produced by the substrate when the robot tries to makes contact with it.

9. Progress To Date

Adhesive technologies were compared, the best one was Electroadhesion. One of the problems encountered was that Electroadhesive pads aren't commercially available [13], however the idea is simple two electrodes next to each other's that are of different polarity with dielectric on the top for insulation.

Although it's easy to produce forces using Electroadhesion, it's complicated to increase this force as there are more than 33 variables that affect the Electroadhesive forces [26]. There are variables which affect the forces produces massively, one of them is the design. There's a 540% improvement in the simulation results by just changing the pad design. According to [26] the worm comb shown in Figure 15 is the best design it's showing a 28% increase in the force if compared to other comb type designs.

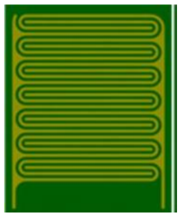


Figure 15 Worm Comb [26]

10. Future Work

Since the worm comb was the best design the next step is to design one of these pads to test it. Figure 16 is showing the steps used before to design an Electroadhesive pad, similar procedure will be done in the university. The worm comb design will be done using Altium Designer. Suppliers will be found to get 23 μm polyester, 20 μm copper and Polyurethane as conformal spray.

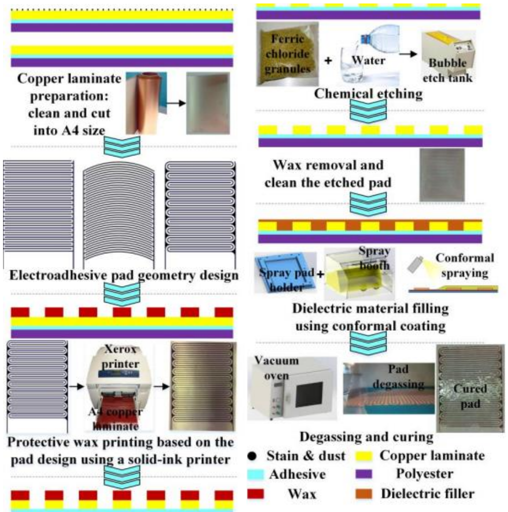


Figure 16 Electroadhesive pads manufacturing steps [26]

11. Conclusion

Robots using other technologies than Electroadhesion showed more success than robots using Electroadhesion. If the technologies are to be compared Electroadhesion has better response, uses lower energy, easier to control, doesn't produce noise, it works if there's dust or moist environment and works on rough and smooth surfaces. The only drawback is that other technologies are better is the produced force. The forces produced by Electroadhesion depends on so many factors if taken into consideration the forces produced by Electroadhesion should be enough for the robot.

Also not so many robots uses Electroadhesion since its relatively new technology, both Waalbot II and W- Climbot are second version for the robots, and the first versions were much worse in both robots, hence if Electroadhesion is used in a robot with good design, enough time for testing and improvements. It should be better than these two robots, since the technology is better.

12. References

[1] C. Hagis, “HISTORY OF ROBOTS”, WAGNER COLLEGE [online] May 2003 available: https://pdfs.semanticscholar.org/c7da/dcf0c86f3fcb6429d11c086ff61b29d3855e.pdf

[2] P. Debenest, E.F. Fukushima, S. Hirose “Gryphon-I - buggy robot for field applications on uneven terrain” [online] 5-7 Aug. 2002 available: http://ieeexplore.ieee.org/document/1195204/

[3] ZME Science (February 2017)” Chinese factory replaces 90% of human workers with robots. Production rises by 250%, defects drop by 80%” [online] available: https://www.zmescience.com/other/economics/china-factory-robots-03022017/ [Accessed 5 November 2017]

[4] PCMag UK (2017)” Drone Regulations: What You Need to Know” [online] available: http://www.noflydrones.co.uk/ [Accessed 5 November 2017]

[6] Alamy Limited “Stock Photo - Industrial building new plant room” Alamy.com, 5 June 2009, [online] Available: http://www.alamy.com/stock-photo-industrial-building-new-plant-room-24466266.html?pv=1&stamp=2&imageid=B65093FC-E8C8-4EBF-B5EC-B1E46F542A5E&p=231833&n=0&orientation=0&pn=1&searchtype=0&IsFromSearch=1&srch=foo%3dbar%26st%3d0%26pn%3d1%26ps%3d100%26sortby%3d2%26resultview%3dsortbyPopular%26npgs%3d0%26qt%3dducting%26qt_raw%3dducting%26lic%3d3%26mr%3d0%26pr%3d0%26ot%3d0%26creative%3d%26ag%3d0%26hc%3d0%26pc%3d%26blackwhite%3d%26cutout%3d%26tbar%3d1%26et%3d0x000000000000000000000%26vp%3d0%26loc%3d0%26imgt%3d0%26dtfr%3d%26dtto%3d%26size%3d0xFF%26archive%3d1%26groupid%3d%26pseudoid%3d%26a%3d%26cdid%3d%26cdsrt%3d%26name%3d%26qn%3d%26apalib%3d0%26apalic%3d%26lightbox%3d%26gname%3d%26gtype%3d%26xstx%3d0%26simid%3d%26saveQry%3d%26editorial%3d1%26nu%3d%26t%3d%26edoptin%3d%26customgeoip%3d%26cap%3d1%26cbstore%3d1%26vd%3d0%26lb%3d%26fi%3d2%26edrf%3d [Accessed 5 November 2017]

[7] H. Prahlad, R. Pelrine, S. Stanford, J. Marlow and R. Kornbluh, "Electroadhesive robots— Design, Fabrication, and Testing of a Proprioceptive Electroadhesion Pad for Space Applications," *2008 IEEE International Conference on Robotics and*

Automation, Pasadena, CA, 2008, pp. 3028-3033.
doi: 10.1109/ROBOT.2008.4543670
keywords: {adhesion;mobile robots;clamping forces;compliant electroadhesion;electrically controllable adhesion technology;electroadhesion;electroadhesive robots;electrostatic charges;legged robots;wall climbing robots;Adhesives;Clamps;Cleaning;Climbing robots;Dielectrics and electrical insulation;Electrostatics;Insulation life;Legged locomotion;Power supplies;Robust control},
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4543670&isnumber=4543169

[8] IEEE Spectrum (6 Jun 2015)"A Compilation of Robots Falling Down at the DARPA Robotics Challenge" [online] available: https://www.youtube.com/watch?v=g0TaYhjpOfo [Accessed 5 November 2017]

[9] Boston Dynamics (27 Mar 2012)" Sand Flea Jumping Robot" [online] available: https://www.youtube.com/watch?v=6b4ZZQkcNEo [Accessed 5 November 2017]

[10] Daniel Schmidt, Karsten Berns, "Climbing robots for maintenance and inspections of vertical structures—A survey of design aspects and technologies, In Robotics and Autonomous Systems", Volume 61, Issue 12, 2013, Pages 1288-1305, ISSN 0921-8890,
Available:http://www.sciencedirect.com/science/article/pii/S0921889013001656

[11] Cao, Changyong & Sun, Xiaoyu & Fang, Yuhui & Qin, Qing-Hua & Yu, Aibing & Feng, Xi-Qiao. "Theoretical model and design of electroadhesive pad with interdigitated electrodes". Materials & Design. Volume 89, Pages 485-491, (2016)

[12] Raju D.Dethe1 ,Dr. S.B. Jaju2 "Developments in Wall Climbing Robots: A Review" International Journal of Engineering Research and General Science Volume 2, Issue 3, April-May 2014 Available:
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.645.4042&rep=rep1&type=pdf

[13]W. J. Tong, Cheng Siong Chin and Wei Peng Lin, "Design of a miniature tri-axis vertical wall structure climbing robot using electroadhesion," *2014 9th IEEE Conference on Industrial Electronics and Applications*, Hangzhou, 2014, pp. 473-477.
doi: 10.1109/ICIEA.2014.6931210

keywords: {adhesion;microrobots;service robots;In-house built electroadhesive;electro-adhesion method;micro-robots;miniature tri-axis vertical wall structure climbing robot;vertical structure inspection;Clamps;Climbing robots;Electrodes;Electrostatics;Force;Legged locomotion;electro-adhesion;microprocessor;miniature wall-climbing robot;three-axis robot;vertical structure},

[15] Grabit IEEE Spectrum: Technology, Engineering, and Science News "Electrostatics: Good for Robot Grippers, and Lots More" 27 Oct 2014

Available:https://spectrum.ieee.org/automaton/robotics/robotics-hardware/electrostatic-robot-grippers [Accessed 5 November 2017]

[16] Ig Mo Koo "Development of Wall Climbing Robot System by Using Impeller Type Adhesion Mechanism", Journal of Intelligent & Robotic Systems, vol. 72, no. 1, pp. 57-72, October 2013

Availble:https://link.springer.com/content/pdf/10.1007%2Fs10846-013-9820-z.pdf

[17] R. Chanchlani, S. K. R. Swami, R. Agarwal, S. Sharma, M. Agrawal and R. Agarwal, "Intelligent Climber: A Wireless Wall-Climbing Robot Utilizing Vacuum Suction and Sand Paper," *2013 Texas Instruments India Educators' Conference*, Bangalore, 2013, pp. 271-276.
doi: 10.1109/TIIEC.2013.55
keywords: {design engineering;friction;mobile robots;robot dynamics;telerobotics;DTMF technology;air suction motor;ceiling;friction;hazardous conditions;inspection;intelligent climber;sand paper;suction mechanism;surveillance applications;vacuum suction;vertical wall;wirelessly operated wall climbing robot;Adhesives;Force;Hair;Mobile robots;Rough surfaces;Surface roughness;Air Blower;DTMF;sand paper;wall climbing;wireless camera},
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6757153&isnumber=6757097

[18] B. Aksak, M. P. Murphy and M. Sitti, "Gecko inspired micro-fibrillar adhesives for wall climbing robots on micro/nanoscale rough surfaces," *2008 IEEE International Conference on Robotics and Automation*, Pasadena, CA, 2008, pp. 3058-3063.
doi: 10.1109/ROBOT.2008.4543675
keywords: {adhesives;mobile robots;bioinspired synthetic dry adhesive fiber

arrays;gecko inspired microfibrillar adhesives;microscale rough surfaces;nanoscale rough surfaces;wall climbing robots;Adhesives;Carbon nanotubes;Climbing robots;Fabrication;Nanobioscience;Optical fiber testing;Robotics and automation;Rough surfaces;Surface contamination;Surface roughness},
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4543675&isnumber=4543169

[19] D. Ge, C. Ren, T. Matsuno and S. Ma, "Guide rail design for a passive suction cup based wall-climbing robot," *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Daejeon, 2016, pp. 5776-5781.
doi: 10.1109/IROS.2016.7759850
keywords: {mobile robots;climbing surface;guide rail design;passive suction cup;robot prototype;wall-climbing robot;Belts;Force;Pressing;Prototypes;Rails;Robots;Rough surfaces},
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7759850&isnumber=7758082

[20] C. Menon, M. Murphy and M. Sitti, "Gecko Inspired Surface Climbing Robots," *2004 IEEE International Conference on Robotics and Biomimetics*, Shenyang, 2004, pp. 431-436.
doi: 10.1109/ROBIO.2004.1521817
keywords: {adhesives;biomimetics;mobile robots;safety;biomimetic adhesives;biomimetic miniature robot;gecko inspired robot;gecko inspired synthetic dry adhesive;mobile robotics;surface climbing robot;wall climbing robot;Adhesives;Animals;Climbing robots;Humans;Inspection;Mobile robots;Orbital robotics;Robotics and automation;Rough surfaces;Service robots;Biomimetic adhesives;biomimetic miniature robots;gecko adhesion;mobile robotics},
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1521817&isnumber=32545

[21] Saravia, Walter, "Design, Fabrication, and Testing of a Proprioceptive Electroadhesion Pad for Space Applications" (2015). *Dissertations and Theses*. 244.
http://commons.erau.edu/edt/244

[22] Alan T. Asbeck, “Scaling Hard Vertical Surfaces with Compliant Microspine Arrays”,
The International Journal of Robotics Research, Vol. 2, no. 12,PP 1165-1179,

December 1, 2006
Available:http://journals.sagepub.com/doi/abs/10.1177/0278364906072511#articleCitationDownloadContainer

[23] Michael P. Murphy, “
Waalbot II: Adhesion Recovery and Improved Performance of a Climbing Robot using Fibrillar Adhesives” The International Journal of Robotics Research Vol. 30, no. 1, PP 118-133, October 13, 2010 Available:
http://journals.sagepub.com/doi/pdf/10.1177/0278364910382862

[23] Michael P. Murphy, “Waalbot II: Adhesion Recovery and Improved Performance of a Climbing Robot using Fibrillar Adhesives” The International Journal of Robotics Research Vol. 30, no. 1, PP 118-133, October 13, 2010 Available:
http://journals.sagepub.com/doi/pdf/10.1177/0278364910382862

[24]H. Zhu, Y. Guan, W. Wu, L. Zhang, X. Zhou and H. Zhang, "Autonomous Pose Detection and Alignment of Suction Modules of a Biped Wall-Climbing Robot," in *IEEE/ASME Transactions on Mechatronics*, vol. 20, no. 2, pp. 653-662, April 2015.
doi: 10.1109/TMECH.2014.2317190
keywords: {adhesion;calibration;intelligent robots;legged locomotion;pose estimation;sensors;telerobotics;airtight chamber;autonomous alignment algorithm;autonomous intelligent climbing;autonomous pose detection;biped wall-climbing robot W-Climbot;calibration;sensing system;suction module alignment;swinging suction module;vacuum adsorption;Acoustics;Adsorption;Joining processes;Joints;Robot sensing systems;Autonomous alignment;pose detection;suction module;wall-climbing robot},
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6825850&isnumber=6936399

[25] Zhu, Haifei & Guan, Yisheng & Wu, Wenqiang & Zhou, Xuefeng & Zhang, Lianmeng & Zhang, Xianmin & Zhang, Hong. (2011). The superior mobility and function of W-Climbot — A bio-inspired modular biped wall-climbing robot. . 10.1109/ROBIO.2011.6181337.

[26] J. Guo, “Geometric Optimisation of Electroadhesive Actuators Based on 3D Electrostatic Simulation and its Experimental Verification”, IFAC-PapersOnLine, vol. 49, no. 21, pp.
309-315, 2016, Available: https://dspace.lboro.ac.uk/dspace-

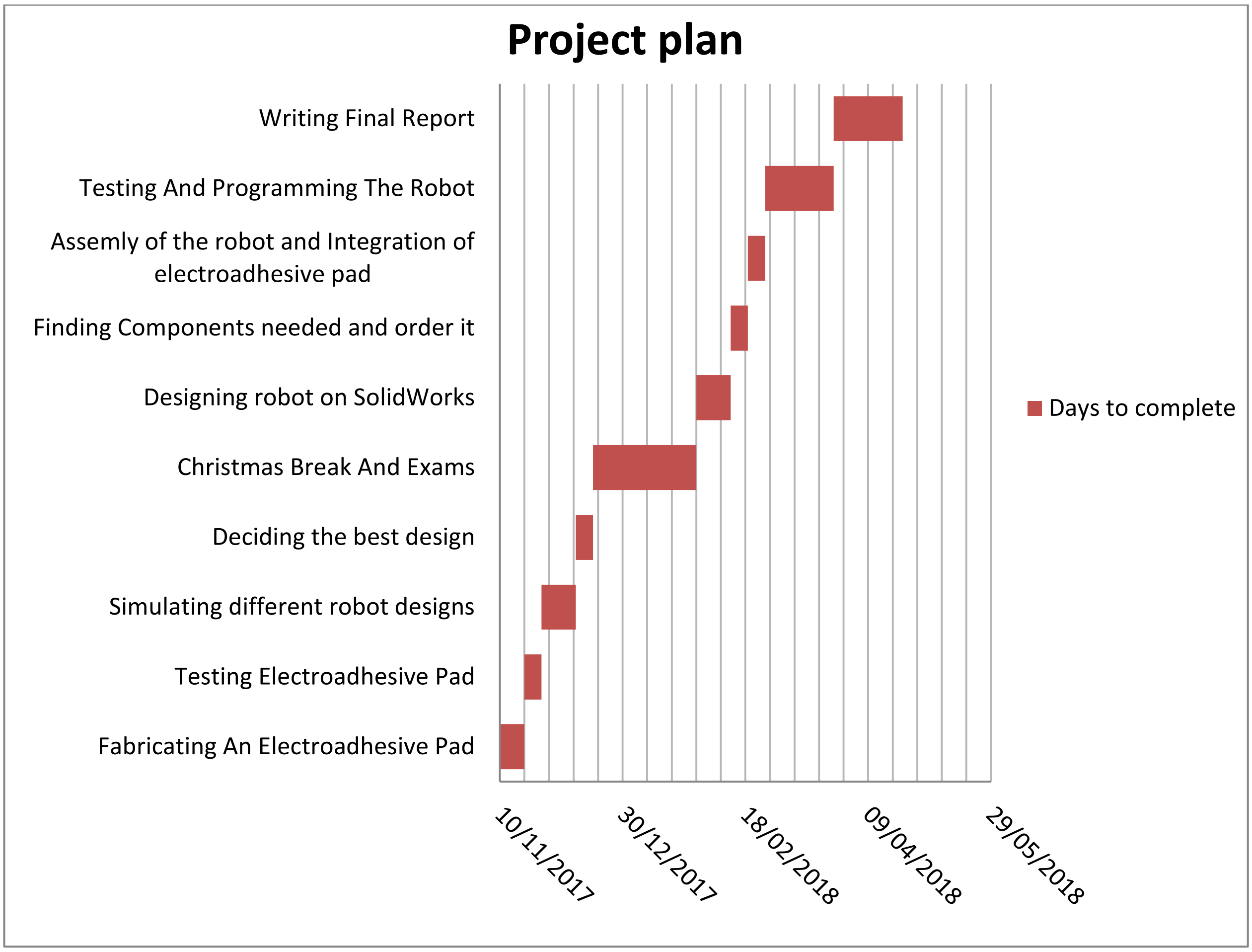
jspui/bitstream/2134/24149/3/Chamberlain_110%20(2).pdf

13. Appendices

13.1. Appendix 1 - Project Specification

Commonly used Locomotion technologies like Wheeled, legged robots and drones restrict the work of their robots to limited areas, some obstacles can stop their work completely. The goal of this project is to develop a robot that can work in places commonly used technologies can't work in, like narrow corridors with a lot of pipes and gaps. Review about adhesion technologies was done, and the outcome was that Electroadhesion is the best to be implemented. The next step is to manufacture Electroadhesive pad, to test and eventually integrate it into a robot.

13.2. Appendix 2 - Project Plan



13.3. Appendix 3 - Risk Assessment

WORK ACTIVITY/ WORKPLACE (WHAT PART OF THE ACTIVITY POSES RISK OF INJURY OR ILLNESS)	HAZARD (S) (SOMETHING THAT COULD CAUSE HARM, ILLNESS OR INJURY)	LIKELY CONSEQUENCES (WHAT WOULD BE THE RESULT OF THE HAZARD)	WHO OR WHAT IS AT RISK (INCLUDE NUMBERS AND GROUPS)	EXISTING CONTROL MEASURES IN USE (WHAT PROTECTS PEOPLE FROM THESE HAZARDS)	WITH EXISTING CONTROLS			
					SEVERITY	LIKELIHOOD	RISK RATING	RISK ACCEPTABLE
Using Electroadhesive pads	Shock because of Electroadhesive pads	Small Electric shock since current is very low	Anyone using the pad	Using good insulator Material	**2**	**1**	**Low**	**Yes**
Using soldering iron	Being burnt or causing fire	High Major Injury	Anyone in the lab	Use fume suckers, ask for training before using	**4**	**1**	**Low**	**Yes**
Working in the laboratory	Electrical	Death, burns	Anyone in the lab	• Don't use equipment not given • don't remover covers • Failure should be reported immediately	**5**	**1**	**Low**	**Yes**
Hot Glue gun	Hot Glue	Sticking fingers together burn	Nour Elghazawy	Ask for training before using glue gun	**2**	**2**	**Low**	**Yes**
Marking out	Hammer and Centre punch	Hurting fingers	Nour Elghazawy	Ask for training before using hammers	**2**	**2**	**4**	**Yes**

RISK ASSESSOR	**NAME: Nour Elghazawy**	**SIGNED: Nour Elghazawy**	**Revised 4/11/2017**	**THIS RISK ASSESSMENT WILL BE SUBJECT TO A REVIEW NO LATER THAN: (12 months)**

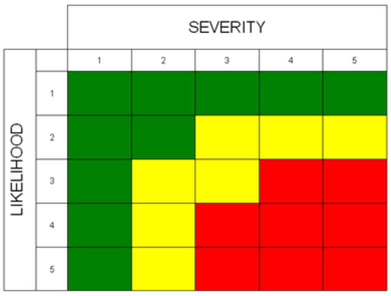
SEVERITY VALUE = **Potential consequence of an incident/injury given current level of controls.**

5 Very High Death / permanent incapacity / widespread loss
4 High Major Injury (Reportable Category) / Severe Incapacity / Serious Loss
3 Moderate Injury / illness of 3 days or more absence (reportable category) / Moderate
2 Slight Minor injury / illness - immediate 1st Aid only / slight loss
1 Negligible No injury or trivial injury / illness / loss

LIKELIHOOD = **what is the potential of an incident or injury occurring given the current level of controls**

5 Almost certain to occur
4 Likely to occur
3 Quite possible to occur
2 Possible in current situation
1 Not likely to occur

The intersection of the chosen column with the chosen row is the Risk classification.



RISK SCORE Key:

1- 5 LOW - Tolerable - Monitor and Manage

6 - 10 MEDIUM - Review and introduce additional controls to mitigate to ALARP

12 - 25 HIGH - Intolerable Stop Work and immediately introduce further control measures

11.2. Appendix 2- Maxwell stress in an electroadhesive pad

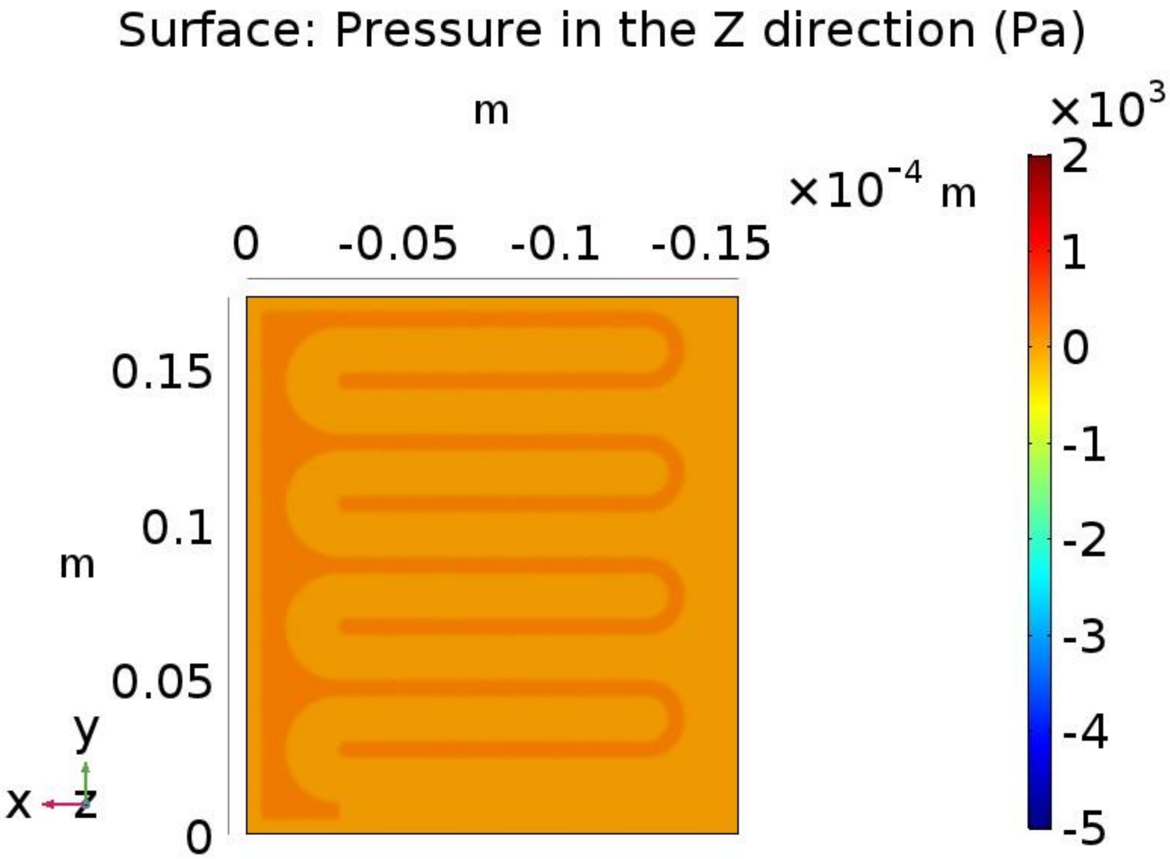


Figure 31: Maxwell stress surface plot

11.3. Appendix 3- 2D Geometry used for the 2D model

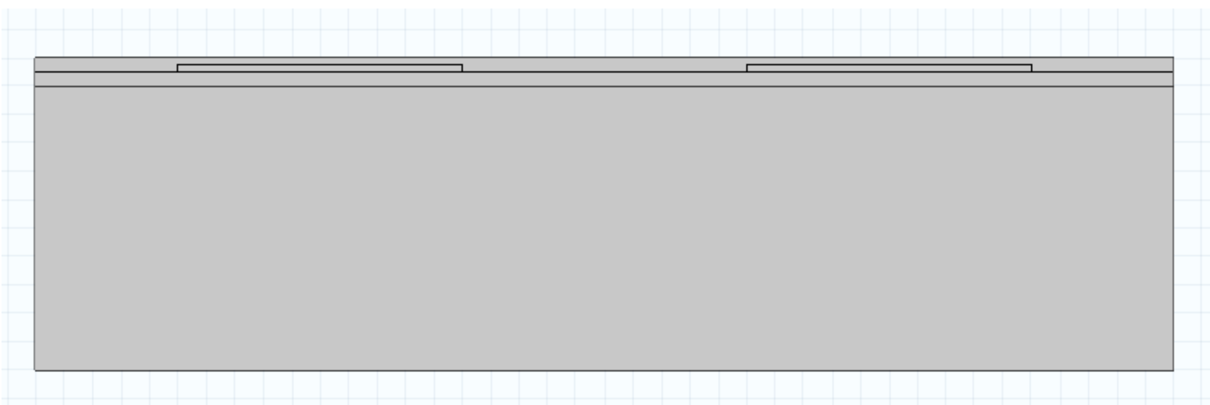


Figure 32: Geometry used in 2D

11.4. Appendix 4- Insulator Thickness Optimum Value

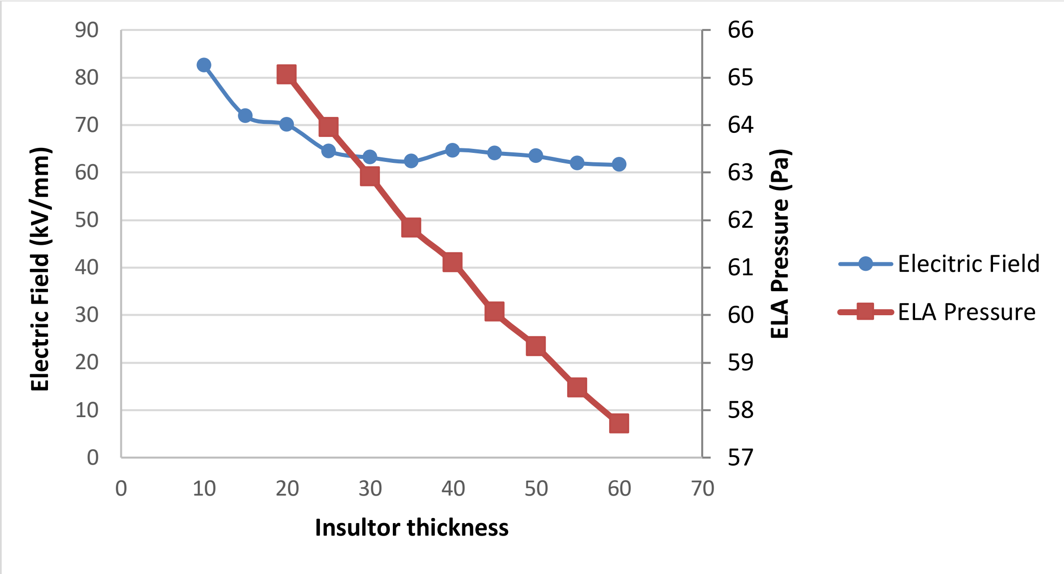


Figure 33: Optimizing the insulator layer

11.5. Appendix 5- Design comparison

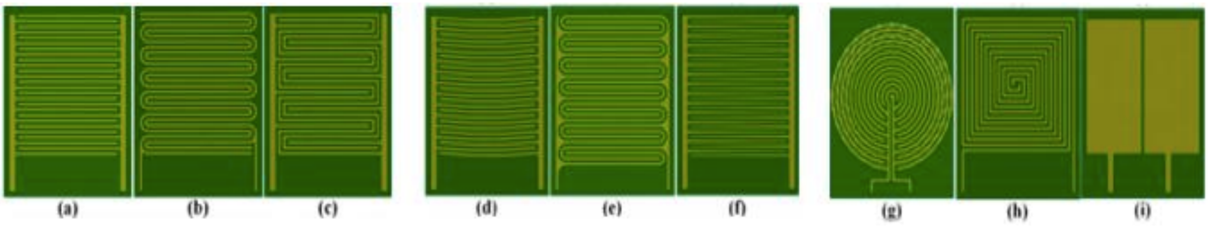


Figure 34: Different pad designs "(a) is the interdigitated or comb shape, (b) is the snake electrode shape, (c) is the serpentine-electrode shape, (d) is the curve-comb shape, (e) is the worm-comb shape, (f) is tooth-comb shape, (g) is the concentric shape, (h) is the spiral shape, and (i) is the double-electrode shape." [3]

The design of the pad has a significant effect on the force generated by the pad. [3] Showed that the worm-comb design has a capacitance which is 540% higher than the value found for double-electrode shape. Capacitance is one of the methods which can be used to optimize the pad design. Also [3] experimentally found that the worm-comb generates around 28% higher forces than the curve comb and the normal comb designs. [3] concluded worm comb shown in Figure 34 (e) is the best design.

11.6. Appendix 6- Pad 1

Figure 35: 0.4 mm electrode 0.4 mm gap pad

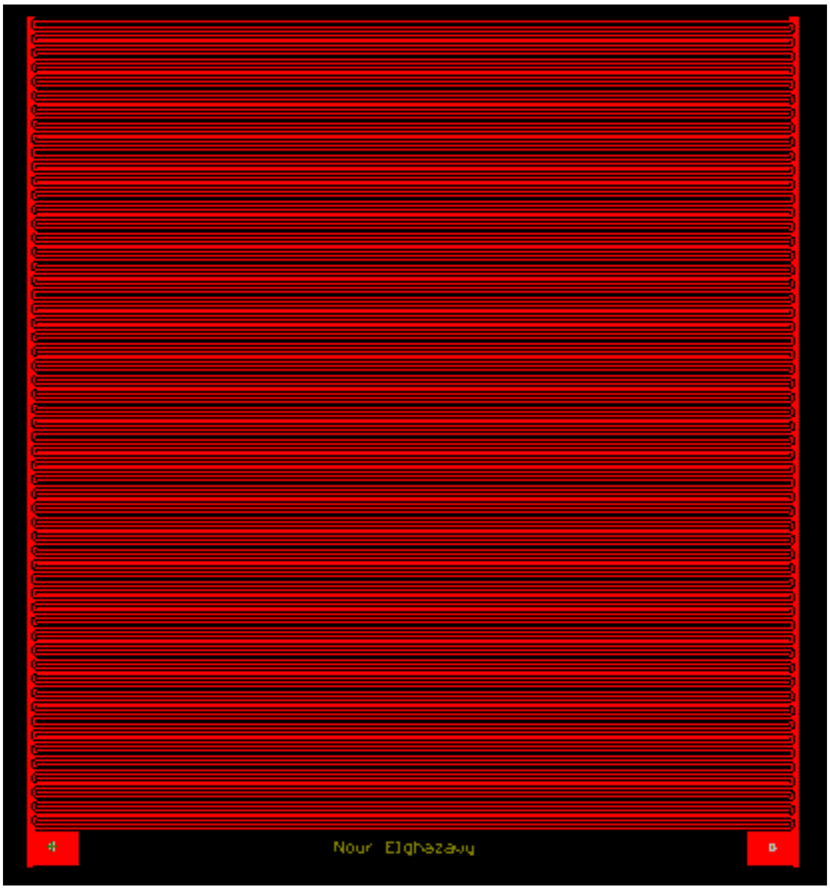


Figure 36: 0.4 mm electrode 0.4 mm gap pad Cad Model

11.7. Appendix 7- Electric field simulation for Pad 2

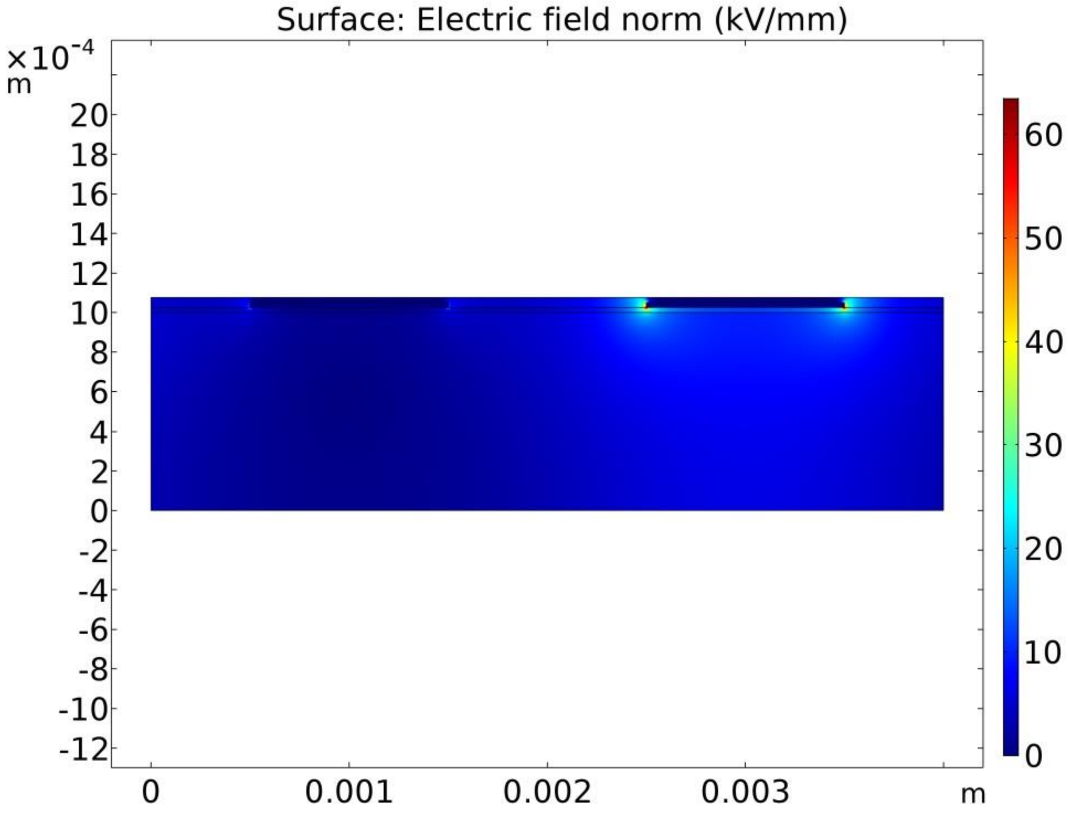


Figure 37: Comsol 2D Electric field simulation

11.8. Appendix 8- Pad 2

Figure 38: 0.4mm electrode 1mm gap

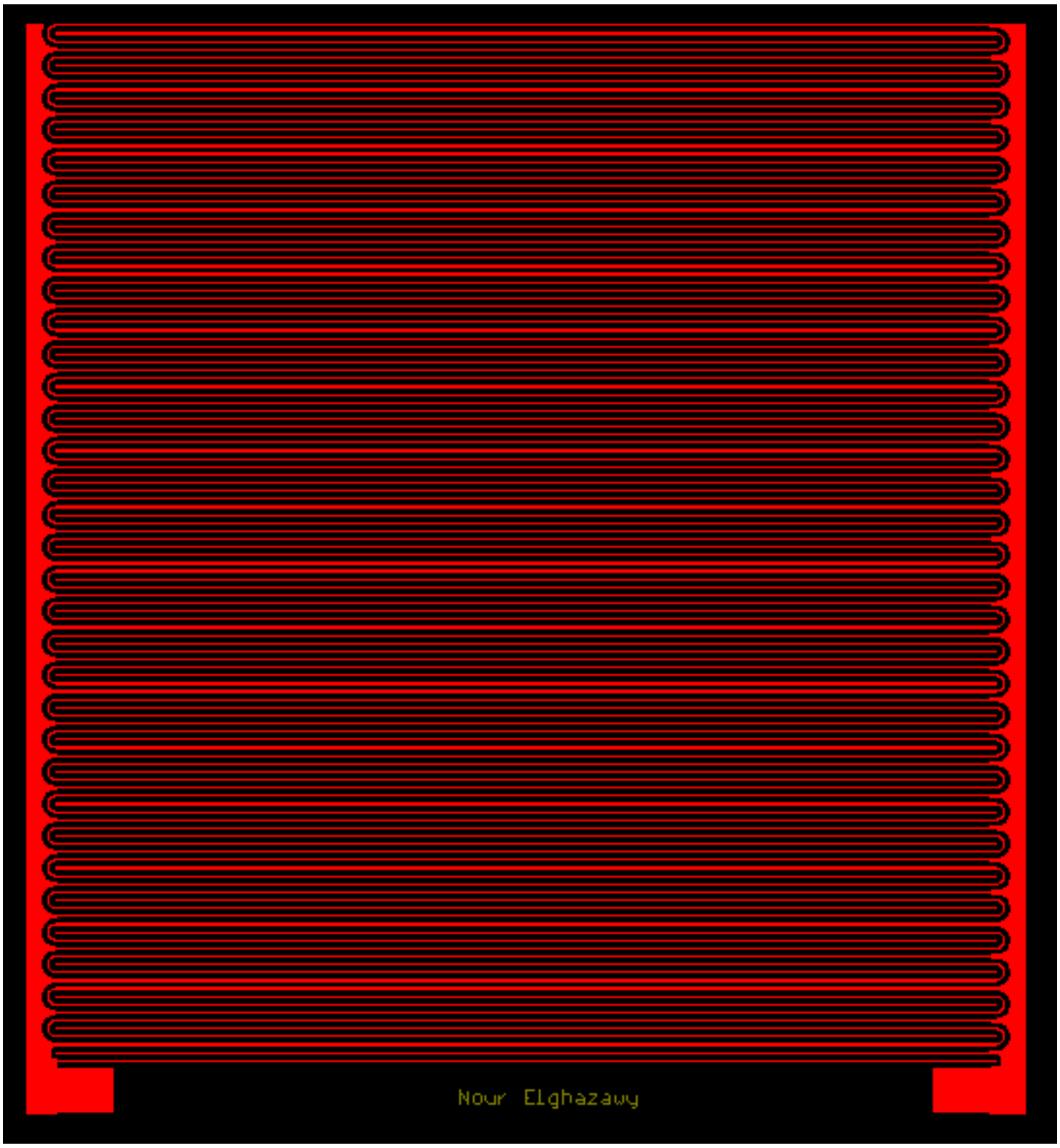


Figure 39: 0.4 mm 1 mm gap Cad model

11.9. Appendix 9- Pad 3

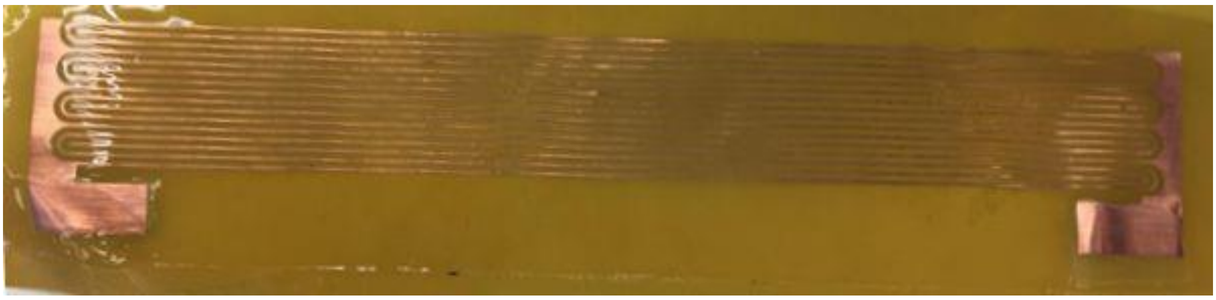


Figure 40: 0.4mm electrode width 1mm gap

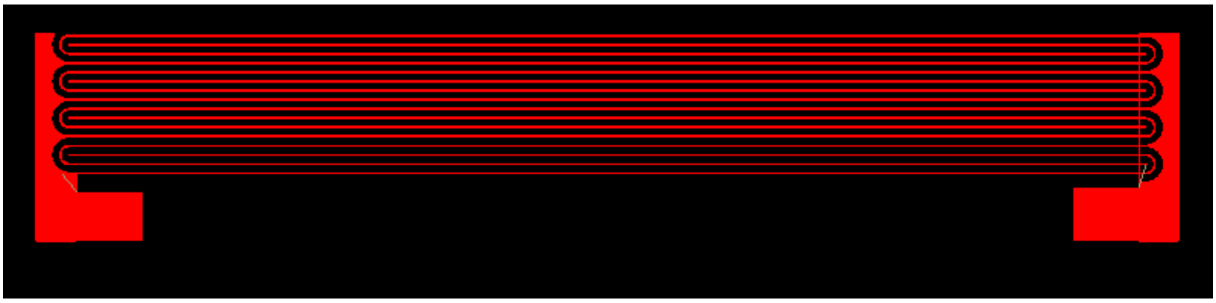


Figure 41: 0.4mm electrode width 1mm gap Cad model

11.10. Appendix 10- Pad 4

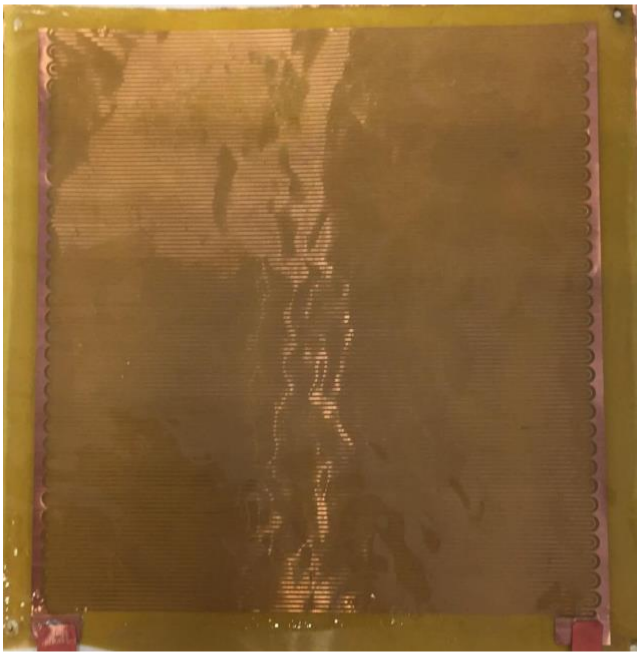


Figure 42: 0.4mm electrode 1mm gap, Big sample

11.11. Appendix 11- Pad 5

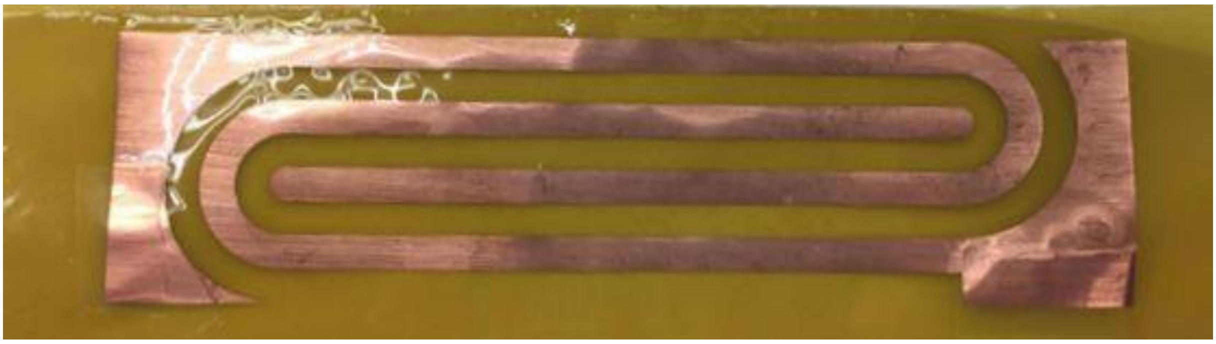


Figure 43: 5 mm electrode 5 mm gap

Figure 44: 5 mm electrode 5 mm gap Cad model

11.12. Appendix 12- Pad 6

Figure 45: 5 mm electrode 5 mm gap

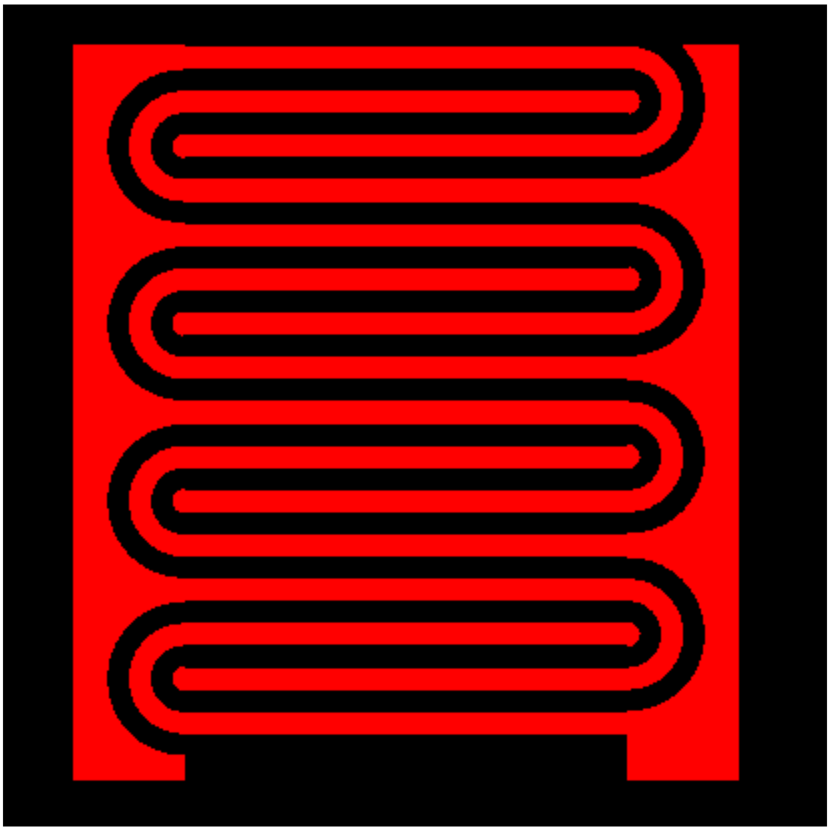


Figure 46: 5 mm electrode 5 mm gap Cad model

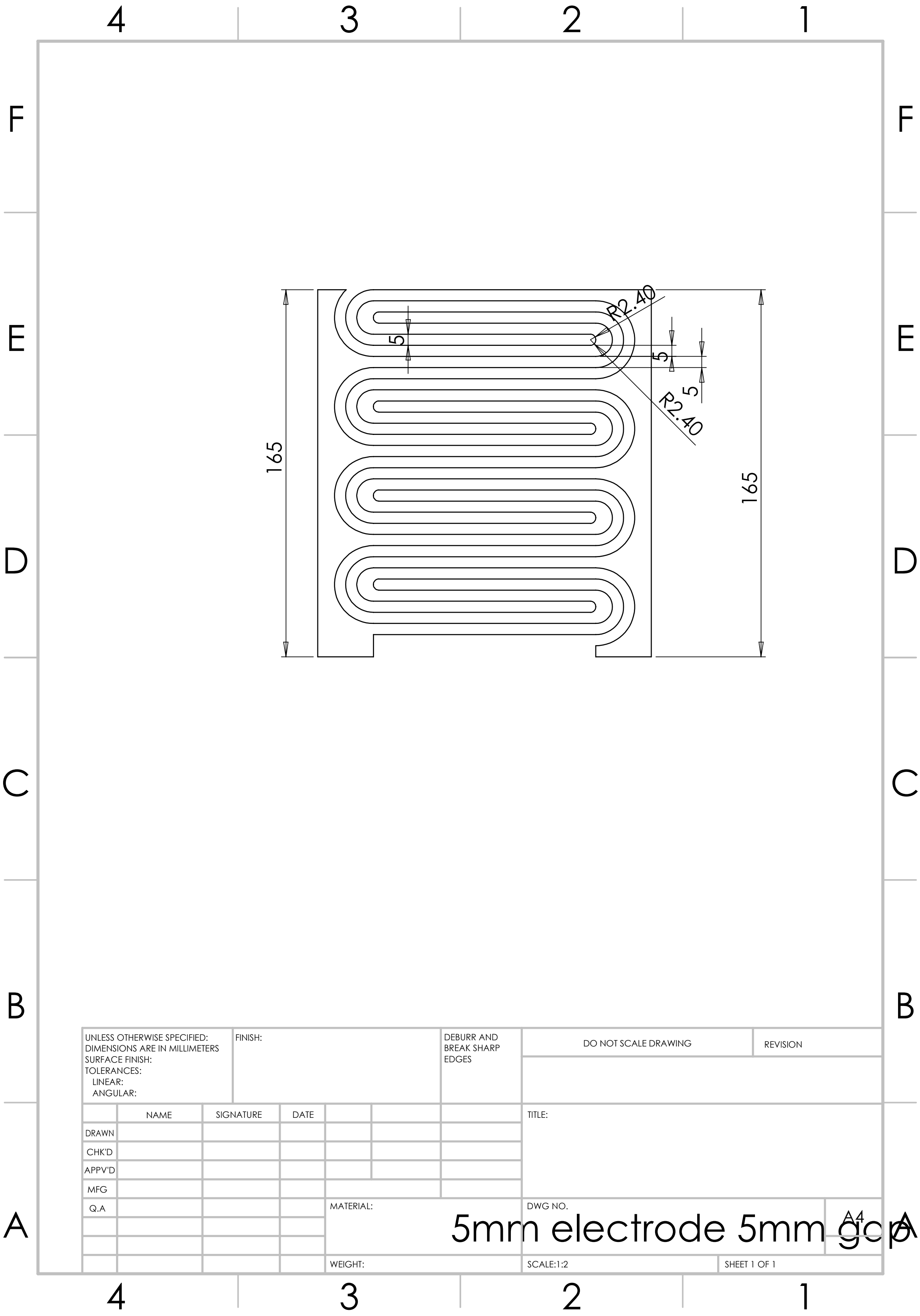


Figure 47: 5 mm electrode 5 mm gap dimensions.

11.13. Appendix 13- Pad 7

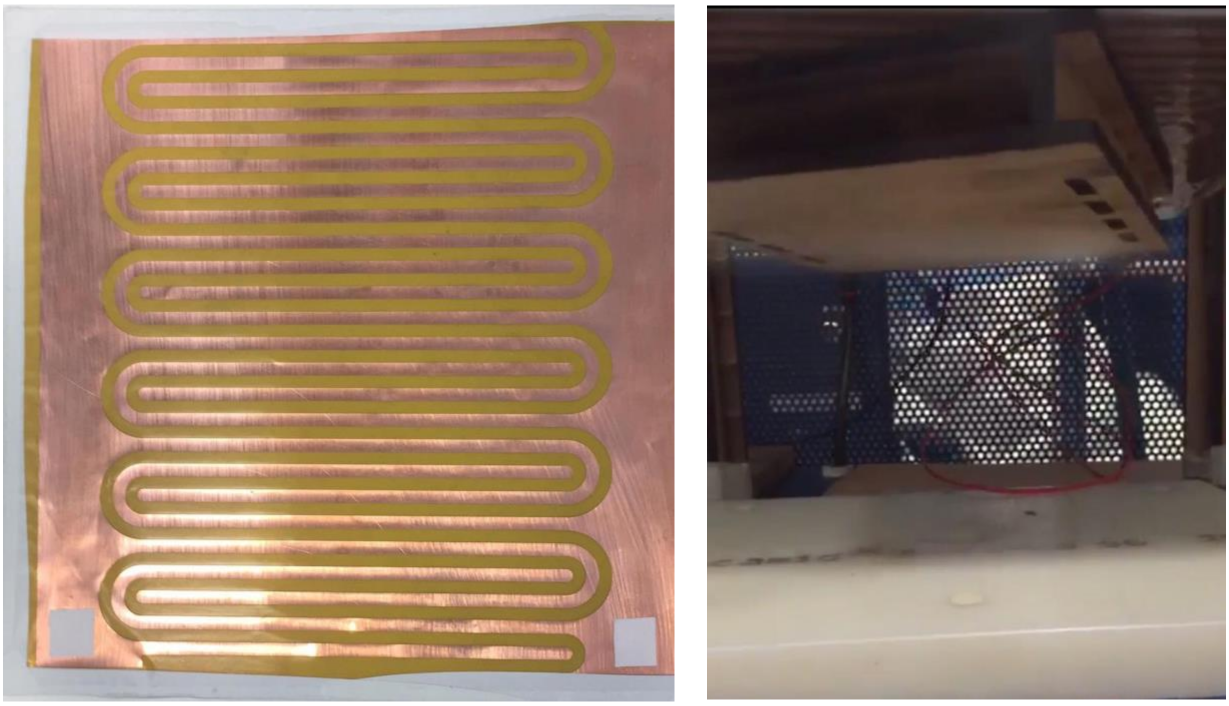


Figure 48: (A) shows a physical pad of 5mm electrode width 5mm gap between the electrodes (B) Pad lifting the weight lifter

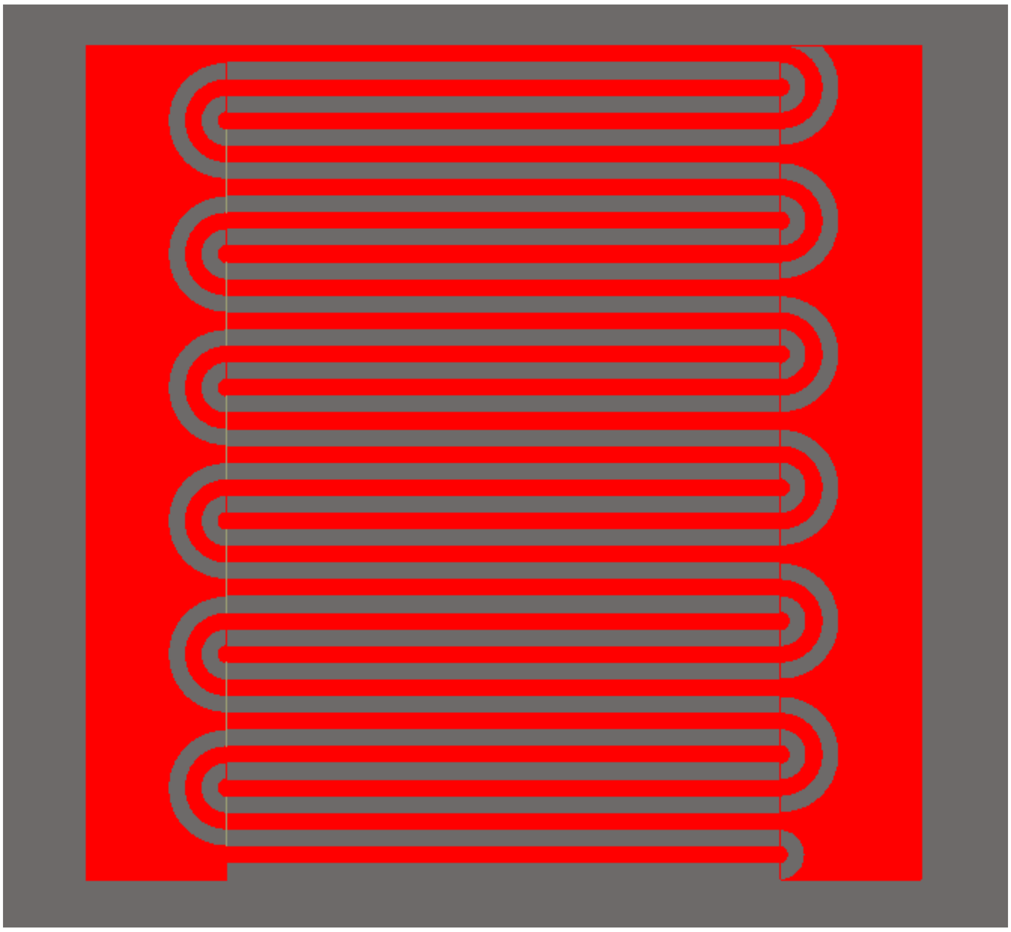


Figure 49: 5 mm electrode 5 mm gap 250 mm × 250 mm

11.14. Appendix 14- Robot Design

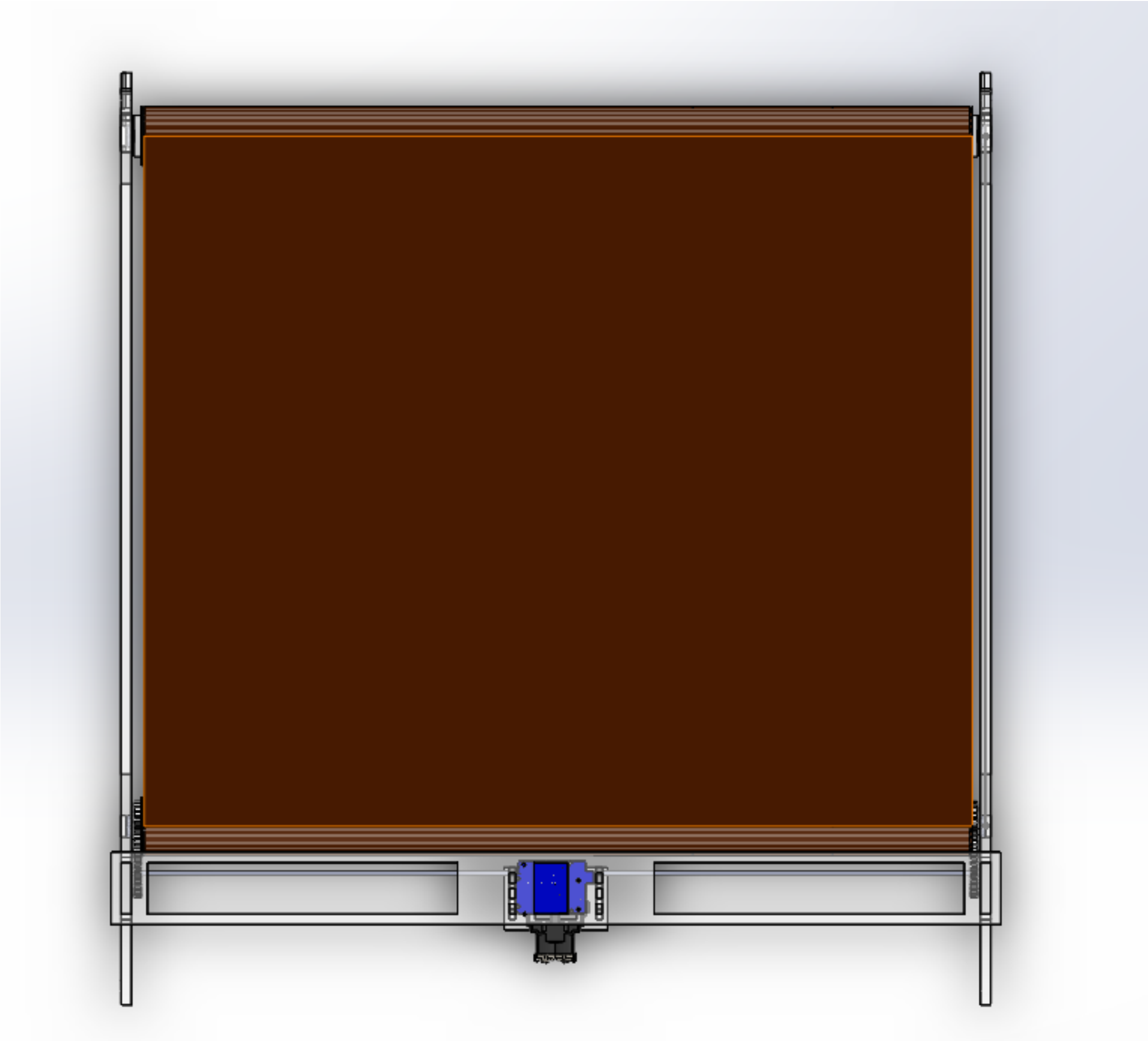


Figure 50: Robot Top View

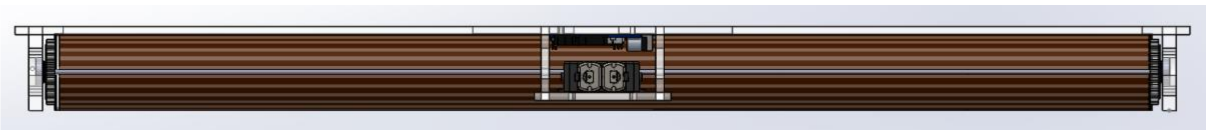


Figure 51:Robot Front View

Figure 52: Robot side view

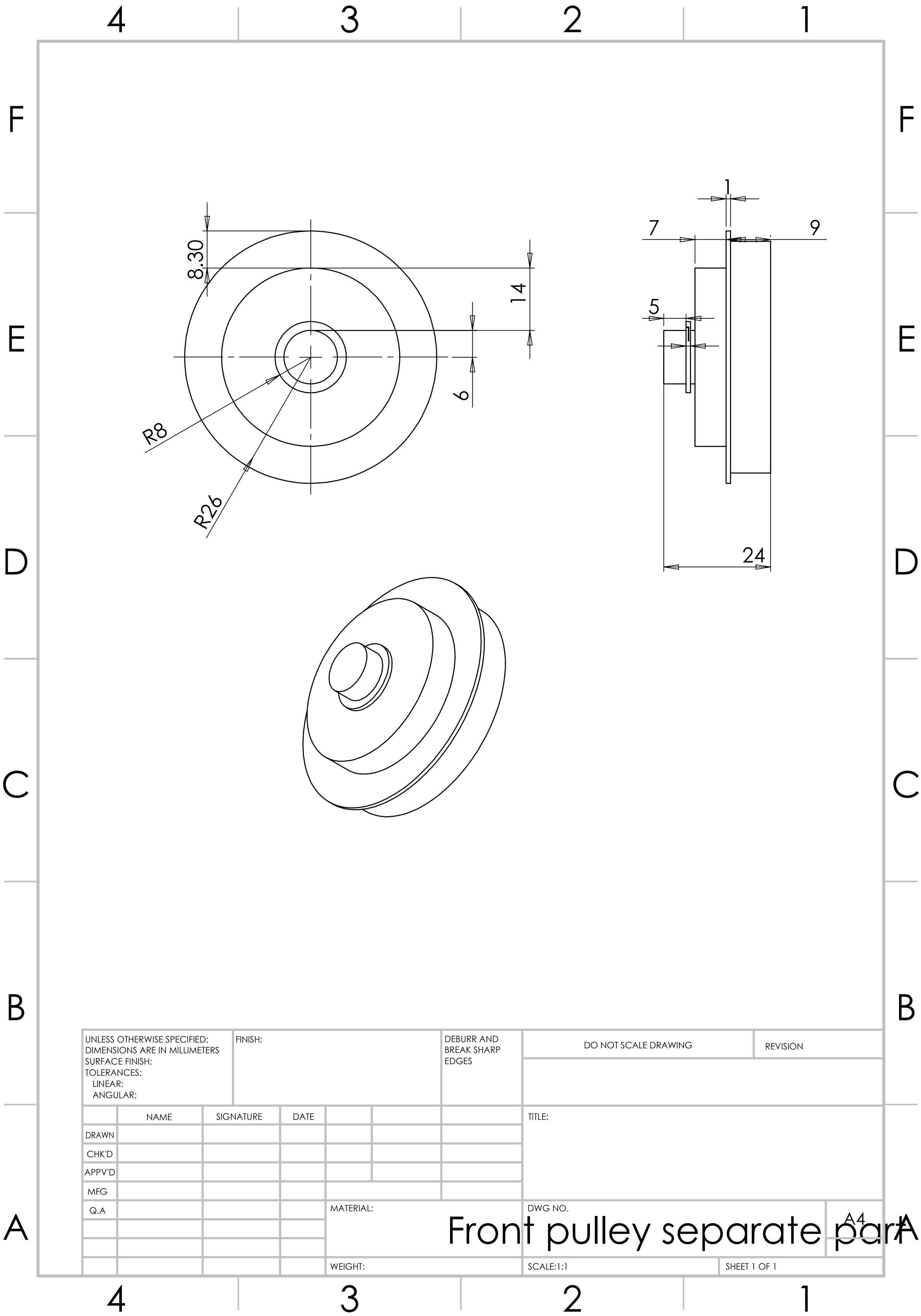


Figure 53: Front Pulley dimensions

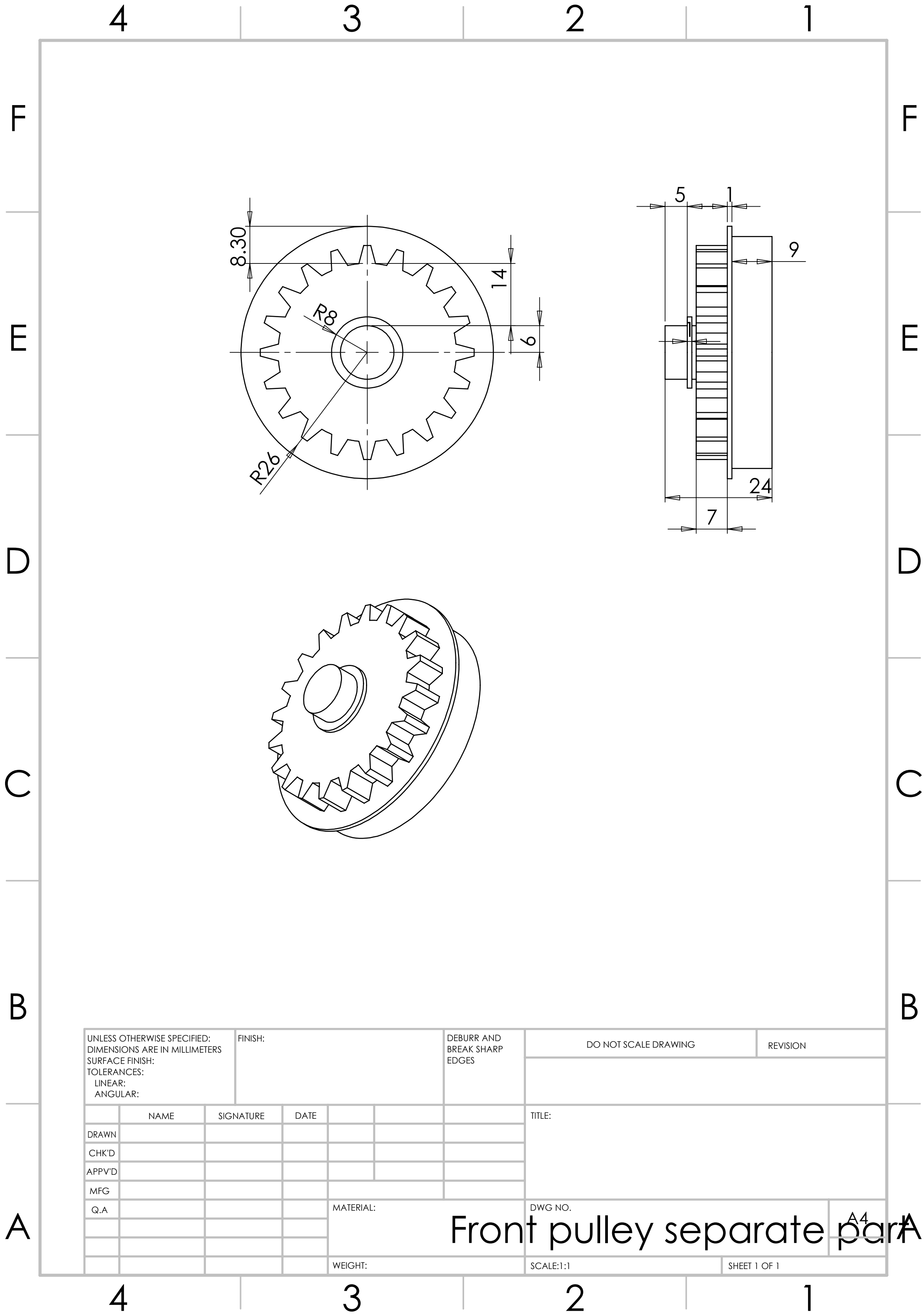


Figure 54: Rear Pulley Dimensions

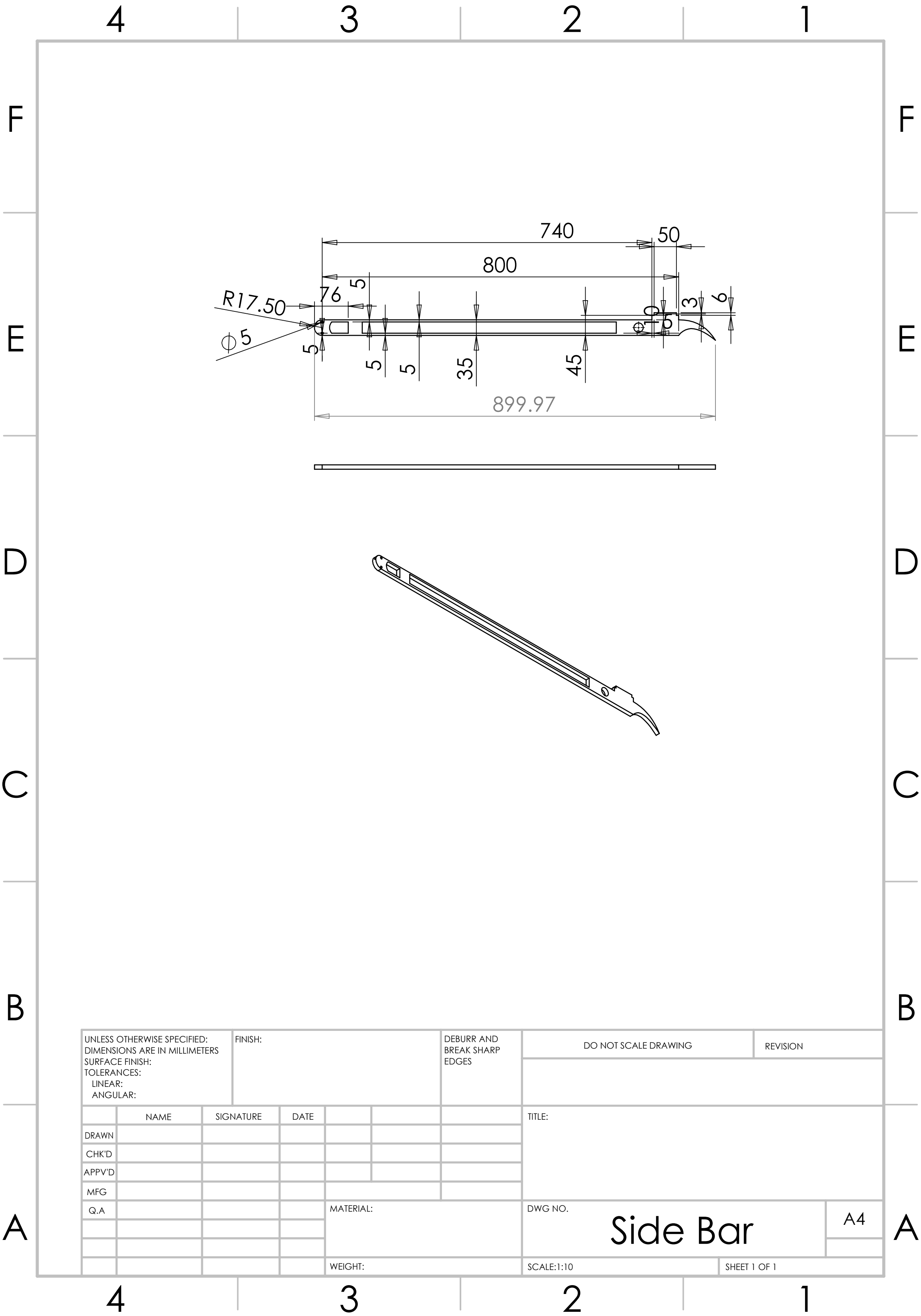


Figure 55: Side bar dimensions

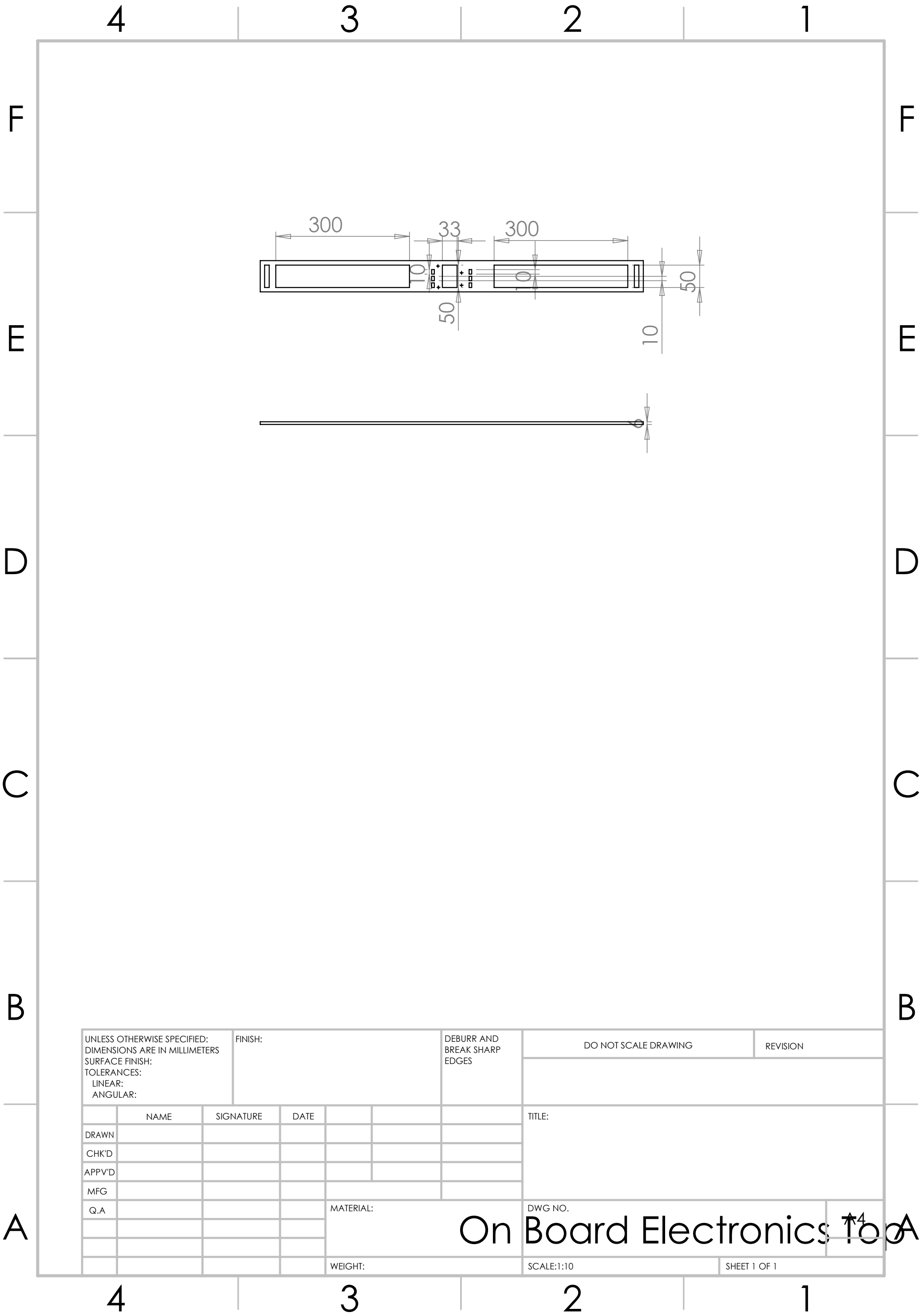


Figure 56: On Board electronics dimensions

11.15. Appendix 15- Weight Lifter

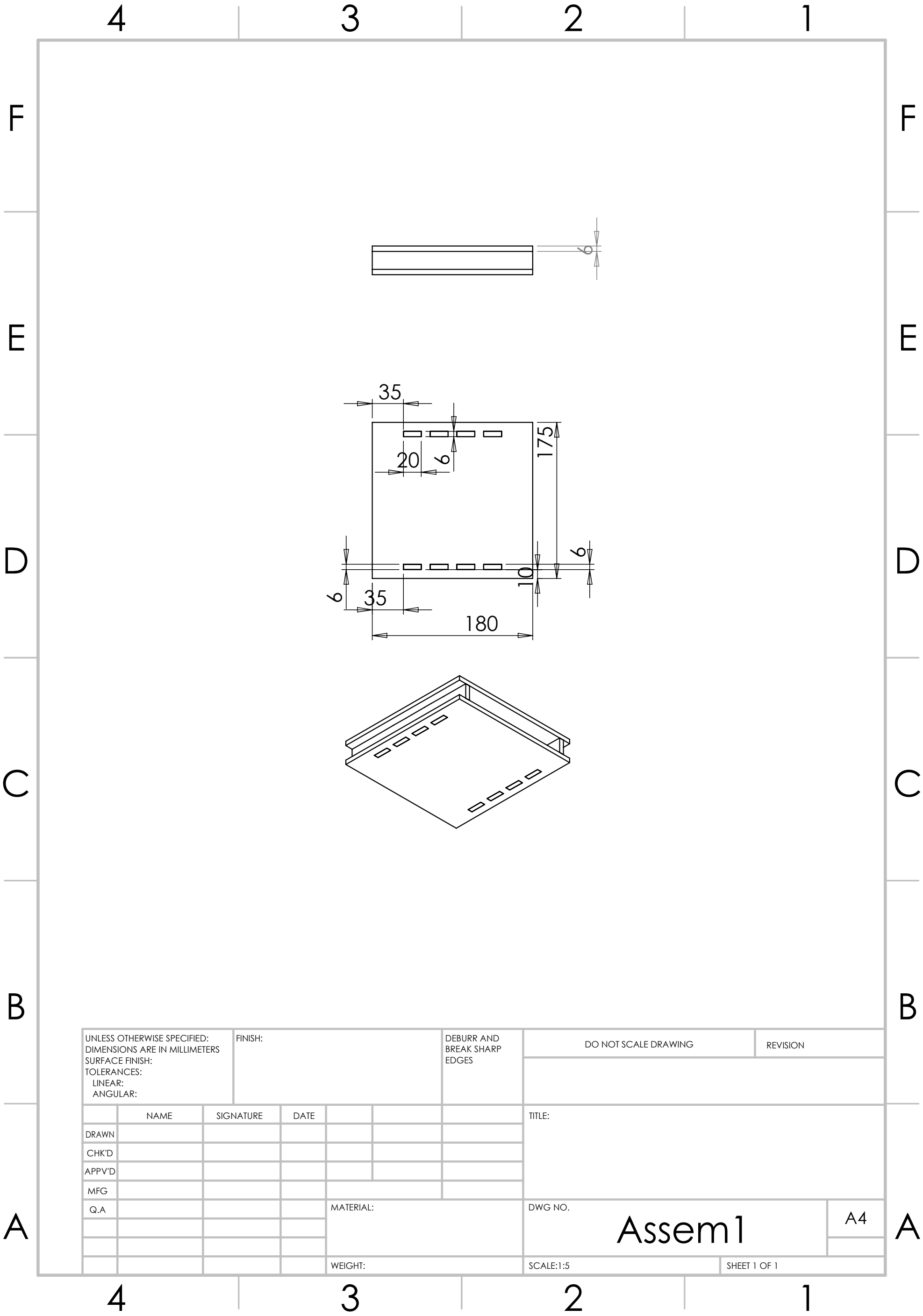


Figure 57: One of the Weight lifters dimensions

11.16. Appendix 16- Failure Pad coating

Figure 58: (A) eye goggles, (B) Gloves, (C) Face mask

Figure 59: (A) Fume Cupboard, (B) Polyurethane Spray

The polyurethane spray used is shown in Figure 59(B) and because its hazardous, protection was used while spraying the pad. The pad was sprayed in the fume cupboard shown in Figure 59(A) for ventilation, furthermore face mask shown in Figure 58(c) was used to reduce the effect of inhalation of the gas. Eye goggles were used for eye protection and rubber gloves were used to avoid any contact of the spray with the skin as shown in Figure 58(B) and (C).

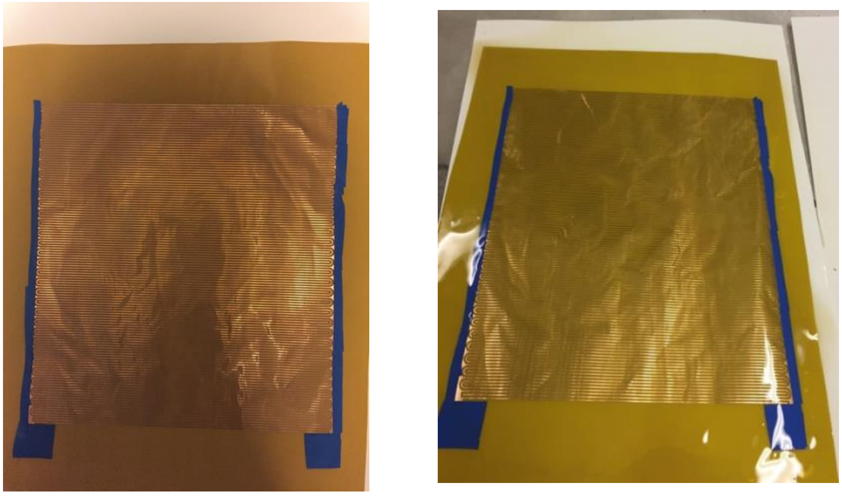


Figure 60: (A) Pad before spraying (B) Pad after spraying

Masking tape was used for the copper parts wanted to be kept exposed without coating to be able to make a connection for the pad. Although the rectangular blocks are the connection electrodes on the sides were also covered with tape, because the mechanism of how the pads were going to be on the robot was not yes chosen, and one of the mechanism was to have a rotating copper track where the electrode on the sides were going to be needed for the connection.

The pad was on a plastic sheet as shown in Figure 60, and then sprayed from a distance of around 200 mm at an angle of around 45° as specified in the data sheet. In the beginning it was tried to spray it a speed of 100 mm/s however because the pad is very flexible and not flat because of the creases in the material, the material had some kind of pockets where the liquid is collected and when the areas where there's less coating was sprayed again the polyurethane simply comes of the pad and some of it leaked on the back of the pad.

The pad was left to dry for 24 hours as specified in the datasheet for room temperature drying. Vacuum oven wasn't used for this pad because there was no access to it at that time. When coming back after 24 hours the pad found to be wrapped around the plastic sheet. And this happened because of the polyurethane which came of the pad on the plastic sheet causing the sheet to wrap and then the pad since the pad was on top of it.

11.17. Appendix 17- Spray Risk Assessment

Safety Documents (Project Risk Assessment) Ref: ** **/**/**

The University of Manchester

University of Manchester National Grid Power Systems Research Centre Laboratories

Title of Experiment / Test:-	Spraying An Electroadhesive Pad and then use a dry oven

Location:-	Ferranti Building

Project Supervisor (must be SAE):-	

The Project Supervisor will usually be the Academic Supervisor when the person carrying out the experiment is a student experimenter.

Name Of Person Carrying Out Expt:-	Nour Elghazawy

Safety Documents Valid From:- ** ** ** To:- ** ** **

For continuous periods of experimentation only. Re-validation of this document is required for breaks in experimentation greater than one month or when test circuit is dismantled and re-assembled.

Level Of Supervision (to be completed by Academic Supervisor/HV Laboratories Manager):

- Experimentation to be carried out in presence of student's Academic Supervisor
- Experimentation to be carried out in the presence of a SAE
- Experimentation to be carried out only with other Authorised Experimenters/Authorised Student Experimenters present in laboratory
- Experimentation may be carried out providing an SAE is in the Centre

A SAE (in area of competence) must always be in the Centre to permit experimentation to take place in the Centre.

Safety Key No. (for all HV experiments and any others requiring this):

Main Point of Isolation:-

Special Precautions/Instructions:-

SANCTION TO EXPERIMENT

EXPERIMENTER DECLARATION: I understand the contents of these safety documents. I am aware that any change in the experiment beyond that identified in these safety documents means that work must stop, the Risk Assessment reviewed and permission to resume has been given and countersigned by the Project Supervisor or HV Laboratories Manager.

Name: ____________________ Signed: ____________________ Date: ____________

Name of SAE 1, Validation:-______________________ Signed:-__________________________

Experiment seen/checked by SAE 1 ☐ yes: ☐ no

Name of SAE 2, Check:-________________________ Signed:-__________________________

Experiment seen/checked by SAE 2 ☐ yes: ☐ no

Assembled experiment MUST be seen & checked by at least one of the authorising SAEs before signing.

Two SAEs must be identified and sign here having confirmed the safety documents to be satisfactorily completed.

Document Cancelled: Date: ___________ Name: __________ Signature:______________

METHOD STATEMENT

Title of Experiment / Test:-	Spraying An Electroadhesive Pad and then using the dry oven		
Prepared by:-	Nour Elghazawy	**Date:-**	13/3/2018

A. Purpose of Experiment: To Avoid Dielectric Break down while Applying High Voltage to the Pad

B. Equipment Being Used / Circuit Diagram (where appropriate):

1) Polyurethane Spray
2) Electroadhesive Pad
3) Gloves
4) Face Mask
5) Eye goggles
6) Dry oven

Use separate sheet if required

C. Experimental Procedure:
1) Put the Pad on a plastic sheet in an area where there's ventilation.
2) Spray the Pad.
3) Put the Pad in a dry oven at a temperature of 80 degrees.
4) Wait for 90 minutes.
5) Take the Pad out of the oven and wait for it cool.

Continue on additional sheet if required

RISK ASSESSMENT
(must address all hazards identified in hazard checklist)

Title Of Experiment / Test:-					Date:-	**.**.**
Prepared By:-	Nour Elghazawy	Validated By:-		Checked By:-	Review:-....Specify	

Hazard (s) & Possible Consequences	Persons or Equipment at Risk	Control measures applied to eliminate / minimise risk	Residual risk with control measures applied			
			Severity	Likelihood	Risk rating	Risk Acceptable?
Polyurethane Contact with skin While spraying the pad May cause dryness of the skin	Experimenter	Use Rubber Gloves for protection	2	1	2	Yes
Polyurethane Contact with eye While spraying the pad May cause Irritating to eyes,	Experimenter	Use Eye goggles for protection	3	1	3	Yes
Polyurethane inhalation May cause irritation to the respiratory system headache, fatigue, dizziness and nausea and vomiting.	Experimenter and people in the lab	Use Face Mask and Spray it an a Ventilated area	4	1	4	Yes
Dangerous for the environment if discharged into watercourses	watercourses Environment the material is disposed in	Don't drain the disposed material, Put it in the garbage	5	1	5	Yes

Risk Assessment Matrix Likelihood (1-5) x Severity (1-5) = Risk (See attached matrix for guidance)	**1 – 5**: **Low**: Tolerable – monitor and manage **6 – 8: Medium:** Review, introduce further controls to reduce to as low as reasonably possible **9 – 25: High:** Intolerable. Do not commence work, further control measures required

RECORD OF CHEMICAL USAGE WITHIN EXPERIMENT

Chemical	Reason For Use	Data Sheet /COSHH Attached?	Are Hazards Resulting From Use Described In Risk Assessment Table Above?	Method Of Disposal
Polyurethane Spray	To Avoid Breaking the Dielectric While Applying high Voltage to the pad	http://www.farnell.com/datasheets/1770441.pdf?_ga=2.106149315.1397786275.1520944923-621122646.1520944923	Yes	Dispose of waste and residues in accordance with local authority requirement. And don't drain it

HAZARD CHECKLIST

You should indicate the hazards present in the experiment in the table below. If a hazard is present, control measures should be stated on the risk assessment. Note that this list is not exhaustive.

Hazard Type	Present	Not Present
Electric Shock From High Voltage (1kV & Over)	No	
Electric Shock From Low Voltage (Under 1kV)	No	
Tripping Hazards	No	
Slipping Hazards	No	
Fire	No	
High Temperatures	No	
Low Temperatures	No	
High Pressure	No	
Low Pressure	No	
Chemical Spillage	No	
Chemical Contact (Ingestion / Eye & Skin Contact)	Yes	
High Noise Levels	No	
Working At Height	No	
Head Height Hazards	No	
Production Of Dust & Fumes	No	
Manual Handling	No	
Production/Use Of Radiation	No	
Use Of Asphyxiating Gases	No	
Chemical inhalation	Yes	
Disposing Risk	Yes	
Any Other Hazards	No	

RISK ASSESSMENT SEVERITY MATRIX

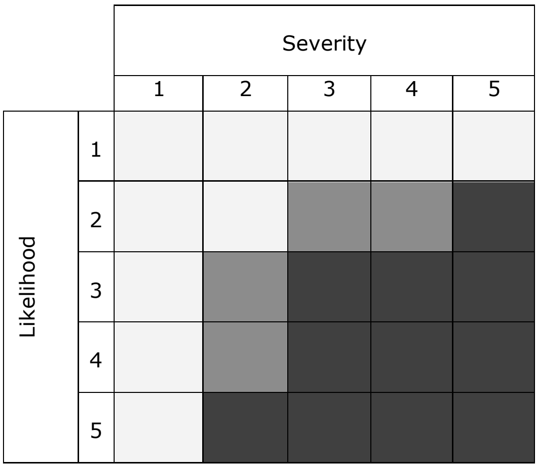
SEVERITY VALUE = Potential consequence of an incident/injury given current level of controls.

5 Very High:- Death / Permanent incapacity / Widespread loss
4 High:- Major Injury (Reportable Category) / Severe Incapacity / Serious Loss
3 Moderate - Injury / Illness of 3 days or more absence (reportable category) / Moderate loss
2 Slight: - Minor injury / Illness – Immediate 1st Aid only / slight loss
1 Negligible No injury or trivial injury / illness / loss

LIKELIHOOD = what is the potential of an incident or injury occurring given the current level of controls.

5 Almost certain to occur
4 Likely to occur
3 Quite possible to occur
2 Not likely to occur
1 Almost certain not to occur

The multiple of Likelihood with Severity is the risk classification value.



Risk Classification Value

1–5: **Low**: Tolerable – monitor and manage

6–8: Medium: Review, introduce further controls to reduce to as low as reasonably possible

9–25: High: Intolerable. Do not commence work, further control measures required

11.18. Appendix 18- Safety Interlock Risk Assessment

MANCHESTER 1824

Safety Documents (Project Risk Assessment) Ref: EEE PFD EER 038

The University of Manchester

University of Manchester National Grid Power Systems Research Centre Laboratories

Title of Experiment / Test:-	Electroadhesive Pad Testing
Location:-	Ferranti Building HV Lab
Project Supervisor (must be SAE):-	Dr Richard Gardner

The Project Supervisor will usually be the Academic Supervisor when the person carrying out the experiment is a student experimenter.

Name Of Person Carrying Out Expt:-	Nour Elghazawy

Safety Documents Valid From:- 13/12/17 To:- 01/07/18

For continuous periods of experimentation only. Re-validation of this document is required for breaks in experimentation greater than one month or when test circuit is dismantled and re-assembled.

Level Of Supervision (to be completed by Academic Supervisor/HV Laboratories Manager):

- Experimentation to be carried out in presence of student's Academic Supervisor ☐
- Experimentation to be carried out in the presence of a SAE ☐
- Experimentation to be carried out only with other Authorised Experimenters/Authorised Student Experimenters present in laboratory ☐
- Experimentation may be carried out providing an SAE is in the Centre x

A SAE (in area of competence) must always be in the Centre to permit experimentation to take place in the Centre.

Safety Key No. (for all HV experiments and any others requiring this): Cage 1

Main Point of Isolation: 13A socket adjacent to cage

Special Precautions/Instructions:- Use nonconductive pulleys and ropes with high dielectric strength.

SANCTION TO EXPERIMENT

EXPERIMENTER DECLARATION: I understand the contents of these safety documents. I am aware that any change in the experiment beyond that identified in these safety documents means that work must stop, the Risk Assessment reviewed and permission to resume has been given and countersigned by the Project Supervisor or HV Laboratories Manager.

Name: Nour Elghazawy Signed: Nour Elghazawy Date: 6/12/2017

Name of SAE 1, Validation:- P. Vidyadhar Signed:-

Experiment seen/checked by SAE 1 ☑ yes: ☐ no

Name of SAE 2, Check:- R. Gardner Signed:-

Experiment seen/checked by SAE 2 ☑ yes: ☐ no

Assembled experiment MUST be seen & checked by at least one of the authorising SAEs before signing.

Two SAEs must be identified and sign here having confirmed the safety documents to be satisfactorily completed.

Document Cancelled: Date: ___________ Name: _________ Signature: _____________

Safety Documents (Project Risk Assessment) Ref: EEE PED TER 0.8

METHOD STATEMENT

Title of Experiment / Test:-	Testing Electroadhesive pad		
Prepared by:-	Nour Elghazawy	**Date:-**	13/12/17

A. Purpose of Experiment: To provide a proof of concept of Electroadhesion (generating a force when HV is applied to a pad) and quantify measure the adhesive force generated.

B. Equipment Being Used / Circuit Diagram (where appropriate):

Electroadhesion is the mechanism of inducing forces by applying voltages to the Electroadhesive pad. The positive charges in the pad will attract the negative charges in the substrate, and the negative charges in the pad will attract the positive charges in the substrate, which will induce force causing the substrate to stick to the pad.

Figure 1 Current Electroadhesive Pad Design

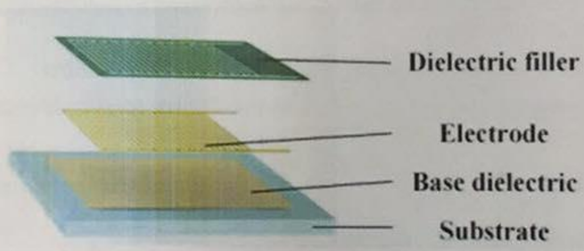


Figure 2 Electroadhesive pad based upon [1]

The Pad is made of base dielectric (figure 2) which is made of polyimide. The next layer is the electrode, which is made of copper, covered by another dielectric layer, which is the material between the electrodes. At the moment this is air. The maximum voltage which can be applied can be calculated using the following formula:

$V_{max} = K \times G$ .... Equation 1 [2]

Where, V_{max} is the maximum voltage that can be applied, K is the dielectric strength of the dielectric filler, G is the gap between the electrodes. For the current design, K is equal to 3000 V/mm, G is 0.4 mm so the maximum voltage is 1200 V. If it's found that the voltage is needed to be increased the dielectric filler will be changed from air to polyurethane which has a dielectric strength of 60 kV/mm which means that the maximum voltage will be 24000 V.

There's another layer below the base dielectric which is made of copper (not shown in the figure), this layer is insulated from the electrodes so it will not cause any problems and it can be etched away. Usually there is a cover (insulator) above the dielectric filler, however this is not needed in this experiment as the pad will be attached to a nonconductive material.

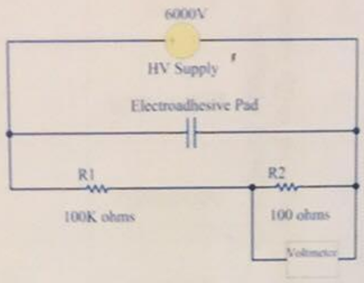


Figure 3 Circuit Diagram

Figure 3 shows the circuit where the Electroadhesive pad is modelled as a capacitor. A voltage divider circuit is used to measure the voltage using normal Voltmeters.

Use separate sheet if required

C. Experimental Procedure:

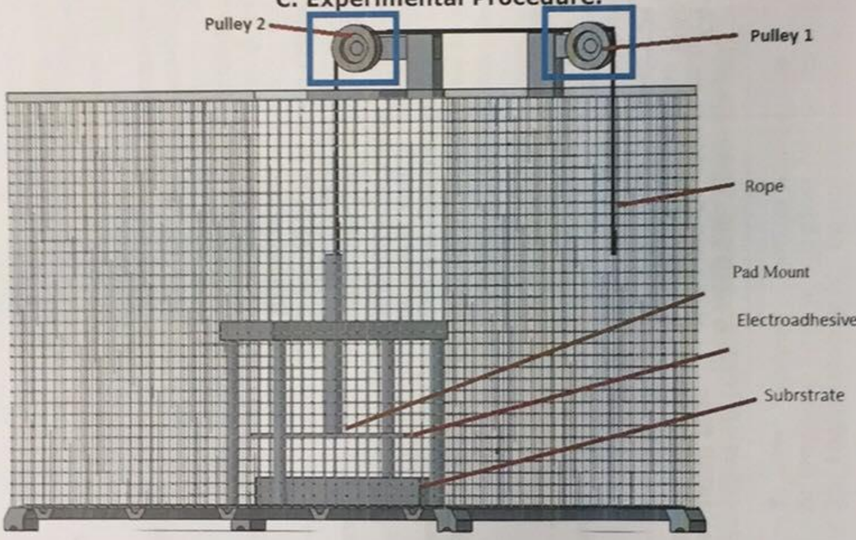


Figure 4 Test Bench

The Elecroadhesive pad will be attached to the pad mount, which will be nonconductive and rigid to keep the pad flat. Non-conductive rope will be attached to the pad mount as shown in figure 4. Two non-conductive pulleys will force the rope to move upward or downward. When the rope is pulled downward the Elecroadhesive pad will move upward, and when the rope is released the pad will move downward until it touches the substrate.

The experiment will start with the pad touching the substrate, then the cage will be closed and the voltage will be applied. The experimenter will then pull the rope downward from outside the cage which will raise the pad upward to check if the substrate stuck to the pad or not. The substrate will be a sheet of paper to prove that there's a force generated. If the experiment is successful the substrate will be wood with attached weights. Other substrates might be tested, all of them are nonconductive if a conductive substrate is to be tested the cover (insulator) layer in the pad will be added first.

Continue on additional sheet if required

Safety Documents (Project Risk Assessment) Ref: EEE PED EER 038

MANCHESTER 1824 The University of Manchester

RISK ASSESSMENT
(must address all hazards identified in hazard checklist)

Title Of Experiment / Test:-		Electroadhesion Testing				Date:-	13/12/17
Prepared By:- Nour Elghazawy	Nour Elghazawy	Validated By:- Richard Gardner		Checked By:- Viddy Peesapati		Review:-....12/12/18	

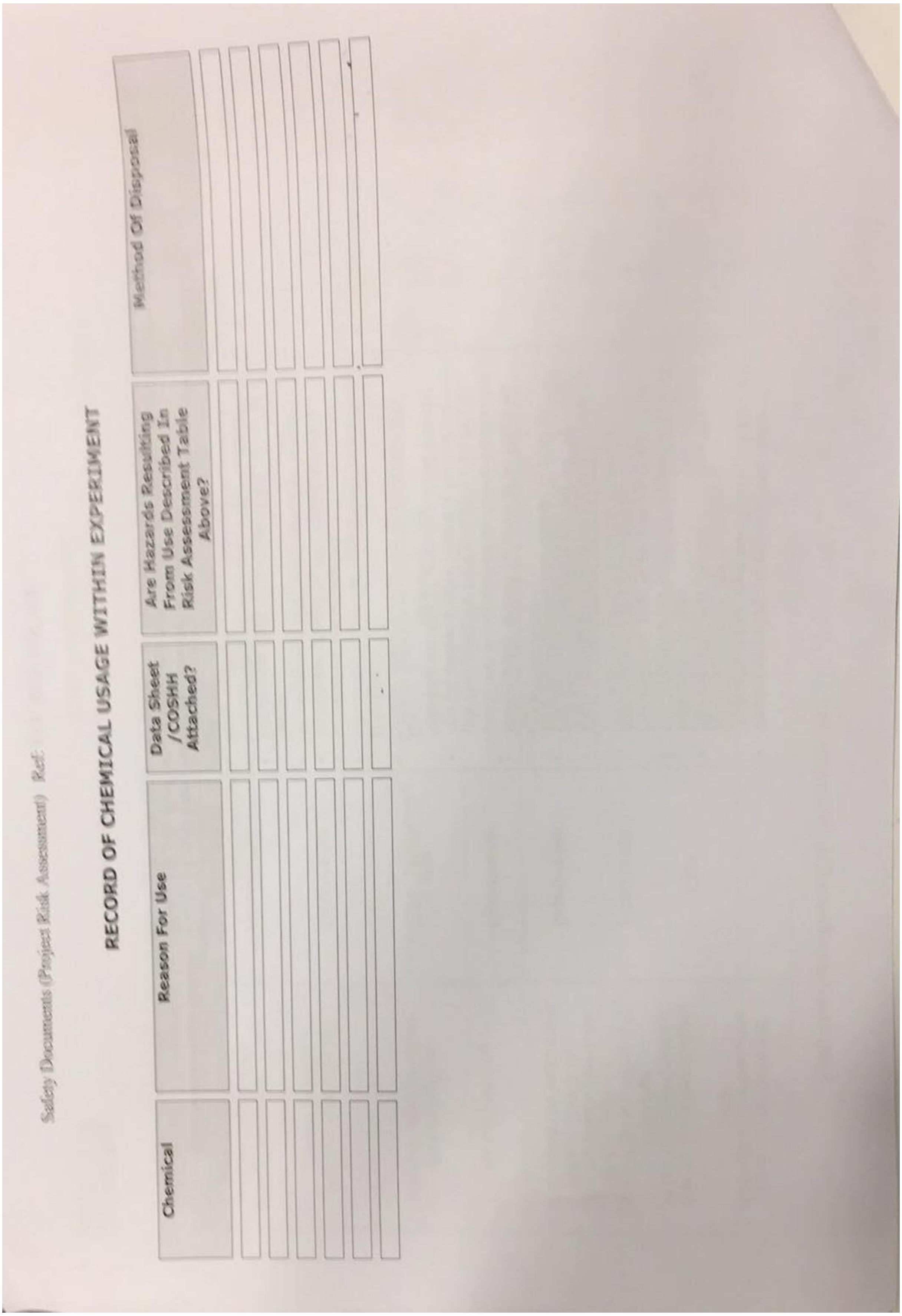
Hazard (s) & Possible Consequences	Persons or Equipment at Risk	Control measures applied to eliminate / minimise risk	Residual risk with control measures applied: Severity	Likelihood	Risk rating	Risk Acceptable?
Electric Shock from High Voltage (1kV & Over) While doing the experiment	Experimenter	• Cage will be used to avoid Electric Shock to the Experimenter • The Interlock control on the front of the cage guarantees that the HV supplies inside of the cage are off while the cage is open • Red warning light is lit when supply is energised and hazard notices are well displayed. • Power supply to HV equipment is controlled by safety key issued daily by staff which is kept by the operator at all time during experimentation.	5	1	5	Yes

Breaking the Dielectric Strength of the Dielectric Filler Electric breakdown which might cause electrostatic discharge	Cage	• Maximum voltage is equal to the Dielectric Strength of the Dielectric filler multiplied by the gap between the electrodes. • The experimenter shouldn't exceed this maximum voltage. • The Experimenter shouldn't exceed 1200V if the dielectric filler is air and 24,000V if the dielectric filler is polyurethane.	2	2	4	Yes
Electric Shock from High Voltage (1kV & Over) After doing the experiment	Experimenter	• Earth stick to be placed on HV supply and the pad when the system is turned off. To make sure that if there's any charge it goes to earth.	3	1	3	Yes
Manual Handling	Experimenter	• Safety shoes should be worn at all times to avoid feet injury caused by falling equipment (weights used via pulley to generate force).				
Fire	Anyone in lab	• The DC power supply provides limited current, reducing the risk of electrical arced induced fire. • Smoke alarm in cage will trip power if it is triggered.	5	1	5	Yes
Electric shock from low voltage (<1 kV)	Experimenter	• All cabling outside of cage should be correctly terminated and shrouded. • Equipment should be PAT tested annually. • All equipment and plugs should be suitably fused.	3	1	3	Yes
Tripping Hazards	Anyone in lab	• Ensure any trailing leads are tidied away or covered with appropriate rubber matting • Keep work area clean and tidy.	2	1	2	Yes

Risk Assessment Matrix Likelihood (1-5) x Severity (1-5) = Risk (See attached matrix for guidance)	**1 – 5: Low**: Tolerable – monitor and manage **6 – 8: Medium:** Review, introduce further controls to reduce to as low as reasonably possible **9 – 25: High:** Intolerable. Do not commence work, further control measures required

Breaking the Dielectric Strength of the Dielectric Filler Electric breakdown which might cause electrostatic discharge	Cage	• Maximum voltage is equal to the Dielectric Strength of the Dielectric filler multiplied by the gap between the electrodes. • The experimenter shouldn't exceed this maximum voltage. • The Experimenter shouldn't exceed 1200V if the dielectric filler is air and 24,000V if the dielectric filler is polyurethane.	2	2	4	Yes
Electric Shock from High Voltage (1kV & Over) After doing the experiment	Experimenter	• Earth stick to be placed on HV supply and the pad when the system is turned off. To make sure that if there's any charge it goes to earth.	3	1	3	Yes
Manual Handling	Experimenter	• Safety shoes should be worn at all times to avoid feet injury caused by falling equipment (weights used via pulley to generate force).				
Fire	Anyone in lab	• The DC power supply provides limited current, reducing the risk of electrical arced induced fire. • Smoke alarm in cage will trip power if it is triggered.	5	1	5	Yes
Electric shock from low voltage (<1 kV)	Experimenter	• All cabling outside of cage should be correctly terminated and shrouded. • Equipment should be PAT tested annually. • All equipment and plugs should be suitably fused.	3	1	3	Yes
Tripping Hazards	Anyone in lab	• Ensure any trailing leads are tidied away or covered with appropriate rubber matting • Keep work area clean and tidy.	2	1	2	Yes

Risk Assessment Matrix	**1 – 5: Low**: Tolerable – monitor and manage
Likelihood (1-5) x Severity (1-5) = Risk	**6 – 8: Medium:** Review, introduce further controls to reduce to as low as reasonably possible
(See attached matrix for guidance)	**9 – 25: High:** Intolerable. Do not commence work, further control measures required



Safety Documents (Project Risk Assessment) Ref:

RECORD OF CHEMICAL USAGE WITHIN EXPERIMENT

Chemical	Reason For Use	Data Sheet /COSHH Attached?	Are Hazards Resulting From Use Described In Risk Assessment Table Above?	Method Of Disposal

HAZARD CHECKLIST

You should indicate the hazards present in the experiment in the table below. If a hazard is present, control measures should be stated on the risk assessment. Note that this list is not exhaustive.

Hazard Type	Present	Not Present
Electric Shock From High Voltage (1kV & Over)	Yes	
Electric Shock From Low Voltage (Under 1kV)	Yes	
Tripping Hazards	Yes	
Slipping Hazards	No	
Fire	Yes	
High Temperatures	No	
Low Temperatures	No	
High Pressure	No	
Low Pressure	No	
Chemical Spillage	No	
Chemical Contact (Ingestion / Eye & Skin Contact)	No	
High Noise Levels	No	
Working At Height	No	
Head Height Hazards	No	
Production Of Dust & Fumes	No	
Manual Handling	Yes	
Production/Use Of Radiation	No	
Use Of Asphyxiating Gases	No	
Breaking the Dielectric Strength of the Dielectric Filler	Yes	

RISK ASSESSMENT SEVERITY MATRIX

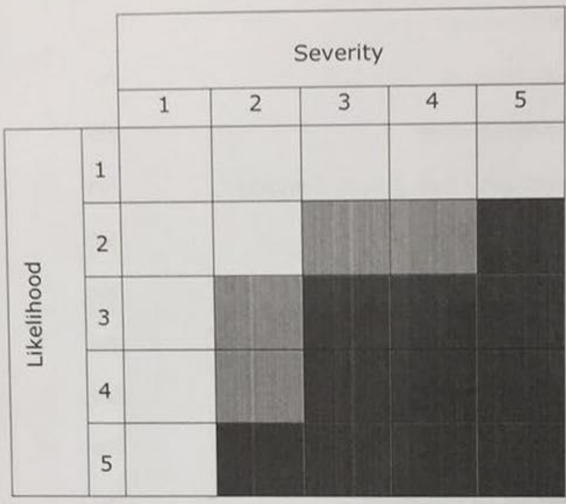
SEVERITY VALUE = Potential consequence of an incident/injury given current level of controls.

5 Very High:- Death / Permanent incapacity / Widespread loss
4 High:- Major Injury (Reportable Category) / Severe Incapacity / Serious Loss
3 Moderate - Injury / Illness of 3 days or more absence (reportable category) / Moderate loss
2 Slight: - Minor injury / Illness – Immediate 1st Aid only / slight loss
1 Negligible No injury or trivial injury / illness / loss

LIKELIHOOD = what is the potential of an incident or injury occurring given the current level of controls.

5 Almost certain to occur
4 Likely to occur
3 Quite possible to occur
2 Not likely to occur
1 Almost certain not to occur

The multiple of Likelihood with Severity is the risk classification value.



Risk Classification Value

1–5: Low: Tolerable – monitor and manage

6–8: Medium: Review, introduce further controls to reduce to as low as reasonably possible

9–25: High: Intolerable. Do not commence work, further control measures required

References

[1] J. Guo, "Geometric Optimisation of Electroadhesive Actuators Based on 3D Electrostatic Simulation and its Experimental Verification", IFAC-PapersOnLine, vol. 49, no. 21, pp.
[2] "Definitions of breakdown voltage and dielectric strength," in *Journal of the A.I.E.E.*, vol. 48, no. 6, pp. 484-484, June 1929.
doi: 10.1109/JAIEE.1929.6537721
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6537721&isnumber=6537688