Electro-adhesive gripper component selection for pick and place of commonly used materials

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SHEFFIELD HALLAM UNIVERSITY

ELECTRO-ADHESIVE GRIPPER COMPONENT SELECTION FOR PICK AND PLACE OF COMMONLY USED MATERIALS

A thesis submitted in partial fulfilment of the requirements of

Sheffield Hallam University for the degree of Doctor of Philosophy

Jatinder Singh

December 2019

Supervisor: Prof Jacques Penders

Co-supervisor: Prof Paul Bingham

I. Candidate Declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.

2. None of the material contained in the thesis has been used in any other submission for an academic award.

3. I am aware of and understand the University's policy on plagiarism and certify that this thesis is my own work. The use of all published or other sources of material consulted have been properly and fully acknowledged.

4. The work undertaken towards the thesis has been conducted in accordance with the SHU Principles of Integrity in Research and the SHU Research Ethics Policy.

5. The word count of the thesis is 31000.

Name	*Jatinder Singh*
Date	*December 2019*
Award	*Doctor of Philosophy*
Faculty	*Materials and Engineering Research Institute*
Director(s) of Studies	*Prof Jacques Penders*

II. Abstract

Automation of handling commonly used materials such as Nitrile gloves, Polypropylene sheet, Polycarbonate sheet, HDPE and Glass poses certain key challenges such as uniform grip of the material, ply separation, smooth operation with no contamination of material, release in correct orientation, tuneable to various loads, efficient speed and accuracy and attaining repeatable and reliable results. This research focuses on electro-adhesive gripping technology as a solution for material handling in an industrial automation setup. Since electro-adhesion is a micro level phenomenon that works on the principles of a parallel plate capacitor, the key components that influence the performance of this gripper are the Electrode structure, Dielectric material, Base material and Power supply. Through literature review, substantiated by experimentation of various configurations/materials that make up individual components of the gripper, following solution was identified to provide repeatable and reliable results with 68.75% efficiency: (a) Interdigitated Electrodes, (b) Liquid dielectrics: Barium titanate mixture (ratio 2:1) deposited evenly on the electrodes, (c) Nylon used as base material, (d) DC power supply for the pick-up cycle, (e) Switch-off of the power supply in release cycle.

For efficiency calculation, an equation was derived where efficiency of achieving repeatable and reliable results is expressed as a percentage of number of experiments with desired outcome vs the total number of experiments conducted. Here desired outcome is further defined as directly proportional to the successful pick up and release of object and inversely proportional to the time taken in each case. Such a universal equation can be used for analysis of experiments on any similar application of automated handling of objects.

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I would like to extend thanks to the many people, who so generously contributed to the work presented in this thesis.

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I am very grateful for the PhD studentship funded by the Innovative UK and AA Robotics to help explore the topic of electro-adhesion from October 2012 onwards. The studentship was managed within the funded Elastomer gripping project and key aspects and focus was also given to the PhD by the funding body for me to secure a successful PhD whilst working on the project.

During this PhD journey, I would like to specially thank my wife Samiksha Singh for her continuous support and priceless comments on the key aspects to keep me going when the times were tough for me to complete the thesis. Her support has been one of the key factors in completion of this PhD.

Last but not the least, I would like to dedicate this thesis to my parents, Mrs. Rajinder Kaur, Mr. Trilochan Singh, Mrs Nisha Gupta, Mr Rajiv Gupta and my daughter, Anisha Singh who have been supporting me throughout this incredible journey, and without whom this thesis would not have been possible.

III. Contents

IV. List of Figures and Tables

V. List of Equations

VI. Research Publications and Patents

Following list of publications were made:

1. GUO, Jianglong, BAMBER, Thomas, SINGH, Jatinder, MANBY, David, BINGHAM, Paul, JUSTHAM, Laura, PETZING, Jon, PENDERS, Jacques and JACKSON, Michael (2017). Experimental study of a flexible and environmentally stable electroadhesive device. Applied Physics Letters, 111 (25), p. 251603.

2. BAMBER, T, GUO, J, SINGH, J, BIGHARAZ, Masoud, PETZING, J, BINGHAM, Paul, JUSTHAM, L, PENDERS, Jacques and JACKSON, M (2017). Visualization methods for understanding the dynamic electroadhesion phenomenon. Journal of Physics D: Applied Physics, 50, p. 205304.

3. SINGH, Jatinder, BINGHAM, Paul, PENDERS, Jacques and MANBY, David (2016). Effects of residual charge on the performance of electro-adhesive grippers. In: ALBOUL, Lyuba, DAMIAN, Dana and AITKENS, Jonathan M., (eds.) Towards autonomous robotic systems, 17th Annual Conference, TAROS 2016, Sheffield, UK, June 26--July 1, 2016, Proceedings. Lecture Notes in Computer Science. Lecture Notes in Artificial Intelligence (9716). Springer International Publishing, 327-338.

List of Patents:

1. P. L. Watt, D. G. Manby, J. Penders, J. Singh, P. A. Bingham, Discriminating Between Materials, EU Patent Application No. 15196484.8 - 1706 (2016).

2. Electroadhesive gripper, UK Patent No. 1608729.8 (inventor, filed on 18th May 2016).

1. INTRODUCTION TO RESEARCH

1.1 Introduction

Industrial automation aims at a fully automated production cycle, where minimal or no human intervention is required. This is gaining widespread interest specifically in the packaging industry, where emphasis is shifting to automatic pick and place of objects and finally packaging and arranging them. Traditionally, in most industrial applications, robots act as an assistive workforce rather than the complete replacement of human labour. Present day robotics is widening the area of applications and thereby aiming to remove this traditional approach of deploying humans and therefore the range of tasks performed by the robotic setups, in order to achieve a wide spectrum of specialist tasks, is a popular area of research.

One such specific area of interest is the handling of commonly used materials or non-rigid materials which are difficult to pick. Handling elastomers and introducing automation into industries that manufacture and package flexible/ difficult to handle materials has always been a challenge due to the nature of the materials used and the constraints involved in handling them. Industries involved in manufacturing of flexible materials use human labour for packaging and exporting of materials through different stages of the manufacturing process, but this technique is error and risk prone, thereby proving to be inefficient in most cases.

Robots reduce operational costs as well as offer accuracy and speed which are significantly higher when compared to human labour. Using different types of end-effectors, robots are able to handle objects ranging from small, complex shapes to objects larger in size, with great accuracy and control.

This research revolves around exploring an efficient gripper solution which can be used for picking up and releasing of commonly used materials that are difficult to handle, in a time efficient manner. The commonly used materials are difficult to handle due to their flexible nature or due to the delicate nature of operation. Further details on key challenges is discussed in section 2.2

The current research focus is mainly on polymeric materials (and Glass), which have been selected based on their wide use and therefore benefits of automating stages of the production and packaging industry. For example, Polypropylene is a widely used plastic material in packaging, labelling, plastic parts etc. It holds a distinct property of resisting many chemical solvents, bases and acids (Kenneth S. Whiteley, 2005)

Polycarbonate is widely used in making high stability capacitors (Serini, 2000) and also it has many other applications where its light weight replaces glass to be used in cases like safety glasses where it offers better protection from UV protection so a potential product for mass production. It is mass produced in the form of covers where it is extensively used in phones covers for Samsung phones.

HDPE (High Density Polyethylene) is the most common product used for packaging such as plastic bags, plastic films, containers including bottles etc. Polyethylene has various classifications where the manufacturing process allows its density to be varied making it suitable for the application where used.

Another polymer widely used in latex free laboratory and medicinal gloves is Nitrile. This is an organic compound with repeating carbon nitrogen structures and one of the most common occurrences of Nitrile is in Nitrile rubber that has high resistance to chemicals and therefore used to make protective gloves, hoses and seals.

Glass (although not flexible material) is a non-crystalline solid material which is widely used and has a variety of applications. It is a potential candidate for selective pick due to being extensively used in glass bottles, glass fibre, glass ceramics etc. The properties of glass can vary extensively depending upon how it is made/used. Glass bottles are extensively recycled and therefore hold a key material to be separated in selective separation method presented in this research work. Recycling glass is a very important factor and every metric ton of waste glass recycled into new items saves 315 kg of carbon dioxide from being released into atmosphere during creation of new glass (Services, 2017).

The research presented in this report explores the best suitable technique for handling commonly used materials as well as understanding the factors that affect the performance of the gripping solution in providing repeatable and reliable results that required to achieve optimal performance in an industrial setup.

1.2 Research Context

Current development denotes that companies are using different types of advance methods for pick up or release purpose but there is a lot of room for improvement and more advanced and time efficient ways can be found out, to produce accurate results that are repeatable and reliable in an industrial setup, as is seen in the report below.

Therefore, this research refers to the automation of handling flexible material such as medicinal gloves and other polymeric materials, in an industrial environment with repeatable and reliable results. In the present industrial scenario, packaging of such material is done manually, which is inefficient and error prone due to human involvement. The context of this research is to find an optimal gripping solution that can be used in these areas where automation of such packaging activities can replace/ reduce human involvement, thereby providing better results.

Requirement of the Gripping solution

The important criteria to consider in such an application are as follows:

1. Creating an effective grip that provides a uniform method of transportation of the flexible material from point A to B and carefully places the material in correct orientation and position.
2. The gripper should be able to pick up a single material at a time without disturbing the rest of the pile (ply separation).
3. No contamination of the material should take place in the transportation process and the material must not get damaged in the process.
4. The process must be Repeatable and Reliable (R2). This requires that the gripper performs with the same efficiency every time.
5. The process must be more efficient and faster (reduce response times) than the existing human centric system that is error prone.
6. Safety considerations and operability must be considered.

There are various techniques present in the market (refer section 2.1) that can be used for providing a gripping solution but as seen later, each has its own pros and cons. In this research, the focus is on using electro-adhesion as a technique for creating a novel gripping solution that can be used in pick and place application of flexible material. This solution can be further extended to other applications such as waste management, where gripper can be tailored for selective pick up of certain objects from a pile of rubbish.

1.3 Research Motivation

This work was done in conjunction with a research project at AA Robotics related to the handling of flexible materials. The motivation is to create a novel gripping solution that can be used to automate the handling of flexible material such as medicinal gloves with repeatable and reliable results, so that such a gripper may be future deployable in the industry to replace/ reduce human labour. The future extension of such a gripper for other applications such as waste management of various types of materials was also within discussion with AA Robotics.

As seen in the research context above, flexible materials such as gloves, pose a unique challenge in the packaging industry. This calls for a need to design a gripping solution that can address these challenges and provide a repeatable and reliable outcome. There are already many grippers present in the market but there is still a need for an optimal solution for specific handling of flexible materials as most of the work done in the packaging industry is dependent on human labour, which makes the operation error prone and inefficient (Efficiency is dependent on the speed at which the person deployed at the station can handle the material which may vary from person to person, thereby not providing repeatable and reliable results). As will be seen in the chapters that follow (section 2.3), there are some grippers present in the market, such as vacuum suction cups, ingressive grippers such as micro-spines and so on but these are not suitable for the current application of pick and place of flexible material and therefore the research motivation for designing an optimal solution that is repeatable and reliable (R2), has driven this research. The motivation driving this research is to design a better technique for gripping flexible materials which is non-intrusive, it does not damage the material, it is configurable to pick different loads, capable of ply separation (pick one object out of a pile) and can provide repeatable and reliable results (under optimised design).

In the current context, the key here is picking up an object as well as placing it back in the desired orientation, therefore release of the object is as

important as picking up the object. This requires detailed research in establishing the key parameters that define the success of a gripping technique as a **pick and place** gripper, where the object is reliably and repeatably placed from point A to B (and similar applications of pick and place in the industry), thereby emphasizing on the release of the object from the gripper. Therefore, research focus must also include analysis of reducing the release time, so that the pick and place cycle can be overall improved.

In general, it is the motivation of this research to find parameters that affect the performance of a gripping solution when used in the handling of flexible material.

It is also an endeavour to further this technique to other applications such as waste management, where a similar phenomenon is needed for selective pick up of certain non-ferrous materials from a pile of rubbish and transport them to a different sorting location and release them in a pile.

Thus, in the light of these findings, this PhD research endeavours to find components that can make a novel gripping solution for handling flexible material that can be deployed in the automation of pick and place of such objects. Also, it is important to analyse the key parameters that play an important role in influencing the performance of such an identified gripper, followed by experiments to evaluate the performance of different configurations and finally make some recommendations that can be used for using the gripper for flexible material in a pick and place application. Further studies also include a case study on waste management using the identified technique.

1.4 Research Questions and methodology

The aim of this research, as stated above, is to find the optimal gripping solution that can be used to automate the handling of flexible materials (for e.g. medicinal gloves) in an industrial application (for e.g. packaging industry) that can provide repeatable and reliable results, thereby making the cycle of operation more efficient and human error free. Therefore, the main aim can be stated as follows:

Identify components for the design of a novel gripping solution for automating the pick and release of flexible material with repeatable and reliable (R2) results.

To address this aim, it is important to first understand the key challenge/ requirements in handling of flexible material and identify various types of gripping solutions present in the current market that are being currently deployed for handling materials. It is also important to determine what are the key factors or parameters that affect the repeatability and reliability of the gripping solution, so that efficient results can be achieved in each cycle of operation. As was discussed in the research motivation, the overall pick up and release cycle of the gripping solution must be efficient, therefore this research must delve into the factors affecting the release time of the gripping solution as well.

Therefore, the research questions can be derived from these motivations and can be summarised as follows:

Research Question RQ1: Which technique is most suitable for handling of commonly used material and what are the key components that constitute the chosen technique when deployed in a pick and place application of commonly used material?

Research Question RQ2: What are the key parameters that influence the pickup and release time of the chosen technique when deployed in a material handling application?

And finally,

Research Question RQ3: What are the components that make the novel gripping solution that can be deployed in a pick and place application of commonly used materials?

To answer the above research questions, following methodology was adopted:

1. Identify the key challenges and requirements of handling materials. Here, the main focus is on medicinal gloves, but for a comparative study, other materials (polymeric materials that usually need to be handled in the industry) can also be listed. A study on the gripping solutions available in the present market to handle the identified materials and create a comparative study about the suitability of these grippers to address the above research criteria.

2. Literature review on the technology that is most appropriate to handle material and a list of components and factors affecting the performance of the chosen technology to address RQ1.

3. From the above study, research the theory of electro-adhesion and create a list of parameters that will be further analysed to reduce the pickup and release time of the gripper, thereby reducing the overall cycle of operation and providing repeatable and reliable results. Based on this, create various configurations of the gripper to address RQ2.

4. Perform experiments to compare the performance of various configurations of the gripper when used on different commonly used materials to address RQ2/ RQ3.

5. Analyse results and present an optimal solution of the chosen gripper when used in a pick and place application of material handling to address RQ3.

1.5 Thesis structure

This report is a synopsis of a detailed research that was carried out for the study of components that make up a most suitable gripping solution that can be used for handling commonly used material. For this study, research questions were generated to address the above. The thesis is structured in a way to address the research questions and methodology.

In chapter 2, a detailed literature review is presented on the theory behind the grippers present in the current market and why electro-adhesion, which is the main phenomenon in an astrictive gripper is chosen as the best method for handling flexible material. This is an important study to narrow down the technique that is then further evaluated.

In chapter 3, further to the chosen technique, electro-adhesion process is further understood, in terms of electrostatic processes and parameters that influence it. Further to this, chapter 4 establishes the components that make an electro-adhesive gripper. These are important in studying the parameters that make an appropriate gripping solution for pick and place application of flexible/ commonly used materials and form an important basis for experimentation done in chapter 5.

In chapter 6, detailed experiments are performed and results presented to prove the claims made in the theory sections, chapters 3 and 4. The results of experiments are analysed based on the efficiency equation to check for repeatability and reliability when used in an industrial application. This concludes the research question RQ3.

Chapter 7 finally concludes the thesis with conclusive results and recommendations on further work that can be conducted in this area of research.

2. A COMPARATIVE STUDY OF GRIPPING SOLUTIONS

2.1. Introduction

The following chapter presents a comparative study of gripping solutions, to understand what techniques are currently present in the market and what are their properties. This will help in establishing which is the most suited technique for the current application of handling commonly used material.

The chapter starts with a brief introduction about the commonly used materials which will be used as an object for a comparative study. These are materials that often need to be handled in the industry and there is benefit of efficiency and time in automating their production lifecycles, such as a pick and place operation. This identification of objects helps in understanding the research criteria and helps in narrowing down the type of gripping solution needed in this research. Along with the types of objects, there are some typical requirements also mentioned, that need to be kept in mind while choosing the gripping technique for handling commonly used material. The chapter further presents a comparative study between the various end effectors present in the market, their suitability in various applications and suitability for the listed requirements of pick and place of commonly used material.

This chapter therefore lists Impactive, Contigutive, Ingressive and Astrictive as the main types of grippers and evaluates the pros and cons of using each of these techniques for handling flexible material. It then presents conclusion to suggest the Astrictive method as the most suitable technique and identifies electro-adhesion (as a type of Astricitve gripper) as the most favourable technology for handling flexible material. ***Thus, RQ1is addressed in this chapter: Which technique is most suitable for handling of commonly used material?***

2.2. Key challenges of handling commonly used material

It is important to first understand the challenges in handling commonly used materials. There are many consumer products which need to be handled with care in the production and packaging environment such as medicinal gloves, mobile protection covers, glass or carry bags. The materials of particular interest to this research are Nitrile gloves, Polypropylene sheet, Polycarbonate sheet, HDPE and glass.

Commonly used materials such as these have specific properties that make it difficult to automate their handling stages in the production and packaging industry due to either being flexible (as in the case of sheets or gloves) or due to delicate nature of operation (such as glass). Taking the example of nitrile gloves, the following observations and challenges were noticed.

Gloves

The key stages in glove production and packaging are mentioned in Appendix A.1, which can be used for a further read and to establish an industrial context to the current research.

Stages beyond the stripping step (9) are done either manually or semi-automatically. The problem with this system is that it is error prone since it involves human labour. The human error and benefits of automation has been discussed by various automation companies (Automation, 2020) (Robotics, 2020) highlighting the benefits of automation. Also, manual systems introduce latency in the production line. The output is also variable, since it is dependent on the person performing the operation and the speed of operation can be different from person to person. Therefore, this is the area that most benefits from automation. However, introducing automation in the production cycle poses many challenges such as:

Ply separation: The gloves are all placed in a pile, one on top of the other. It is difficult to devise a method to pick up a single glove at a time, from the pile of flatly laid gloves and place it in a uniformly spaced manner on to a conveyor belt. Therefore, there is a ***requirement for uniform pick and place of a single object from a pile***.

Contamination or glove deformation: Gloves are majorly used in industries such as the food industry and the medical sector, where contaminated gloves cannot be used. Therefore, the production cycle must not use gripping solutions that may either contaminate the glove or deform it in any form. The entire production line must be clean in operation and be able to transport the glove without undamaging it. Therefore, there is a ***requirement of using a technique that is contamination proof and does not cause any deformation to the object.***

Positioning of the gloves on the belt: It is important to maintain certain orientation of the glove as it is picked up and placed on the conveyor belt. Repositioning can be a challenge since the glove can catch some air during transportation and therefore lose its orientation when released in its final position. Here, it is important to note that there are general requirements on the orientation of the glove on the conveyor belt. Therefore, there is a ***requirement of releasing the object in a specific orientation.***

Weight of the glove: There can be variations in the size of the gloves, which changes their weight and shape. The gripping solution must be able to pick up any load irrespective of the change of weight. Therefore, there is a ***requirement to make the gripping solution tuneable to various loads***.

Speed: Due to the high operating speed the robot and gripper may disturb the pile while attempting to pick up one glove. Also, the speed at which the gripper efficiently picks and places the gloves must be higher than human labour in order to provide fruitful results of automation. Therefore, there is a ***requirement to design a gripping solution that is time efficient.***

Repeatable and reliable (R2) results: The gripper design must provide ***repeatable and reliable results*** as the production and packaging lines are run continuously every day.

2.3. Grippers or End effectors used for handling objects

The end effector of an Industrial robotic system, also known as gripper or a gripping solution, is the end-point of the robotic arm that acts as an active link between the object to be picked up and the robot. As stated in (Association, 2013) one of the most important aspect in a gripper is its design. A badly designed gripper can lead to problems in the application where it is being used. Thus, the function of a gripper is dependent on the application where it is being deployed, which includes (Monkman et all, 2007):

- Temporary maintenance of a definite position and orientation of the object relative to the gripper and the handling equipment.
- Retaining of static (weight), dynamic (motion, acceleration or deceleration) or process specific forces and moments.
- Determination and change of position and orientation of the object relative to the handling equipment by means of wrist axes
- Specific technical operations performed with, or in conjunction with, the gripper.

In automation, the use of gripping solutions is prominent. These are used not only in robotics but also in various other industries which require grippers for efficient handling. A few areas, as stated by Monkman et all (2007), where gripping solutions are used are as follows:

- Industrial robots (handling and manipulation of objects)
- Hard automation (assembling, micro assembling, machining and packaging)

- NC machines (tool change) and special purpose machines.
- Hand-guided manipulators (remote prehension, medical, aerospace, nautical)
- Work piece turret devices in manufacturing technology.
- Rope and chain lifting tools (load-carrying equipment)
- Service robots (prehension tools potentially similar to prosthetic hands)

The packaging and manufacturing industry also have an increasing demand for deployable end- effectors that can provide repeatable and reliable results. This has further motivated to produce grippers which are intelligent and can be integrated with sensors and feedback systems to make them work in a complex environment, thereby making the design of the gripper more complicated.

In terms of application area and technology used, grippers can be divided into the following sub types (Monkman et all, 1995):

Gripping Method	Gripping Effect on Material	
	Non – Permeating	Permeating
Impactive	Jaws: Clamps, Chucks	Pinch: Clu-picker, Walton devices
Ingressive	Brush: Wire, hook and Loop	Pins: Pick lift, Polytex, Hackels
Contigutive	Chemical adhesion	Thermal adhesion
Astrictive	Magnetic, Electroadhesion	Vacuum Suction

Table 2-1 Description of Gripping Types (Monkman G. et all, 1995)

Impactive Grippers

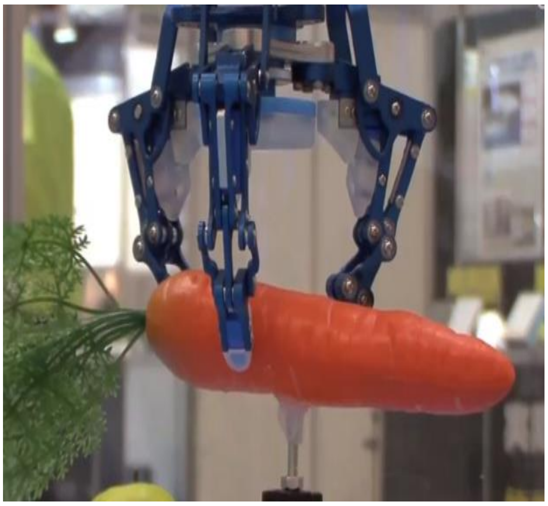


Figure 2-2 Impactive Gripper (DigInfo, 2012)

Impactive grippers have usually a two fingered or three fingered structure (Jaws or Clamps) aimed at gripping a rigid material either by clamping from around or from inside the material, as in the case of a hollow structure like pipes or tubes. Impactive grippers, with the use of touch sensors, can be used to manipulate the force they apply on the object and therefore are able to grip an object which is non-rigid. A direct impact is applied on the object if this gripper is used, hence the name. Impactive grippers also have pinch mechanisms although they do not penetrate the material completely however, they tend to disturb the stack of similar material, making it difficult to pick up one object at a time. It can also be difficult to achieve precision in releasing the object in certain orientation. Considering the example of pick and place of nitrile glove, since impactive gripper uses grabbing method to pick up the glove, correct orientation of the glove will be lost when placing it back on the pile, therefore limiting its use.

In a further development in Impactive grippers, a D-Hand gripper was made by Double Research. D-Hand mimics the structure of human hand and is intelligent enough to apply uniform pressure on the object. It is capable of picking up complex, irregular objects. More research has been conducted by Double Research and Development group to make the D-Hand intelligent enough to handle randomly stacked objects without disturbing the orientation (DigInfo, 2012). This was an improvement on the basic design of impactive grippers and addressed the issue of uniform release to maintain orientation. However, the problem of ply separation in case of flexible materials and unable to adapt to varying loads still remains.

Ingressive Grippers

Figure 2-3: Ingressive gripper (Aaron Pamess, 2012)

Ingressive grippers, as the name suggest, penetrate through the object in order to form a grip. This is not suitable for polymeric material (flexible material in the context of this research) as the object is prone to damage and may result in formation of void in some materials like carbon fibre (Monkman G. et all, 1995). Also, it is not suitable for glass as it is not penetrable. Mostly pins, needles or hackles are used to form the grip. This gripper is used mostly in textile, carbon and glass fibre handling. (Monkman, et all, 2007). One such example of this type of gripper is Gravity- Independent gripper made by NASA(Aaron Pamess, 2012) who demonstrated gravity independent mobility and drilling on natural rock using micro-spines. Micro-spines are used for firm grip of rocks and are capable of working in any gravitational field. Basically, made for space experi-mentation the robot is demonstrated to pick up rock weighing 13Kg and has ideal end effector for space experimentation. However, in the case of flexible material handling, it is unsuitable as it can deform the flexible material.

Contigutive Grippers

Figure 2-4 Contigutive gripper (Aaron Pamess, 2012)

Contigutive grippers contain adhesive substances on their end effectors, such as glue or various other chemical adhesives. These grippers directly contact the object on the surface and use adhesion to pick up the object. Although this is a good idea for the pickup of objects, the release of the object is not easy, thereby making them inefficient for the pickup and release cycle. Also, they tend to leave some residue on the object, thereby causing contamination therefore not suitable for nitrile gloves that are used in medicinal applications or the food industry.

If these grippers are used in the clothing industry, then Permatack adhesive grippers which were previously designed for use with textiles (G.J. Monkman S. , 1991) (Strauss, 2012) give efficient results in this section of the grippers. The adhesive used in this case are either water or solvent washable, allowing contamination to be removed but with an additional step. Although over time, small residue such as tiny fibres can collect on the surface of the gripper, which eventually blocks the forces of attraction thereby making the gripper inefficient over time. Therefore, these do not provide repeatable and reliable results in the current context.

Astrictive Grippers

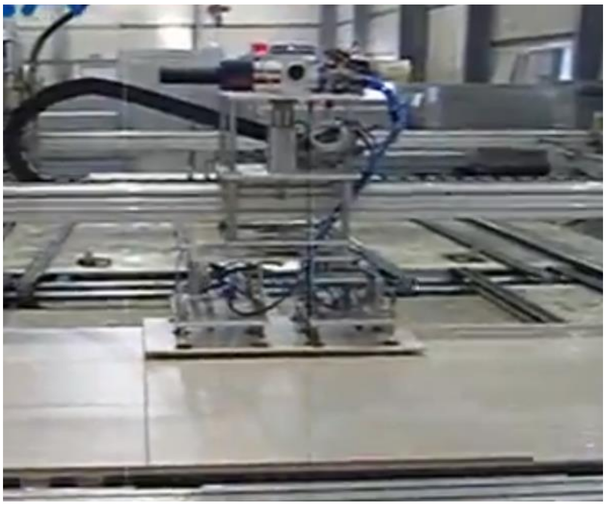


Figure 2-5 Astrictive gripper (Aaron Pamess, 2012)

Astrictive, as the name suggests, refers to grippers that use some sort of binding force or suction forces applied to object surface. This could be vacuum or suction forces, electro-adhesion and magnetic attraction.

Astrictive grippers have been of key interest to researchers in wall climbing robots where there is an extensive force required to clamp and unclamp on the object. They give the flexibility to climb vertically which can be used for rescue or military purposes. Common types include suction cups and magnetic adhesion. Suction cups have originally been used to climb on certain objects (Strauss, 2012) (Ambitex, 2013) and magnetic wheels version used to climb on ferromagnetic walls, both with severe limitations on the type of wall the gripper can climb. More recently dry adhesive technology which mimic gecko feet with tiny setae have been explored (K. Autum, 2006). Dry adhesive technology works using Vander Waals forces of attachment and offers good clamping forces with no residue left behind on the object wall. However, they suffer from disadvantage of “being on” all the time which reduces their effectiveness with due course (K. Autum, 2006).

In a further development, researchers have introduced a technique which uses electro adhesion in wall climbing robots (HarshaPrahlad, 2008). Electo-adhesion is the term used for adhesive force generation caused due to attraction of opposite charges between two objects. In this case, using polarisation technique, electrostatic field effect is used to induce opposite charge on the object to picked up and thus the attractive forces are generated between the object and the gripping solution. The technique can be used on either conductive or non-conductive objects. This type of gripper is of specific interest to the current research project as it is non-intrusive and does not modify the properties of the object to be picked up. It works at electrical level; therefore, the physical properties are not modified. Also, it does not cause any contamination to the object. It is light weight and can be used to carry a range of loads.

2.4. Comparison of Various End Effector Handling Techniques

Since this research is based on developing a novel gripping solution that can be used for efficient pick and place of materials such as medicinal gloves, glass, polymeric sheets etc, it is important to choose a suitable gripper design that can be deployed for such an application without damaging the properties of the material. Also, it is important to be able to pick up one object from a pile stacked together and the gripper should be able to efficiently transport the object and release it in proper place, without distorting the orientation of the object in the destination pile. Also, since this is an industrial application, the gripper must be light weight (to keep the overall weight low of the robot) and easily mountable on a robotic arm to carry out its functions. It must be repeatable and reliable solution that is tuneable to various loads and can provide faster results when compared to a human counterpart. Keeping these requirements in mind, above grippers were analysed for providing efficient pick and place of flexible materials.
As discussed in section 2.3, Ingressive grippers can puncture and damage the flexible material and therefore cannot be used for objects such as gloves. Impactive grippers are unable to be pick-up flexible materials while maintaining their correct orientation and therefore can distort the complete stack. Also placing of the flexible material in the correct orientation using impactive grippers can be difficult to achieve. Contigutive grippers can contaminate the gloves and thus neither of the three can provide a good

method for pick and place of flexible material with the above-mentioned requirements.

For flexible material, astrictive grippers are the most favourable grippers for experimentation and automation and deployment in the packaging industry. It is important that uniform force be applied to the surface of the flexible material so that smooth pick and place can be achieved, without any distortion and contamination as well as maintaining the structure of the stack. Vacuum suction forces have been previously tested by AA Robotics on flexible material such as gloves with inefficient results and uncontrolled behaviour since the pressure is applied to limited areas, thereby causing non- uniform forces and ultimately leading to sailing or imbalanced transport of the flexible material from source to destination point. There is also a problem with releasing the flexible material in a proper manner onto the stack while maintaining orientation. Thus, vacuum suction pumps are not suitable for elastomers as the handling capability is very low using this technique. Magnetic attraction of nonferrous elastomers is not possible.

As electro adhesion proves to be a promising technology for wall climbing robots, similar experimental setups can be made using electro adhesion to pick up and release flexible materials. Clamping and unclamping done by wall climbing robots (H. Prahlad, 2008) is the closest match to pick up and release mechanism (as discussed further). Electro-adhesion can work on a number of objects and applies a uniform force, thus overcomes the disadvantages of other gripping solutions. Also, it is a light weight gripper that can provide repeatable and reliable results with the correct set of parameters. However, the parameters that affect its performance are a further topic of this research. Although a promising technology but it is a new unexplored avenue. There are many parameters that affect the repeatability and reliability of the electro-adhesive gripper. The relationship amongst those parameters is not fully studied, therefore this research attempts to address some of these issues.

Type of Gripper	Technology	Surface Force	Contamination/ deformation of object	Ply separation	Tuneable to loads	Position of release	Speed	R2 results	Applicability
Impactive	2 fingered/ 3 fingered structure, D Hand	Force exerted uniformly on the surface of rigid objects, however not suitable for flexible material	No contamination or deformation of object	Unable to apply suitable force on flexible materials for ply separation	Fixed to a particular load, no tuning possible after design	Unable to release flexible material with uniformity	Fast pick up and release of rigid objects but unable to effectively pick up flexible material	High for rigid objects but not repeatable results for flexible materials	More appropriate for rigid objects but not suitable to handle flexible material due to non-uniformity of force applied on the surface of flexible material
Ingressive	Microspines	Depending upon the holding points the force can be uniform or non-uniform	Object can be deformed as this is intrusive	Can achieve ply separation through permeation	Fixed to a particular load, no tuning possible after design	Unable to release flexible material with uniformity	Fast pick up of flexible materials but release may not be uniform	Low R2 as the release cycle is not predictable	Not suitable for flexible material as they are permeating in nature and cause deformation
Contigutive	Chemical adhesion	Uniform force can be obtained depending on the size of the gripper	Some chemicals can leave residue behind on the surface causing contamination	Can achieve ply separation through chemical adhesion	Fixed to a particular load, no tuning possible after design	Unable to release flexible material with uniformity	Fast pick up of flexible materials but release may not be uniform	Low R2 as the release cycle is not predictable	Not suitable for flexible material as they are cause contamination
Astrictive	Suction Cups	Difficult to fine tune the force according to the surface for flexible materials	No contamination or deformation of object	Unable to apply suitable force on flexible materials for ply separa-	Can be tuned to a set of loads by varying the suction applied	Unable to release flexible material with uniformity	Fast pick up of flexible materials but release may not be uniform	Low R2 as the release cycle is not predictable	Can be used for flexible material handling but poor R2 results due to non-uniformity of release of object
Astrictive	Electro-adhesion	Uniform force on the object	No contamination or deformation of object	Able to perform ply separation	Can be tuned to a set of loads by varying the parameters	uniform release can be achieved	Have the potential of achieving the desired pickup and release times, based on further research	Have the potential to achieve R2 results, based on research	Can be used for flexible material handling and present a good case for further research

Table 2-6 Comparison of various gripping solutions

2.5. Conclusion

Based on the above study, for the current application of handling flexible material, the use of electro-adhesion as a gripping technique presents a more appropriate solution when compared to others since it is non-intrusive, it does not deform the object, it is able to perform ply separation, it is tuneable to various loads and it can perform pickup as well as release of the object in the desired orientation as it provides a uniform load. Therefore, this is a technique with promising repeatable and reliable results. However, this is an emerging technology and needs further research regarding the parameters that affect the performance of the gripper when used in a pick and place application. For this, it is important to identify what are the components that form this type of gripper, so that the affecting parameters can be listed. This forms the basis of future chapters in this report and subsequent research questions are thus answered.

3. PARAMETERS THAT AFFECT THE PICK AND PLACE OF SUBRSTATES WHEN USING AN ELECTRO-ADHESION GRIPPER

3.1 Introduction

This chapter presents the theoretical concept of electro-adhesion and its relevance in being used as a gripping technique for pick and place of flexible and other commonly used materials such as glove and glass. The chapter contains the principle of electro-adhesion, where the theory of parallel plate capacitor is used to explain the electro-adhesive effect on the object also knows as the substrate. Since it acts as a parallel plate capacitor, there is storage of charge and therefore for effective release, this charge must be dissipated. This is an important concept to understand since it helps to answer the research question ***RQ2: What are the key parameters that influence the pickup and release time of the chosen technique when deployed in a material handling application?***

Little research has been done for deploying electro-adhesion as a gripping solution for material handling in the industrial setup. The key here being pick as well as place, where release of the substrate is as important as pick up of the substrate. There have been experiments to suggest how electro-adhesive technique can be used to pick up different types of loads and used in applications such as MEMs and wall climbing robots, thereby demonstrating the ability to attach the substrate to the gripper. However there has been little research in establishing the key parameters that define the success of this technique as a pick **and place** gripper, where the substrate is reliably and repeatably placed from point A to B (and similar applications of pick and place in the industry), thereby emphasizing on the release of the substrate from the gripper. This is key for an industrial setup where repeatable and reliable results are required. Therefore, there is extensive research on picking up various loads using electro-adhesion and improving the design of the electrodes to provide the most effective solution for picking up these loads, yet little research has been done on reducing the release time, so that the pick and place cycle can be overall improved.

The reason why releasing is an important topic because (as will be seen in later chapters) electro-adhesion works at a micro level. It is a phenomenon that causes polarisation of the substrate, whereby temporary changes are made to the charge distribution on the surface of the substrate. This contributes to the pickup of the substrate by the electro-adhesive gripper and therefore depolarisation techniques are an important factor to consider for the release of the substrate by the gripper. The factors contributing to the depolarisation caused due to electro-adhesion, which contribute to the release of the substrate has not been extensively researched and since the overall performance of the gripper depends on effective pick up as well as release, therefore this research is motivated to explore key parameters that influence the release time in electro-adhesion when used as a successful gripping solution for pick and place of flexible material.

It is also an endeavour to further this technique to other applications such as waste management, where a similar phenomenon is needed for selective pick up of certain materials from a pile of rubbish and transport them to a different sorting location and release them in a pile.

3.2 Principle of Electro-Adhesion

Since electro-adhesion is a micro level phenomenon, the properties of materials at microlevel must be studied. For this purpose, the discussion of how the electrons are placed at atomic level in conductors and insulators is presented. Following is the figure 3.1 for molecular level arrangement of insulators.

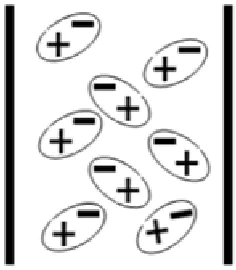


Figure 3-1Insulator Polar Molecular arrangement (Electrical4U, 2019)

The above figure 3.1 represents an insulator in the absence of an electric field. As can be seen from the above diagram, in an insulator, electrons are closely bound to their atoms and therefore the bond between electrons and protons is strong.

In the case of conductors, the electrons are free from their atoms and therefore the bond between the electrons and protons can be easily broken, thereby making the electrons free to move in the presence of electric field, as can be seen in the diagram below.

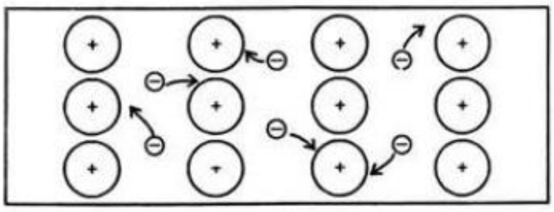


Figure 3-2 Conductor molecule arrangement (Roshni, 2019)

3.2.1 Concepts affecting the Molecular Polarizability

When placed in an electric field, conductors and insulators behave differently due to the atomic bonds and availability of electrons that can break away and move further away from the atom. Conductors have a vast number of free electrons due to weak atomic bonds. This allows easy flow of current in the presence of an electric field. Insulators on the other hand, do not have free electrons and therefore obstruct the flow of current when placed in an electric field. Therefore, under the effect of electric field, electrons of the conductor are able to break their bonds, therefore allowing current to flow through the metal, as depicted in the figure below where the direction of movement of electrons is shown.

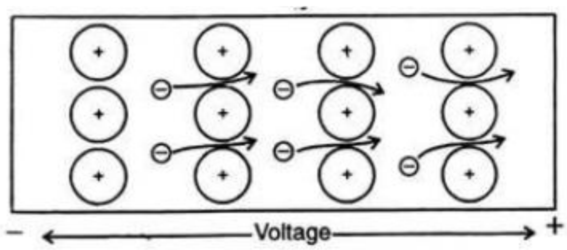


Figure 3-3 Electron movement In the presence of Electric field (Roshni, 2019)

In insulators, however, electrons are not able to break away from the atom, instead they exhibit the phenomenon of polarisation.

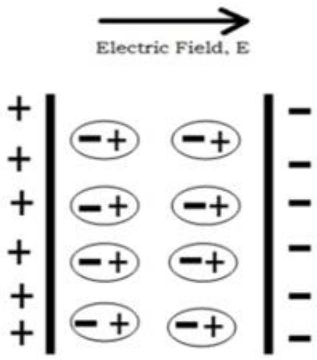


Figure 3-4 Polar Molecules in presence of electric field (Electrical4U, 2019)

Polarisation is the process in which there is a shift in the average equilibrium positions of charges of an insulator when placed in an electric field. Also known as dielectric polarisation (since insulators that get polarised are also known as dielectric materials), the positive charges are displaced in the direction of the applied electric field and the negative charges are displaced in the direction opposite to the direction of the applied electric field.

In electromagnetism, the ability or measure of how easily a dielectric material gets polarised in response to an electric field is termed as **Electric Susceptibility** (χ_e)

Therefore, polarisation P is directly proportional to the electric susceptibility of the dielectric material and is represented as follows

$$P = \boldsymbol{\varepsilon_o} XeE$$

Where

$\boldsymbol{\varepsilon_0}$ is the permittivity of free space

χ_e is the electric susceptibility

E is the electric filed

P is the polarisation

i. Polarisation equation (Jackson, 1999)

Here, another term is introduced – **Permittivity**. Permittivity of free space $\boldsymbol{\varepsilon_0}$, also known as vacuum permittivity is an ideal physical constant which represents the value of absolute dielectric permittivity of vacuum. In general, permittivity represents the measure of capacitance that is encountered in a material, when forming an electric field. Therefore, permittivity is a material's ability to store charge in the polarisation of the material. Thus, it can be inferred that materials that have high electric susceptibility are easily polarised in an electric field, thereby have high capacity to store charge and therefore have high permittivity.

The ability of a material to store electrical energy is termed as the dielectric constant and is represented as a ratio of the permittivity of material to the permittivity of free space (relative permittivity). This ratio is also termed as the dielectric constant

Relative permittivity k

$$k = \varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$$

Where,

$\boldsymbol{\varepsilon}$ is the permittivity of material

$\boldsymbol{\varepsilon_0}$ is the permittivity of free space

ii. Relative permittivity equation (Jackson, 1999)

Relation between permittivity and electric susceptibility

$$Xe = k - 1$$

Where

χ_e is the electric susceptibility

k is the relative permittivity

iii. Relation between electric susceptibility and relative permittivity (Jackson, 1999)

therefore, the equation for permittivity can also be expressed as

$$\varepsilon = \varepsilon_r \varepsilon_o = (1 + Xe)\varepsilon_o$$

iv. Permittivity of material and electric susceptibility relation (Jackson, 1999)

In theory, it can be considered that in conductors, as the permittivity is high, dielectric constant can be considered high but as conductors pass electric current through them, they are not able to store charge and therefore dielectric constant is not considered. Conduction in conductors eclipses the process of polarisation.

Molecular arrangement of Polymers

A polymer, as the name suggests, is a structure made up of many repeating units (Council, 2019). These repeating units are often made of two main elements, carbon and hydrogen. These can also be made of other elements such as oxygen, nitrogen, fluorine, phosphorous, and silicon. To make a polymeric chain, many links can be chemically hooked or polymerized together. Polymers are made of carbon atoms bonded together, one to the next, into long chains that are called the backbone of the polymer. Polyethylene (PE) and polypropylene (PP) are such types of polymers. There can be other backbones as well, such as Polycarbonate (PC) is a polymer with oxygen as the backbone structure, Nitrile contains nitrogen as the backbone that is bonded to carbon.

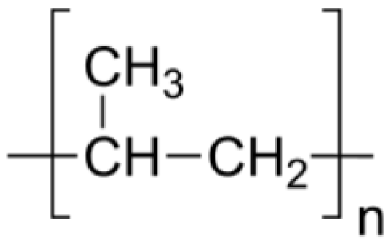


Figure 3-5 Repeating structure of Polypropylene

Since distribution of charge plays an important role in electro-adhesion, understanding the structure or orientation of molecules of these polymeric materials, helps in studying their use in an electro-adhesive gripper.

Polymer structures can either be polar or non-polar. As seen in the research done by (K. Nagasawa, 2010) Polycarbonate is a polar type of polymeric material which shows low charge accumulation and very less saturation time. Polypropylene is a non-polar type of polymeric material which shows medium charge accumulation and saturation time whereas Polyethylene (also non polar type) show large amounts of charge accumulation and therefore has a higher saturation time. Therefore, non-polar polymeric material can have the ability to support higher loads in an electro-adhesive gripper due to large charge accumulation (resulting in large voltage and attractive forces), but since there is a larger charge accumulation, the release time may be increased (since it will take longer to dissipate the built-up charge). For smaller loads, polar polymeric material may serve as a better dielectric, since it can provide a good balance of charge accumulation that is good enough to generate forces to pick up the substrate and for a quick release.

3.2.2 Relaxation time

If charge is stored in a capacitor due to polarisation, overtime, it decays due to resettlement/reestablishment of equilibrium of charges of polarised dielectric material (and some due to conductivity as there are no perfect insulators). This charge decay time is called dielectric relaxation time. The overall time taken to achieve a relaxation state is dependent on the overall charge accumulation on the dielectric that is placed on the electrodes. If a dielectric is chosen with a high charge accumulation (as in the case of the non-polar polymers), then the relaxation time increases, thereby the substrate is held for longer duration by the gripper, thereby increasing the release time. In the current context of electro-adhesive gripper, therefore materials chosen for dielectric must not have a very high charge accumulation in order to achieve a quick release cycle.

Depolarisation can be achieved only once the voltage is switched off and there is no more source for charge accumulation, therefore after removing the dielectric material from the electric field. The relaxation time can be improved/reduced by (A) Grounding the substrate (B) passing an AC voltage that provides opposite cycles of voltage, so that charge settlement happens faster.

There have been attempts to fasten the release of the substrate using reverse polarity control (United States of America Patent No. US20130186699A1, 2013) and using air-jets to mechanically detach the substrate (Monkman G. J., Res. 1995). These methods however can be expensive and increase the complexity of the gripper. Another key approach has been release by vibration which is found to be effective (Koelemeijer, 2008) and have been tested by integrating the vibrator within the gripper itself (H. Demaghsi, 2014). A recently conducted study has achieved a release speed of less than 500ms (Xing Gao, 2019). The vibration based release solution although effective yet can be complicated to be added on the Electro-adhesive gripper on a production line where the requirements focus on the packaging of the substrate as well.

3.2.4 Parallel plate capacitor

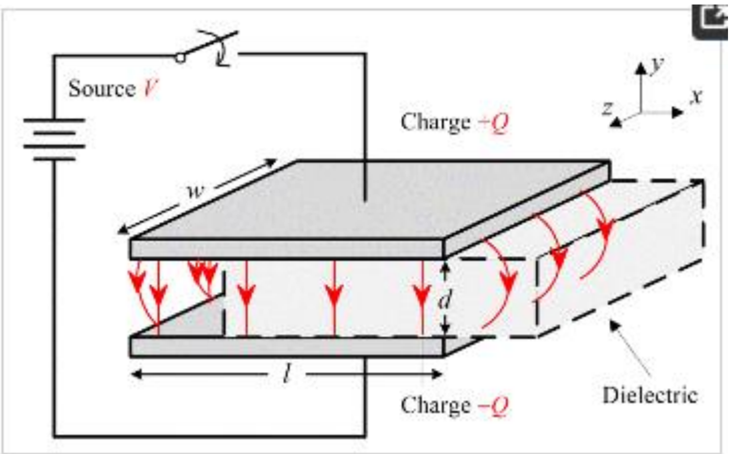


Figure 3-6Parallel Plate Capacitor (Keng Huat Koh M. S., 2014)

Parallel plate capacitor is the simplest form of capacitance that can be achieved by simply placing two conductive electrodes at a distance parallel to each other and separated by a dielectric. This arrangement ensures that when this capacitor is placed in the electric field, charges developed on the plates of the capacitor are not allowed to pass from electrode to the other, thereby creating a storage house for charge.

$$C = \varepsilon_o \varepsilon_r A/d$$

Where

C is the capacitance

ε_0 is the permittivity of free space

ε_r is the relative permittivity

A is the area (w*l)

And d is the distance between the electrodes

v. *Capacitance equation*

When a substrate is now placed in the vicinity of parallel plate capacitor, alternate charges are developed on the surface of the substrate. In metals, this process is called electrostatic induction.

Therefore, for conductors, electrostatic induction can be described as the process where negative charges are induced on one side and positive charges on the opposite side of the conductor by an external electrostatic field produced by charged insulator. This exerts an attractive force between the capacitor and the substrate.

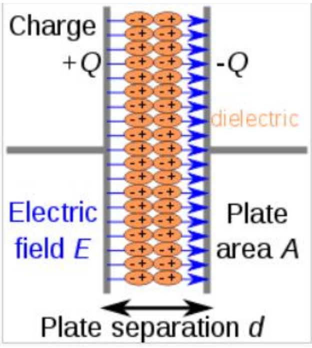


Figure 3-7A polarised dielectric material (Wikipedia, 2019)

In insulators/dielectrics, process of polarisation occurs as shown above in figure 3.6, when the insulator substrate is placed in the vicinity of a charged capacitor, thereby exerting attractive forces between the capacitor and substrate as there is no free movement of electrons. Since current is not allowed to pass and since insulators have high polarizability, they can be viewed as electrical obstructions that can be used for storage of charge which makes them perfect materials to be used in a parallel plate capacitor. Therefore, when dielectrics are placed on the electrode plates of the capacitor, polarisation of dielectric increases the capacitors overall surface charge, thereby increasing the ability of the capacitor to attract more materials around it. This can be viewed as a gluing effect or an electro adhesive effect that a material experiences when placed in the vicinity of a high density charge accumulated capacitor.

This electro adhesive phenomenon can be contact or contactless for both types of substrates (insulators and conductors). However, in an experiment conducted by (J. Jin, 1995), it was found that for insulating substrates, the electro adhesive forces generated due to polarisation take a long time (minutes or tens of minutes) to reach maximum forces due to the dynamic characteristics of the experiment. Hence for quick pickup, contact between substrate and electrode was considered most effective.

This idea was confirmed in experiments performed by (Monkman G, 1987), where they concluded that for insulating substrates, electro adhesive forces were generated between the substrate and the electrode due to electric polarisation (orientational and interfacial) and were increased on contact of the electrodes with the substrate to be picked up.

The electroadhesive forces generated between the substrate and the electrode is directly proportional to the applied electric field and the charge density accumulated at the dielectric surface. Force calculation formula for parallel plate capacitor is denoted by (Jiubing Mao, 2014), (Keng Huat Koh M. S., 2014)

$$f = \frac{\varepsilon_r \varepsilon_0 V^2}{2d^2}$$

Where

f is the force between the two plates (N),

ε_r is the relative permittivity of the dielectric,

ε_o is the relative permittivity of the vacuum,

V is the voltage applied to the plate's measure in Volts (V) and

d is the distance between the plates (mm).

vi. Force equation of a parallel plate capacitor

The key point in the above force calculation formula is that the force generated is directly proportional to the relative permittivity of the dielectric material. A material with higher dielectric constant should generate more force. This forms the basis of electro-adhesive gripping solutions for handling various material loads.

3.2.5 Failure causes of electro-adhesion

There are various factors that influence the performance of an electro-adhesive gripper. The most important role in a electro-adhesion gripper is played by the dielectric that is placed on top of the electrode plates for insulating them and for charge accumulation.

Dielectric plays an important role in providing a non-conductive layer on the electrodes, so that there is sufficient charge accumulation and no shorts are created between the electrode plates of the parallel plate capacitor. A dielectric may lose its non-conduction properties since there are no true insulators and all materials have their limits. If dielectric properties are lost, then electro-adhesion gripper is considered non-functional due to electrical breakdown and can no longer provide any adhesion to the substrate.

Some of the reasons of such a breakdown are listed below:

Dielectric strength

Dielectric strength is the maximum electric field that a material can withstand without breakdown and losing its insulating properties (as there are no perfect insulators).

Therefore, maximum voltage applied to the electrodes in an electro-adhesive gripper must be smaller than the breakdown voltage or less than the dielectric strength.

At breakdown, electric field frees the bound electrons, which causes a back-ground radiation that collides with other molecules at high velocities, causing them to also breakdown, thereby causing a breakdown avalanche.

Therefore, electrically conductive paths are developed which allow disruptive discharge through the material, thereby destroying its insulating abilities. As the electro-adhesion works at very high voltage, dielectric material used in this par-allel plate application must have a high dielectric strength to sustain its insulat-ing properties even at high voltage ranges.

All materials have certain conditions and limits where they work as insulators or conductors. Above these limits, the properties of all materials change. For ex-ample, the dielectric properties are frequency dependent. Similarly, the non-conductivity of dielectrics is also bound to certain limits, beyond which material starts to breakdown and starts conducting (since there are no perfect insulators).This is the reason why choosing the correct material to work as dielectric medium in a parallel place capacitor for storage of charge, it is important to study material breakdown when acting as an insulator.

For metals, even though the dielectric constant is high, they cannot be used as a dielectric material, as under the effect of electric field, they will instantly breakdown and start conducting. Therefore, there will be no storage of charge in parallel place capacitor.

Airgaps between the electrode surface and dielectric

Due to processes used to deposit the dielectric on the electrode plates, certain inaccuracies can exist, that can cause airgaps between the electrode plates and the dielectric material used. This means that there are 2 layers on the electrodes: One of air and one of the dielectric. The dielectric layer has a higher dielectric constant and dielectric strength compared to air. When a high voltage is applied to the electrodes, air can breakdown much before the dielectric layer and therefore breakdown can occur at a much lower voltage than anticipated for the gripping cycle. This can also cause breakdown and conduction in the dielectric layer due to presence of a larger amount of free charge that results from air breakdown.

Incorrect electrode structure

A uniform electrode structure is essential for uniform charge accumulation. If there are inaccuracies in the structure of the electrode such as sharp edges or non-uniform sizes, then uneven charges will be developed. Uneven charge accumulations can cause corona discharge when electric field concentration is high enough to ionize the surrounding air. This leads to electrical breakdown around sharp edges, thereby creating conductive layers that can temporarily or permanently damage the electro-adhesion gripper.

Electrical breakdown in solids

Material breakdown in dielectrics could be due to thermal breakdown caused due to thermal agitation caused by continuous polarization and exposure to high electric field. The thermal excitation for a prolonged period can result in breakdown of solid dielectrics.

3.3 Conclusion

In this chapter, basic concepts around the electro-adhesive technology were summarised. The chapter presented differences in behaviour of conductors and insulators under the influence of electric field. In insulators, polarisation effect causes charge accumulation to occur, which is the main reason for adhesive nature of an electro-adhesive gripper. As seen above, a high concentration of charge accumulation causes polarisation of neighbouring materials, which creates a force of attraction on the material.

Electro-adhesive gripper works as a parallel plate capacitor. Therefore, the forces generated to pick up the substrate when placed in the vicinity of the parallel plate capacitor are of a magnitude as dictated by the equations stated above in the theory of parallel plate capacitor. Also, the chapter above presents theory that suggests important parameters that influence the storage of charge in a parallel plate capacitor such as the role of dielectric constant of the insulator. A higher dielectric constant means that a larger charge accumulation will take place, therefore larger forces will be generated to pick up the substrate. However, a larger concentration of charges also takes a longer time in a release time, thereby prolonging the release cycle. Factors that may lead to break down of electro-adhesive gripper were also listed in this chapter.

This is an important observation when choosing the component selections that make the electrodes and dielectrics, since it can be used to understand the overall force that will be needed to pick up the substrate, the overall release time of the substrate and ultimately of the overall performance of the electro-adhesive gripper in an industrial setup for material handling of various substrates.

4. KEY COMPONENTS OF THE CHOSEN ELECTRO-ADHESIVE GRIPPER

4.1 Introduction

It is important to understand the key components that make up a gripping solution when deployed in a pick and place application of flexible materials, since this will help in establishing the base for future chapters that address the parameters affecting the efficiency of the chosen gripping solution. In a typical automation scenario, the gripping solution or the end effector is deployed on a robotic arm, which can typically be 4 or 6 axes (depending on application where it is used). This end effector is responsible for interacting with the flexible material (substrate) that needs to be handled. In the current context, only the end effector is in scope and the rest of the robotic arm is not in scope of this research.

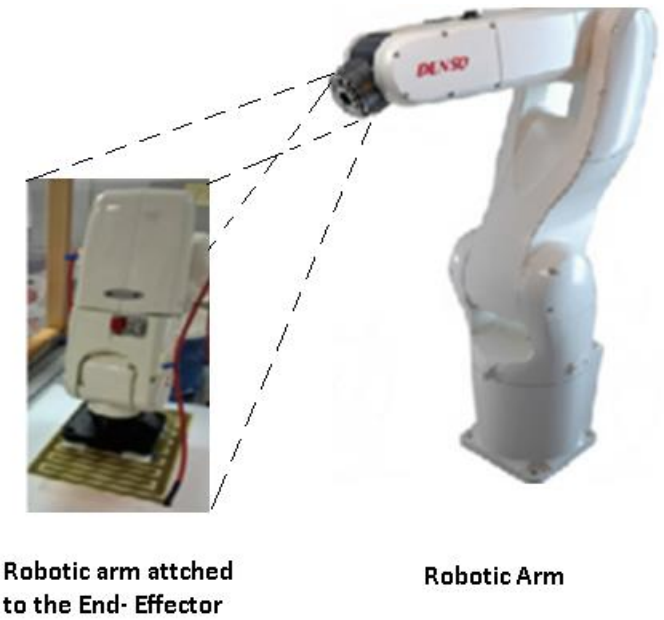


Figure 4-1 Denso Robotic Arm with electro-adhesion gripper

As seen in chapter 2, electro-adhesion proves to be the most suitable technology when choosing an astrictive type of gripper that can be used in the handling of flexible materials. There has been some indication of use of electro-adhesion technique for the pickup of various loads and used in applications such as

MEMs and wall climbing robots (H. Prahlad, 2008), thereby demonstrating the ability to attach the substrate to the gripper. However, it is important to establish the key components that constitute this gripper, which can then be assessed in the following chapters regarding their impact on the performance of the gripper.

The following chapter defines the main components of the Electro-adhesive gripper and presents extensive literature review on the components. It also lists the configurations this gripper can be used in; mono polar or bipolar setup. To further understand the topic, current applications have also been listed, since this helps in establishing how this technology is presently being deployed.

Therefore, this chapter helps to answer the research question RQ1: ***what are the key components that constitute the chosen technique when deployed in a pick and place application of commonly used material?***

4.2 Electro-adhesive gripper components

4.2.1 Key Components diagram

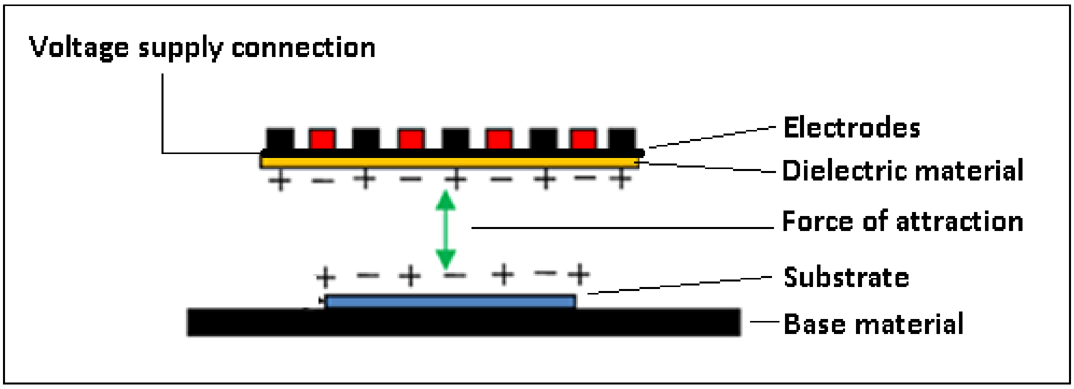


Figure 4-2 Key Components of electro-adhesion gripper

The key components of an Electro-adhesive gripper are represented in the diagram above. These are as follows:

Substrate

Substrate refers to the object which needs to be handled by the electro-adhesive gripper.

With the electro-adhesion clamping technique the substrate can be either an insulator or conductor. The structure of the substrate contributes to its molecular polarizability, which determines how much shear force will be needed to pick up the substrate. Thus, depending on the nature of the substrate, the electrode composition is chosen.

The selection of substrate is based on extensive research done on the types of flexible materials that are used in industry, for which automation can be made possible. It was found that flexible materials used in the industry such as medicinal gloves, mobile covers, polybags etc are types of polymeric material. As seen in section 2.1, there are some flexible materials that have been identified for current research. These are summarised in the table below:

1. Nitrile
   - Gloves
   - Small sheet of Nitrile
   - Large sheet of Nitrile
2. Glass
   - Composite glass
   - Pure glass
3. Polypropylene
4. High Density Polyethylene (HDPE)
5. Polycarbonate

The above substrate list was chosen based on the application where materials are flexible in nature except for Glass composite and Gorilla Glass (Pure Glass). The materials hold different dielectric properties and enable the experiments to be conducted on a variety of insulators rather than focussing on one.

Polycarbonate is a polar polymer (Nagasawa, Honjoh, Takada, Miyake, & Tanaka, 2010) which is widely used in many industrial applications and also on products which are part of our daily life. It is similar to other polar materials showed a small amount of charge accumulation about 5 to 20C/m3 and long saturation time about 1 to 20 minutes (Nagasawa, Honjoh, Takada, Miyake, & Tanaka, 2010)

Polyethylene unlike Polycarbonate is a non-polar polymer (Nagasawa, Honjoh, Takada, Miyake, & Tanaka, 2010) which shows the properties of a large amount of electric charge accumulation over 50C/m3 and long saturation time over 80/minutes. Polyethylene is one of the highest annually produced material, 80/million tonnes (Dr. Otto G. Piringer, 2008)

Electrodes

Electrodes are the main part of the electro-adhesion grippers. They produce the alternate positive and negative charges that are concentrated in one region through the use of a dielectric. These charges are key requirement for ensuring a uniform and sufficient grip is maintained to handle the substrate. Good conductors are the most suitable form of electrodes as they are available to provide the charges. Aluminium, Copper, Carbon are materials with good conductivity and are suitable to be used as electrodes. However, carbon mixed with polymer binder is the most suitable form of electrode (H. Prahlad, 2008) since the polymer binder helps to keep the carbon composed even at high voltages (which are necessary to be applied for electro-adhesion to take place).

The arrangement of the electrodes lays the foundation for the electrostatic forces generated by the gripper. Several arrangements have been experimented previously that have resulted in different electrode shapes such as (Juan P. Diaz Tellez, 2011):

a) Jagged

b) Rectangular in a square configuration

c) Semi-circular:

d) Interdigitated (Comb Structure)

e) Rectangular in an oblong configuration

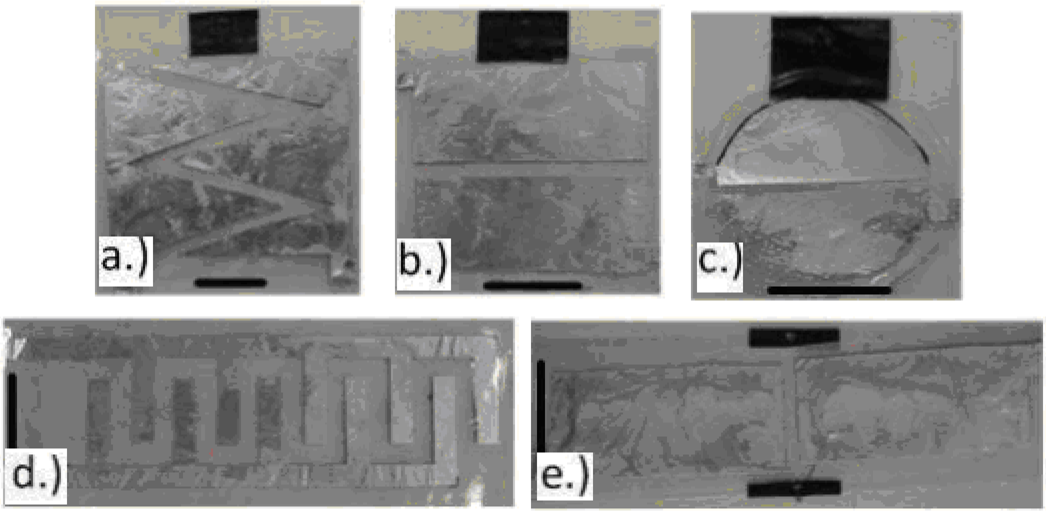


Figure 4-3 Electrode shapes (Juan P. Diaz Tellez, 2011)

Different experiments were conducted by (Juan P. Diaz Tellez, 2011) the results represent that the adhesion force generated is dependent on the configuration of the electrode. The experimental results were limited to 4KV, as the materials were not able to handle very high voltages due to break down of the dielectric between the electrodes and the substrate thus causing a short circuit. Therefore, the short circuit resulted in breakdown of electrostatic interaction which represents a no-load condition. The results obtained from the experiment are shown in the graph 4.2 below. The results show that type (d) electrode are able to provide maximum pressure (shear force).

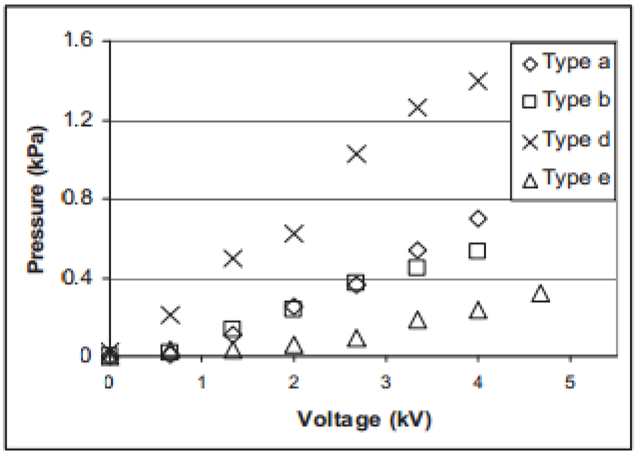


Figure 4-4Results on electrode shapes. (Juan P. Diaz Tellez, 2011)

Inter-digitated Electrodes

From the above experiments, it was noted that the Interdigitated electrode arrangement provided the best results for handling of flexible materials. Interdigitated electrode arrangement is represented by a number of positive and negative electrodes arranged next to one another in a comb like structure. This is the shape which provides the strongest shear forces as stated in the experiments above. As supported by another experiment (Keng Huat Koh K. C., 2012), the best results obtained are from interdigitated electrodes since the electrostatic adhesive force increases as the net electric field generated between positive and negative electrodes is increased. Electric field activity in interdigitated electrodes is shown below in figure 4.3.

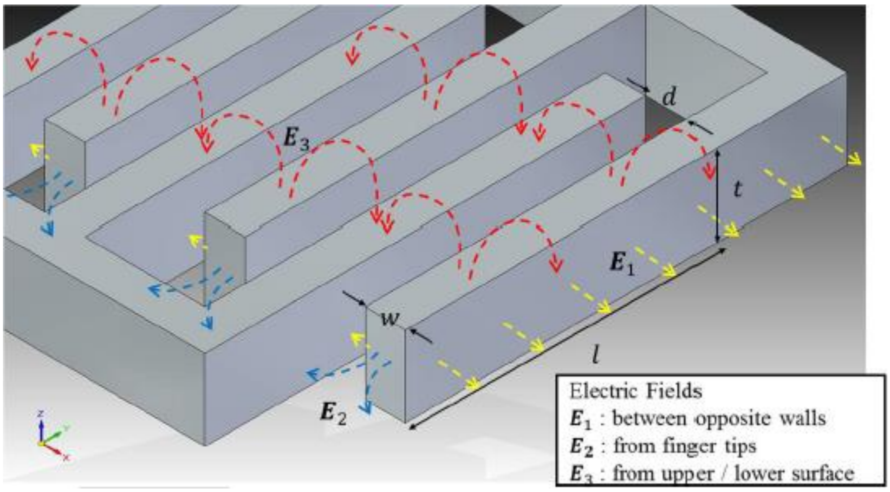


Figure 4-5Interdigitated electrodes (Keng Huat Koh K. C., 2012)

Force generated for object adhesion by the pad can be written as (Keng Huat Koh K. C., 2012)

$$F_N = \frac{0.5 \in_0 \in_r w l V^2}{d^2} + \frac{0.265 \in_0 \in_r w^{0.5} l V^2}{d^{1.5}}$$

Where

$\in_0$ = permittivity of free space

$\in_r$ = relative permittivity (dielectric constant) of insulating material

V = Static Potential difference

W = width of the electrode

l = overlap length of the fingers

vii. Force equation for object adhesion

The above equation is the force generated by one pair of comb electrode.

Simulation results are shown in a table 4.4 below

Parameters	Aluminum /PE	Aluminum /PP
Electrode width, w [mm]	8.0	
Electrode length, l [mm]	500	
Spacing gap, d [mm]	0.5	
Pairs of comb electrode, N	58	
Active area, A [cm^2]	4930	
Max applied voltage, V [kV]	10	12
Max ESA force, F_e [N]	1023.60	1473.90
Max ESA pressure, P_N [N/cm^2]	0.208	0.299

Table 4-6 Simulation results of electrostatic pad (Keng Huat Koh K. C., 2012)

The results obtained, as stated by (Keng Huat Koh K. C., 2012), are achieved through simulation experiments but in actual experiments, slight variations were noticed due to other factors such as cohesion force that is prominent at high voltage operations.

From the results received from simulating data and other results obtained from research, it is clear that interdigitated electrodes give more adhesive force than any other setup. Therefore, interdigitated electrodes are chosen as a configuration to perform experiments in this research for developing an electro-adhesion gripper for pick and place application of flexible materials. The aim will be to perform experiments to check the performance of this configuration for the current application.

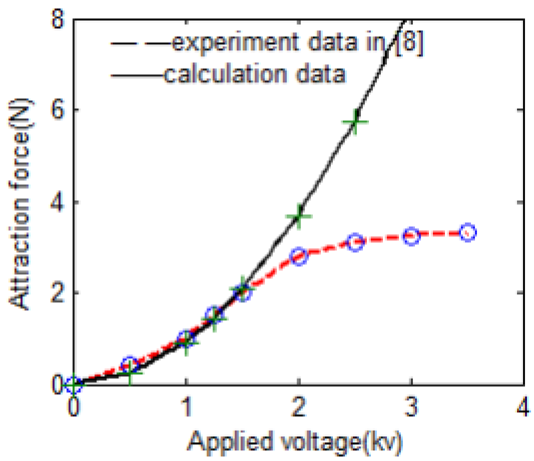


Figure 4-7Calculation data and experimental data results (Hua SHEN, 2012)

Dielectric

As discussed in chapter 3, dielectric is an essential part of the electro-adhesive gripper. The conductive electrodes, when subjected to high voltage, deposit charge on top of the insulating dielectric, which acts as a storage area for this charge. The deposited charges on the dielectric when brought close to the substrate, polarises the substrate and generates electro-adhesion force to lift it up. Therefore, insulating capabilities of dielectric play vital role for the working of electro-adhesive gripper.

Dielectric also provides an insulating layer between the electrode and the substrate, thereby preventing the stored charge to pass from electrodes to substrate Thus, it is an important factor to the prevention of short circuit in case of conductive substrates. Therefore, even though electro-adhesive grippers require very high voltages to operate, since the dielectric layer does not allow the passage of charge, the current drawn is near zero and therefore the overall power dissipation is minimal.

It is to be noted that since electro-adhesion takes place at the micro level, the molecular properties of the materials used play an important role in defining the efficiency of the gripper in handling flexible material. Thus, if one configuration of electrode-dielectric can perform well with one substrate, it is not necessary that this combination is going to perform as well with a different substrate. (H. Prahlad, 2008)

For elastomers that form the flexible material, liquid dielectrics were researched to be most suitable as elastomers are not rigid and the contact made is more ideal with liquid dielectric. They are able to provide a more even distribution of charge on the electrodes, thereby making the force more even on the substrate to be picked up (G.J.Monkman, 1995)

Polymers can be used as dielectric materials, as they are insulators which have the advantage of being easily processed, are flexible, cheaper, and can be better tailored for specific applications. As stated by (Polymerdatabase.com, 2019) they also have the required chemical resistance needed for dielectric materials.

With effective results obtained in one of the papers submitted in 2007 (Akio, 2007), polyimide was identified as a potential candidate for using as a dielectric material. With dielectric constant 3.2 for polyimide it can act as an insulating layer for 5kV or beyond. Another polymer that was identified with a high dielectric that can provide insulation at high voltages was Polyurethane (Gallagher, 2019).

For the construction of a dielectric, a component must be chosen which has high dielectric strength (Kashy 2016). The molecular polarisation of a materials is an exponential function of the dielectric relaxation time. Consequently, materials with rapid dielectric relaxation time make poor candidates for electro-adhesion (Monkman G. J., 2016). Therefore, in an electro-adhesion gripper application, it is important to use materials with high dielectrics.

One of the components identified in this research was Barium titanate (BT) which has a dielectric constant from 1250 at room temperature. Pure Barium titanate comes in the form of powder which makes it difficult to be used as a dielectric layer on the electro-adhesion gripper pad, since it was identified that dielectrics in the liquid form are the best method, as they can be evenly coated on the electrode that provides an even layer for charge accumulation on the electrodes. In order to make a liquid dielectric, Barium powder must be mixed with paint and water to make it viscous enough to be coated using a spray gun. Different ratios of the material can then be experimented, in order to check which ratio of BT mixture is best suited for the current application of pick and place of flexible material by an electro-adhesion gripper. One of the aims of this research will be to try these different ratios, along with other identified dielectrics (as above) to check which configuration is best for the current application.

Dielectric strength plays a vital role in the electro-adhesion gripper. Different dielectric materials behave differently and can have different pick up capabilities and release times. As per (Keng Huat Koh M. S., 2014) the higher the dielectric strength the higher will be force for the electro-adhesion gripper but at the same time higher will be the residual charge as well leading to delay in the release of the substrate/elastomer.

A comparative study on dielectric strengths of various materials mentioned above shows the following results, as in table 4.6:

	Electrical Properties		
Electrode	Dielectric Strength (kV/mm)	Dielectric Constant	Reference
Barium Ti-tanate	Density dependent	1250	(Kashy 2016) (D.Schomann 1975)
	150kV/mm (Barium Titanate Ceramics)		
Polyurethane	60kV/mm	3.6	(Electrolube 2016)
Polyimide	205kV/mm	3.5	(Dupoint 2016)

Table 4-8 Comparative Study of Dielectric materials

Dielectrics in an electro-adhesion gripper setup provide two main purposes. As mentioned above, they provide a concentration of stored charge on the electrode. The other purpose is to create an insulating layer between the electrodes so that there is no leakage current between them. This is to ensure there is no electrocution between electrodes and the overall power consumption of the device is minimal.

However, in the case of substrates made out of flexible material, that are nonconductive, research suggests that there can be a configuration of electro-adhesion gripper with no dielectric usage on the electrodes, thereby using bare electrodes for the electro-adhesion gripper. Since the substrate itself is nonconductive, there is minimal chance of leakage current.

Current literature review suggests that this theory is inconclusive and therefore there are insufficient results to support the use of a no-dielectric configuration in an electro-adhesion gripper used for an industrial application providing R2 results. The aim of the experiments in this research therefore will also be to explore this configuration as a possibility.

Base Material

Base material in simple terms, is the structure that supports the substrate before it is picked up by the gripper. Therefore, it is the platform that holds the substrate, from which the gripper can be picked up. In the industrial application, this can be the conveyor belt on which the flexible material is being transported or simply a location on bench where the material has been placed. At micro level, the material on which the substrate is placed can have an impact on the spacial orientation of the charges of the substrate, thereby affecting its ability to get successfully polarised by the electrodes of the electro-adhesion gripper and in turn be picked up by the electro-adhesion gripper. Base material must be chosen such that it has a stabilizing (low dielectric) effect on the substrate.

Properties of materials used for base such as its dielectric strength, relaxation time, specific conductivity play a vital role in influencing the performance of electro-adhesion gripper.

Although it can be observed that materials have similar dielectric strength but there are other properties like relaxation time, water absorbance rate based on which different substrate materials were chosen.

Material	Dielectric Constant Er	Relaxation time T(secs)
Nylon	3.5 – 4.0	0.00003
Polystyrene	2	0.0018
Polyester	3.0 – 7.0	200
Polythene	2.3	2000
Plywood	1.4 – 2.9	-
Polycarbonate	2.8 - 3.4	-

Table 4-9Properties of Base materials used (G.J.Monkman P. T., 1989)

There is no current research on the effects of base material on the performance of an electro-adhesion gripper in picking up flexible material. However, based on our hypothesis above and due to its rapid relaxation time and (suspected) hygroscopic nature, Nylon appears to be a suitable material to be used as a base material. If used as a base material Nylon can have significant advantages and can give stable and efficient results to the electro-adhesion gripper performance in a pick and place application of flexible materials. Also, in case of an accidental contact between the electrodes and the base material, nylon would ensure that no charge is escaped.

Other polymers with similar dielectric strengths can also be chosen for the current application, such as, Polycarbonate and polystyrene. Plywood also forms a good candidate for study in this context due to its non-conductive properties, thereby preventing electrocution in the event of accidental electrode contact.

Power supply type (AC/ DC)

Voltage here refers to the energy provided to the electro-adhesive gripper to get charged and attract the substrate. As seen in the Electrodes section above, the voltage range of operation in case of electro-adhesion technique can be very large, going as high as 2- 5 KV in some cases (depending on the experiment). This forms an important component of the electro-adhesive gripper since it directly impacts the amount electrostatic force generated by the gripper to attract the substrate. A DC voltage supply provides a constant source of charges to be deposited on the electrodes, thereby ensuring enough force is generated in order to pick up the substrate. Though a constant source of charge supplied to the electrodes would mean that the release time may be longer, even after the supply is shut off. In this case, there can be two methods to discharge this charge accumulation quickly. The substrate could either be grounded, so that the charges are quickly dissipated thereby releasing the substrate from the grip of the electro-adhesion gripper. Or it can be supplied with an AC voltage, to provide for negative cycles of voltage that can help with the charge dissipation. Another theory suggests providing only AC power supply to the electro-adhesion gripper (US Patent No. US20130186699A1, 2013) for the pick up as well as the release cycle. This allows for a trade-off between charge accumulation needed for pick up and release. However, further research is needed if AC supply voltage is enough to generate enough charge accumulation for the polarisation of the substrate and thereby provide efficient R2 results in a repetitive cycle, which is needed in the current application.

Pickup and release of substrate by an electrode in parallel plate capacitor configuration

In an electro-adhesive gripper, electrodes are coated with a layer of dielectric material and connected to a power source. The substrate or object to be picked up, is placed on a base material. In a bipolar setup, one set of electrodes is connected to the positive rail and one to the negative of the power supply.

When power supply is switched on, the electrodes, being conductive, allow electric current to pass through them but the dielectrics, being insulator do not allow the transfer of this current between the positive and negative rails of the electrodes. Instead, in the presence of the strong electric field, the dielectric medium gets polarised, causing a charge accumulation on the surface. When the substrate (also an insulator in this case) comes in vicinity of this charge dense area (contact or contactless), also gets polarised, causing adhesion due to the resulting forces of attraction.

The amount of adhesive forces generated to pick up the substrate depends on the total charge accumulation which is directly proportional to the relative permittivity of the dielectric. Therefore, electro-adhesive grippers can be made tuneable to various loads by controlling the charge accumulation on the surface of the dielectric. However, larger amounts of accumulated charge take longer to dissipate in the release cycle, posing a trade-off between polarisation to pick the object and depolarisation to release the object from the grip of the electro-adhesive gripper. Combining the correct materials for example nylon, used as a base material, the bonding is such that charge distribution is better, grounding of objects in release cycle and using dielectrics with just sufficient permittivity can be some of the methods used to balance this trade off.

4.2.2 Mono Polar and Bipolar setup

An electro-adhesive gripper can be setup in two main configurations, based on the polarity of the electrodes.

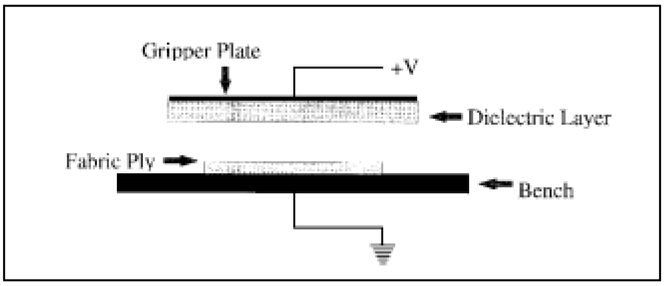


Figure 4-10 Single pole gripper (Zhang, 1999)

A monopolar setup consists of a single electrode (shown above as the gripper plate) and a dielectric material, in the form of a dielectric layer placed on top of the electrode. The dielectric plate isolates the conductive electrode plate from the substrate, which may or may not be conductive, depending on the chosen material that needs to be handled. The electrode is given a voltage of few kV which tends to impose the opposite charge on the substrate. (Zhang, 1999)

In order to pick up the substrate, a Grip force is applied, which is proportional to the area of electrode which is being charged by applying voltage. This is also known as the Grip pressure and can be represented as follows:

$$\text{Grip Pressure (in Pa)} = [\mathcal{E}_0][V\mathcal{E}_r/\{d+k_r g\}]^2$$

Where $\mathcal{E}_0 = 8.85.10^{-12}$

V = electrode – substrate voltage,

$\mathcal{E}_r$ = dielectric constant

d = dielectric thickness

g = gap size

viii. Grip pressure equation (Electrogrip, 2013)

To release the substrate, voltage supply to the electrode is removed, thereby no grip pressure is applied and the substrate free falls due to gravity.

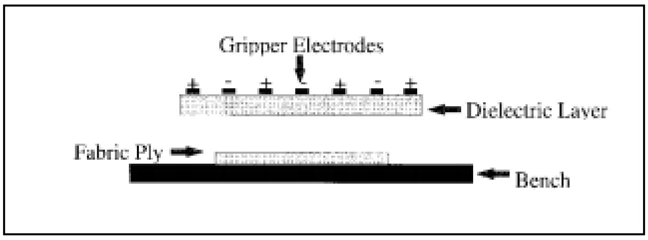


Figure 4-11 Bipolar gripper (Zhang, 1999)

A Bipolar gripper has both negative and positive electrodes. Thus, both positive and negative charges are developed on the electrodes, making a stronger overall electric field. Interdigitated electrodes are a type of bipolar setup.

4.2.3 Current Applications

The current applications of electro-adhesion denote the areas in which this technology has been researched and successfully deployed. This is important to understand the potential of the technique and can help to determine its suitability for handling flexible materials.

Electrostatics and electrostatic induction phenomenon were first discovered in 1700s but the modern electro-adhesion theory was based on discoveries made in the 1900s (Johnsen-Rahbek effect in 1923 and later Balakrishan in 1950). Many experiments have been performed on electro-adhesion since then. In a conference paper published by NASA (Langley research centre) in 1967, claims were made on factors influencing electro-adhesion forces and use of electro-adhesion forces and use of electro-adhesive grippers for material handling in space.

In general, the literature review shows that electro-adhesive applications can be categorised in two main areas: Material handling and robotic climbing.

Wall climbing robots

With the different types of locomotion techniques used by robots, there were not many successful techniques identified and developed for the robots to move vertically and climb walls with a strong grip. This posed as a restriction to the usage of robots in applications such as in military and rescue purposes, where wall climbing plays an essential part in the deployment. Some experiments were performed with vacuum suction cups, however loss of suction and influence of the surface of the wall on the performance of the gripper posed as major limitations to the technique.

With the ability of clamping and unclamping, able to adhere to any kind of surface and no loss of adhesion, experiments based on electro-adhesion proved to be more successful (H. Prahlad, 2008). (Grabit, 2019)

Wall climbing robots provide good indication of the potentials of electro-adhesion in clamping and unclamping that can be used for using this technique for electro-adhesive gripping solutions.

Successful monitoring of charges and accurate results have been recorded using this technique, especially in the case of wall climbing robots. Different robots with additional compliant flaps and tank type robots with flaps can climb walls at record speeds. A response time of less than 10-50 ms has been recorded for clamping and unclamping action which denotes stability in this technique (H. Prahlad, 2008). This is an important consideration when deducing the total time of manufacturing process, as use of electro-adhesive gripper must not increase the total production time. Also, it needs to be a reliable system which aims at removing human involvement. Thus, to make it a time efficient system, it needs to have lower response times.

Since using this electro adhesion technique power can be saved by switching on and off in sequence with fast response times, this power saving mode is best suited for biomimetic robots.

Some of the other applications of electrostatic technology are

- Laser Printing, Dust Cleaning, Cathode Ray tube technology (Zhang, 1999)
- Assembling of Millimetre sized parts (self-aligning electrostatic gripper for assembly of millimetre sized parts, as known as MEMS)

Further important contribution was made by Monkman et al in 1986, where important contributions in the field of electro-adhesion were made such as basic principles of fabric materials handling by electro-adhesion and deployment of electro-adhesive grippers and conveyor belts for handling clothing. Here he also talked about ply separation and adaptive electro-adhesive grippers for different handling weights of materials.

In more recent past, Grabit inc was found (Grabit, 2019) in 2011. This was the first company that was established with a view of commercially deploying electro-adhesive grippers in handling materials. Since then, this has been expanded with further collaboration companies with same aim of researching further enhancements in electro-adhesion technology for commercial use.

Applications and research in the area of electro-adhesion prove that this technique has good potential for deployment in gripping technologies however the literature review shows that more research is needed to successfully deploy this kind of gripper in a pick and place application for repeatable and reliable results in an industrial application.

4.3 A note on the industrial setup for safe operation

In the electro-adhesive technology, high voltage is required in order to provide enough charges that can polarise the substrate, thereby picking it up. In theory, the use of dielectric on the electrodes should ensure that there is no current leakage between the electrodes, as any current leakage could cause electrocution that could in turn be detrimental to the electrodes' performance. As mentioned by (Keng Huat Koh M. S., 2014) at high electric field, there can be some conduction even in dielectrics, as there are no perfect insulators. High field conduction is explained by theories such as Schottky, tunnelling, Pool-Frenkel, ion or electron hoping and space charge. These are typical of solid dielectrics in particular such as polyimide films, polyproline films etc. The leakage current caused due to this high conduction phenomenon can reduce the efficiency of the capacitor system needed for adhesion in electro-adhesion gripper, thereby making it less likely to achieve R2 results in an industrial setup.

In this research, we suggest that to counter for this, liquid dielectrics must be used to coat the electrodes, that may help in reducing the chances of dielectric conduction due to electric break down. It remains important to compare results of solid film dielectrics versus liquid dielectrics that are coated on the electrode directly. This study can only be concluded by further experimentation as, at present, there is no research available on this comparative study.

There are other reasons for leakage current that could impact the performance of electro-adhesion gripper, such as corona discharge in the air. Corona discharge can occur if the air around the electrode gets ionized due to the presence of a strong electric field, thus forming a conductive region. Also, there can be ESD/ EMC effects that can hamper the performance of the electro-adhesion gripper. Since in an industrial set up, it is not possible to place robots in vacuum, these effects must be counteracted in other ways. Our research suggests use of precautionary methods such as Faradays cage and tune the voltage of operation in such a way that leakage effects due to Corona effect can be reduced to minimal without compromising the performance of the electro adhesive gripper. Importance of using nonconductive material as a choice to make the base material component is also highlighted above for safe operation in an industrial setup, so that in case of an accidental contact between the electrodes and the base material, there is no leakage current.

In the industrial setup, quick release of the substrate is equally as important as the pickup. Current literature review suggests many papers have been published on how to provide an efficient pick up of various substrates and how to tune an Electro-adhesive gripper to pick up even heavy/ varying loads. However, little research exists about how the experiments can be tuned in order to provide quick release time. In this research, focus must be maintained regarding reduction of release time as well as pickup for successful deployment in an industrial setup.

4.4 Conclusion

From the literature review conducted, we can summarize the main components of an Electro-adhesive gripper to be the substrate, the electrodes, the base material, the dielectric and the power supply. Theory related to each of these components was presented, along with various materials that can be used to make each of these components. Since the properties of materials plays an important role in the performance of the Electro-adhesive gripper in providing R2 results, a discussion was presented in this chapter regarding how different types of materials that make up the individual components can have different impacts on its performance.

From the above literature review, it was concluded that in theory, interdigitated electrodes used in a bipolar setup can provide the best configuration for an Electro-adhesive gripper. Further, for dielectric, materials such as polyimide, polyurethane, barium titanate (various strength mixtures). It was discussed that liquid dielectrics coated on the electrodes can in theory be more effective in evenly distributing the charge on the electrode and therefore force applied to pick up the substrate is more effective. Liquid dielectrics also are less prone to leakage current. This area of research needs further experimentation to provide more concrete results as current literature review remains insufficient. Also, a configuration of Electro-adhesive gripper with no dielectric was explored. As per the present theory, this can provide sufficient results in picking up non-conductive flexible materials. However, this also needs to be substantiated with further experimentation.

For the base material component, various materials with lower dielectrics were suggested such as Nylon, Plywood, polycarbonate and polystyrene. Here it was concluded that a base material with no/least conductivity and low relative dielectric permittivity is best suited for the current application of Electro-adhesive gripper in pick and place of flexible material as it ensures charge distribution on the substrate is not affected and there is no conduction between electrodes in case of an accidental touch to the base material. Further experimentation is needed to conclude which is the best material in this case.

For the power supply component, it was concluded that in theory, a DC supply can prove most effective in providing enough power to the Electro-adhesive gripper for pick up but this is a trade off between providing sufficient force for pick up and quick release of substrate. Too much charge accumulation can cause for a longer release time. Therefore, it is important also to dissipate the accumulated charges in the release cycle. Here, multiple methods were introduced to achieve quick release time, such as grounding of the substrate, using AC power supply in the release cycle or simply switching off the power supply. Here, again there is insufficient literature review, therefore any further conclusions need to be substantiated with further experimentation.

Hence the following parameter table can be derived:

Base Material	Nylon
	Polycarbonate
	Plywood
	Polystyrene
Dielectric	Polyimide
	Barium Titanate coating 1
	Barium Titanate coating 2
	Barium Titanate coating 3
	Polyurethane
	No Dielectric (Bare Electrodes)
Electrodes	Interdigitated
	Concentric
Power Supply	DC
	AC

Table 4-12 Parameter table

Safety mechanism for industrial setup were also researched, which are needed due to high voltage nature of the operation. Here, it was suggested to use liquid dielectrics and nonconductive base material in this Electro-adhesive gripper setup, so that leakage currents can be reduced to minimal. Also, to reduce effects of corona discharge, ESD or EMC, it was suggested to perform experiments in a safe setup such as a Faradays cage.

At the end of the chapter, some current application areas were listed where electro-adhesive technique has already been utilised, therefore proven in use. These include wall climbing robots, MEMS, laser printing etc. These existing applications prove the concept of electro-adhesion in general which provides confidence that this technique can be used in pick-up of various substrates, but it was identified that little research has been conducted on how quick release times can be achieved. Pick up and release time both were identified to be equally important in the current industrial application of Electro-adhesive gripper in pick and place of flexible material. Therefore, further experiments in this research must take into consideration both pick up and release times.

Hence this was an important chapter to identify the parameters that affect the performance of an Electro-adhesive gripper in handling flexible material and form the ideology for further experimentation to find the optimal solution for Electro-adhesive gripper in providing R2 result

5. EXPERIMENTAL METHOD

5.1. Introduction

This section consists of the experimentation performed to test the theory about the various configurations/ parameters that can be used in an Electro-adhesive gripper, to check their influence on the performance of the Electro-adhesive gripper in flexible material handling. Here, we present the experiment methodology of varying one parameter at time while keeping others constant, for deep comparative study between different materials that can be used to form the component of the gripper. We also present an efficiency equation that can be used to analyse the results of these exhaustive experiments. This equation was especially devised for this research, although it can be extended to analyse results of any similar experimental setup. Lastly, we present a result analysis of efficiencies achieved to derive the best configuration of Electro-adhesive gripper that be used in a pick place application of a wide range of flexible materials and provide R2 results.

This answers the research question RQ3: ***What are the components that make the novel gripping solution that can be deployed in a pick and place application of commonly used materials?***

5.2. Theory

5.2.1 Experiment setup ideology

For successful pick up and release of polymeric material such as gloves on a production line that is running continuously every day, the employed gripping solution must provide repeatable and reliable (R2) gripping results so that the efficiency of the line is not compromised. Therefore, an optimal gripping solution is needed, which is the aim of this research (section 1.4). To reach such an optimal solution, experiments were devised such that various configurations of the electro-adhesive setup can be analysed, by changing only one parameter at a time and comparing the results. This allows for individual comparative study and a deep analysis of the impact of parameters on the performance of the electro-adhesive gripping solution. To achieve this, a parameter table was devised, that lists all the parameters that will be studied (such as base material, substrate, electrodes, power supply and dielectric along with their inter-dependence on each other) and an efficiency equation that can be used to calculate the efficiency of the devised configuration (as listed in the below chapter).

5.2.2 Efficiency equation

In order to assess the outcome of an experiment and perform comparative study of various configurations of the Electro-Adhesive gripper, there is a need to create some means of measuring the performance of the gripping solution in effective pick up and release of the substrate. This section presents a simplistic equation that can be used as a tool for analysis of desired outcome, thereby reflecting the performance of any gripping solution in providing repeatable and reliable results. Using this equation, experimental results can be evaluated and analysed for a complete cycle of pickup and release of various substrates. Therefore, it represents a criterion for determining the success of the experiment that has been devised for a particular configuration of parameters used to pick up and release a particular substrate.

Parameter (K) that defines an effective gripping solution.

R2 can be defined as achieving consistent results (that is desired outcome is achieved) for every cycle of pick up and release. Thus, the R2 needs to be analysed in terms of efficiency of the gripping solution in providing consistent results. A measure to calculate efficiency is needed to judge the effectiveness of the gripper on a production line scale. Therefore, we define efficiency as the ratio of number of successful pick-up and release cycles /trials to the total number of cycles/trials performed. Higher the efficiency (ŋ), higher is the ability to achieve R2 results.

$$ŋ = \frac{number\ of\ trials\ with\ desired\ outcome}{total\ number\ of\ trials} * 100$$

ix. Efficiency equation

This universal equation was devised before the conduction of experiments and can be used to analyse not only electro-adhesive griping solution, but any gripping solution is used to provide R2 results. In this case, to analyse ŋ, first desired outcome (successful pick and release) needs to be defined. Since the focus is on analysing an effective gripping solution for pick and release cycle, in order to achieve R2, a successful outcome depends on the following relationship:

$$Desired\ outcome \propto \frac{assured\ pick\ up * assured\ release}{(Time\ to\ pick\ up) * (Time\ to\ release)}$$

x. Desired outcome equation

Thus, we define parameter for desired outcome

$$K = (P * R)/(T_P * T_R)$$

Where,

P = {0,1} 0 = Substrate not picked up

1 = Substrate picked up

R = {0,1} 0 = Substrate not released

1 = Substrate released

T_P = Time to pickup

T_R = Time to release

xi. Parameter for desired outcome

By calculating the values of above variables in each conducted experiment, the desired outcome (K) can be calculated and thereby analysis on efficiency can be performed. Thus, this equation can be used to analyse and compare experiments involved in this application for electro-adhesive gripping solutions used for pick up and release of various substrates.

From the above equation, it can be seen that in order to achieve a desired outcome, P and R must have a value 1. This means that in a cycle, if the substrate is not picked up, P = 0 and therefore desired outcome K = 0. Same case exists for release cycle (R is 0 if P is 0).

If the P or R is 0, then we deem the experiment result as not applicable, since the numerator of the equation becomes zero, thereby giving zero efficiency. The legend used to denote this in the experiments is as follows:

Key

(green)	Repeatable
(red)	Not Repeatable
(grey)	Not Applicable

Also, for maximum K, T_P and T_R value must be as small as possible (instantaneous pick and release). T_P and T_R are parameters which needs to be defined by the user and can vary depending upon the automation cycle or the application where automation is used. For analysis of the electro-adhesive gripper used in this study, it has been agreed for T_P and T_R to have a minimum value of 1 (anything below 1 is rounded off to 1 due to measurement constrains and inefficiencies in the setup, (≥ 1sec = rapid release)). In this research, above equation has been used to analyse the output of the Electro-adhesive gripper in multiple configurations as per the parameter table (section 5.2.3), by varying one parameter at a time. The above presented method is only valid if all materials under investigation are under same number of trials. This allows for comparative study of the parameters using the efficiency equation as the deciding factor. This therefore helps in achieving a gripping solution with optimum R2 results.

An example of the study conducted was presented ((Singh, Jacques Penders, & Manby, 2016) as below

	Glass		Nitrile		HDPE		Polycarbonate	
Voltage (V)	D	B	D	B	D	B	D	B
500	0	0	0	0	0	0	0	0
1000	0	1	1	0	0	0	0	0
1500	0	1	0.5	0	0	1	0	0
2000	0	1	0.5	1	0	1	0	1
2500	1	1	0.2	1	0	1	0	1
3000	1	1	0.125	1	0	1	1	1
Overall desired outcome	2	5	2.325	3	0	4	1	3

Table 5-1 Desire outcome (K) calculation (Singh, Jacques Penders, & Manby, 2016)

The above table show promising results for the B electrodes with usage of K (parameter for desired outcome). All the substrates were released instantaneously, and the pick-up voltages were also reduced (with nitrile glove as exception). HDPE was of particular interest, since it was not picked at all by the D electrode whereas the B electrode was successfully able to pick and release it. This proves that even though there is storage of charge, enough force is not generated to pick HDPE, therefore force calculations alone cannot be used to determine the performance of an EAG.

The desired outcome as calculated above is demonstrated above as a method of identifying the performance of an EAG. It gives user the flexibility of defining the Tp and Tr based on requirement of the industry where the EAG is to be used.

5.2.3 Parameter table comprising of experimental conditions

As listed in the theory section (section 4.2), there are various parameters that affect the electro-adhesive property of the gripper. The aim of the experimentation is to vary one parameter at a time, while keeping the others constant, in order to perform comparative study and analysis of how the parameters affect the performance of the gripping solution. This method of changing one parameter at a time allows for controlled experimentation and ease of drawing conclusion about the effects of that particular parameter being varied. This helps in a comprehensive parameter study. Once the parameter has been proven to agree with the theory of why it was chosen, it is kept constant for the next set of experiments and a different parameter is then varied, while keeping all others constant. This will help in reaching an optimal solution for the pick and place of flexible materials such as the following substrates:

1. Nitrile
    a. gloves
    b. Small sheet of Nitrile
    c. Large sheet of Nitrile
2. Glass
    a. Composite glass
    b. Pure glass/ gorilla glass
3. Polypropylene
4. HDPE
5. Polycarbonate

Below is a table that lists the different experiments and components that make up the parameters that influence electro-adhesion:

		Components			
Experiments		Base Material	Dielectric	Electrodes	Power Supply
	Base Material	Varying	BT2	Interdigitated	DC
	Dielectric	Nylon	Varying	Interdigitated	DC
	Electrodes	Nylon	BT2	Varying	DC
	Power Supply	Nylon	BT2	Interdigitated	Varing

Table 5-2 Parameter list

How to read this table: For example, the first set of experiments are done keeping following parameters constant: Dielectric constant to Barium Titanate coating 2, electrodes constant to Interdigitated type, Power supply to DC supply and vary the different types of Base materials such as Nylon, Polycarbonate, Plywood and Polystyrene. This allows us to study the effects that different types of base materials can have on gripping efficiency of the Electro-adhesive gripper in pick and place of above mentioned substrates (experiments are performed for all substrates mentioned). The number of trials for each material conducted is 4 except for Power supply where the number of trials were only 2 due to limited resources

5.3. Construction

5.3.1. Safety precautions and Faraday's cage

Faraday Cage was used to isolate the entire robotic setup and protect the user from electrocution. This prevents breakdown of electrodes due to reasons mentioned in theory section. A wooden structure surrounded by aluminium mesh was made. All the sides of the structure are electrically connected to one another, thereby enclosing the entire setup that does not allow any charge to escape. The aluminium mesh is then finally grounded for any undue charges to escape to the earth, thereby protecting the entire setup. In this setup, it is important that the aluminium mesh is grounded, as it can potentially become a high charge capacitor, which can be dangerous if left ungrounded due to high charge storage producing effects such as arching and creating sparks which may further lead to fire. Therefore, it is important to ground the cage properly and have complete connectivity between all sides.

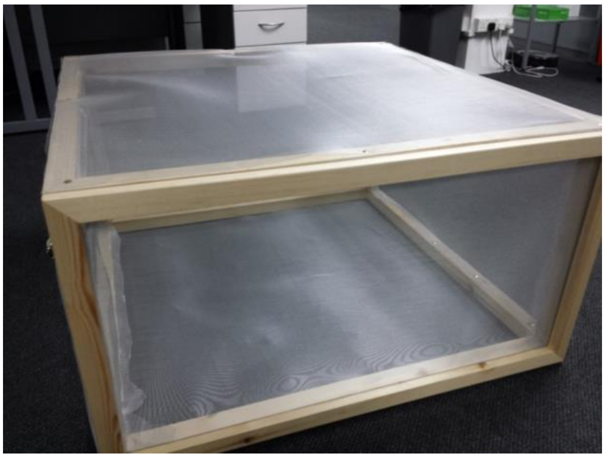


Figure 5-3 Faraday's cage

Special earth plugs were used to ensure safe connection to ground as shown below.

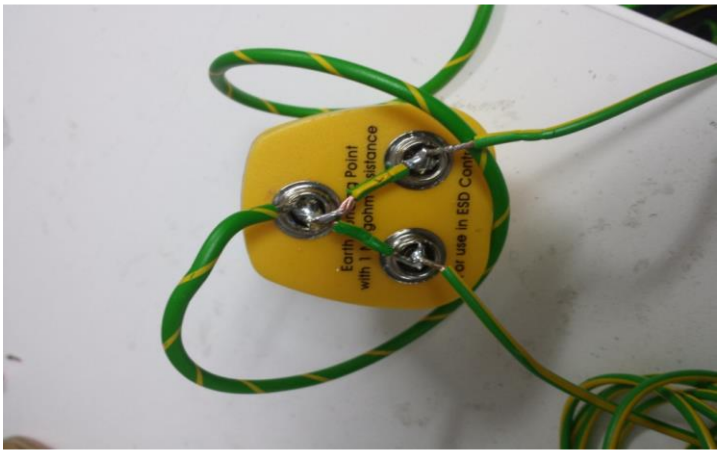


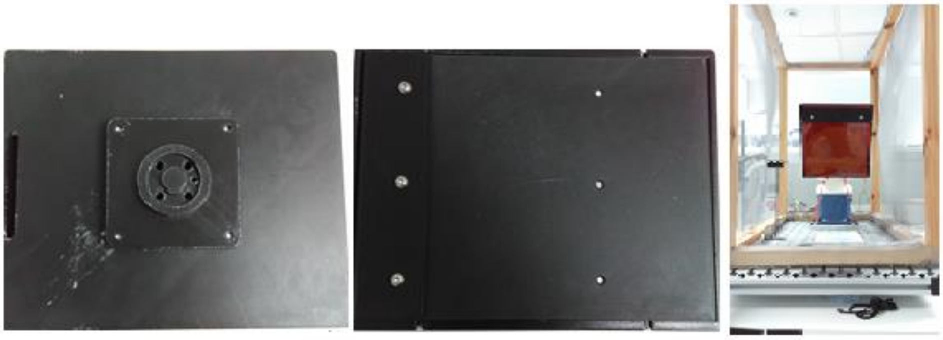
Figure 5-4 Anti-Static ESD No shock Grounding UK Plug

All the equipment was PAT tested by the experienced university technical staff for extra safety and proper risk assessment (form in appendix) was done under technical supervision.

Figure 5-5 PAT Testing equipment

5.3.2 Denso setup

For the robotic arm, a Denso robot was used. Below figures represent the denso setup. [A] shows the top view of the gripper that connects to the denso robotic arm. [B] represents the bottom of the gripper, where the electroadhesive pads are placed. [C] represents the complete robotic setup placed in the Farraday’s cage with the electroadhesive pads mounted on the robotic arm.



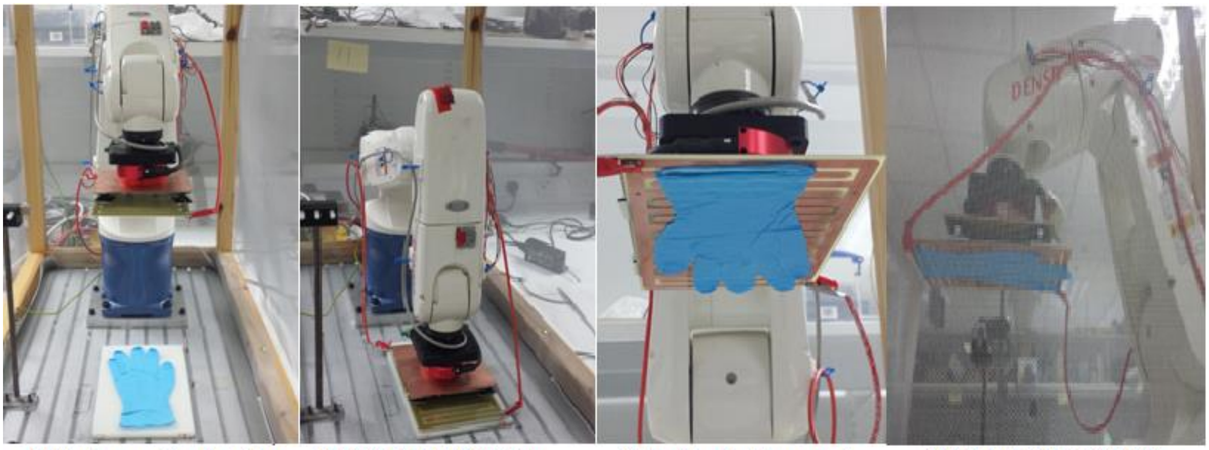
A. Top view of gripper holder

B. Bottom view of gripper holder

C. Gripper holder with sample mounted on the DENSO robot

Figure 5-6 Denso Robot Setup

Following figure represents a complete cycle of operation of pick and place of the substrate (nitrile glove) by the Robotic arm. This shows the robotic arm in action.



A) Starting position A of the robot to approach the substrate

B) Position B of Robot to make contact and pick up the susbtrate

C) Position C of the robot to release the susbtrate

D) Image from outside the faraday cage: robot holding the substrate

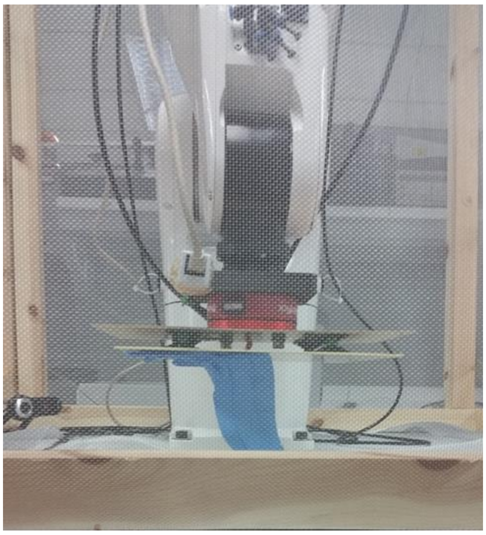


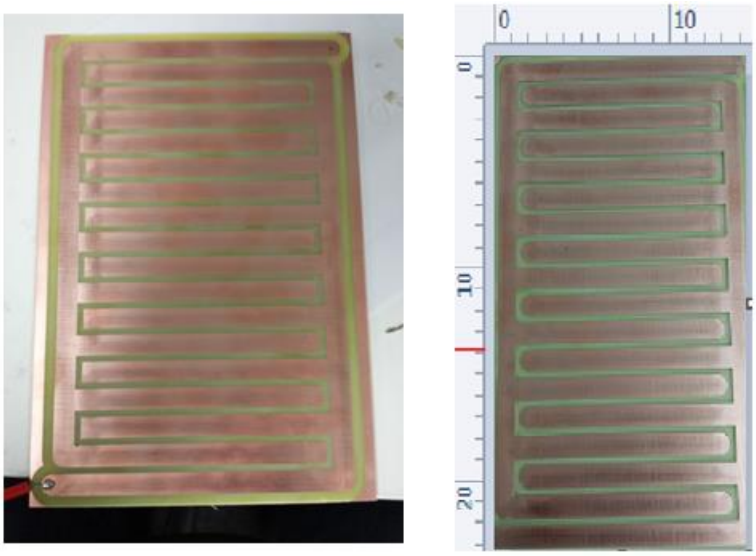
Figure 5-7 Different Working positions of Denso Robot

5.3.3 Construction of individual components

Individual components were specifically designed for the experimentation in this research. The construction of individual components is listed below.

Electrodes construction

From theory, Copper electrodes in an interdigitated configuration were selected as the best component for electroadhesive pads in this research. For the first prototype experiments, Copper electrodes were be used and were prepared by using PCB milling process (standard laboratory procedure). As per the dimensions of the substrates, 26x16 cm electrodes with a gap of 3mm between them were created, that were considered sufficient to pick up all the substrates used in the experiments.



Bare electrodes   Size dimensions of electrodes

Figure 5-8 Copper Electrodes (prepared by Milling process)

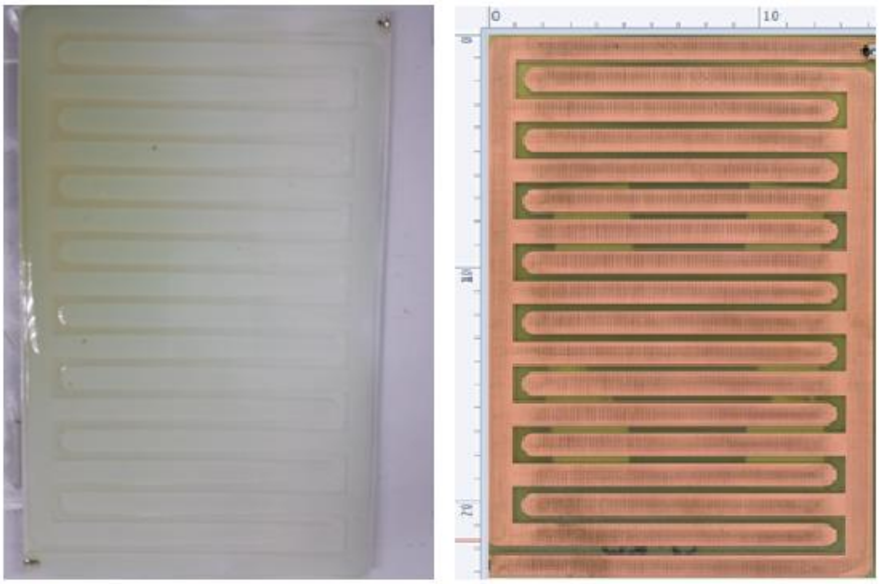
As can be seen in the figure above, two opposite points of contact were made on the electrodes, where the power supply lines were connected.

Dielectrics placement on the electrodes to create the electroadhesive pad

Polyimide sheet was placed on top of the electrode, to cover the surface completely. Adhesive glue was used on the edges to fix the sheet firmly on the electrodes, as shown in the figure below.

Figure 5-9 Polyimide based Electro-adhesive gripper

For experiments conducted using Polyurethane as a dielectric, polyurethane was sourced as a sealant (Electrolube, Electrolube Polyurethane, 2019) which was then sprayed on the bare electrodes, thereby forming an even coating on them, as shown in the figure below. Here, there was no need of any additional adhesive material, since the spraying method ensured that the sealant is converted to a foam that can be easily used to cover the electrode surface.



Polyurethane spray over electrodes

Size dimenstions of dried Polyurethane dielectric over electrodes

Figure 5-10 Polyurethane based Electro-adhesive gripper

For experiments related to Barium titanate acting as the dielectric component of the electroadhesive pad, coating method was used.

Pure Barium titanate comes in the form of powder which makes it difficult to be used as a dielectric layer on the Electro-adhesive gripper pad. It was decided to mix Barium powder with paint and water to make it viscous enough to be coated using a spray gun.

BT mixture comprises of three main parts which include paint, water and Barium titanate

Barium Titanate
Sourced from: Fisher Scientific (ACROS Organics)

Name of product: **Barium titanate(IV), 99%, ACROS Organics™** (Scientific, 2019)

Paint
Sourced from: Wilko

Name of product: Dulux primer and Undercoat

Different ratios of the material were tried for testing using the standard at SHU for good pickup and release times. Different ratios tried are mentioned below

BT Mixture: Three different ratios of BT mixtures have been prepared

- BT mixture 1 (1 part of BT in solution)
- BT mixture 2 (2 parts of BT in solution)
- BT mixture 3 (3 parts of BT in solution)

Pure Barium titanate comes in the form of powder which makes it difficult to be used as a dielectric layer on the Electro-adhesive gripper pad. It was decided to mix Barium powder with paint and water to make it viscous enough to be coated using a spray gun. Different ratios of the material were tried for testing using the standard at SHU for good pickup and release times. It was decided that certain ratios of barium titanate mixed with paint and water only work, as below:

	BT 1 mixture	**BT 2 mixture**	**BT 3 mixture**
Mass of total solution (gm)	283.1	346.7	410.3
Mass of paint + BT (gm)	86.2 + 63.6	86.2 + 127.2	86.2 + 190.8
Mass of water (gm)	133.3	133.3	133.3

Table 5-11: Different Experimental configuration of BT 2 mixture material

Steps followed in preparation of BT mixture

1. A weighing scale from RS components was used with a resolution of 0.001 was used to efficiently measure the weight of the mixture while being prepared
2. Firstly, paint was poured in the container and then slowly water was added in the paint with slow steering, diluting the paint
3. BT being in powdered form was mixed in the last to the solution with slow steering to the mixture. BT was added depending upon the ratio being prepared. Due to the small particle size of BT (0.03% Max. (+325 Mesh), 0.85 to 1.45 Micron (Horiba, D50), BT was thoroughly mixed giving it a uniform suspension in the mixture

It was confirmed using a microscope that BT is suspended uniformly in the solution making it a potential part of the mixture with high dielectric strength.

It was found that during the steering process a lot of bubbles were formed in the container. It was necessary to degas the container for reducing of bubbles before any coating can be applied onto the pad/Electro-adhesive gripper otherwise the bubbles can make a major impact on the performance of the coating (bubbles have a tendency to conduct causing damage to the pad)

Spraying: An airgun from RM Tools was used to coat the pads with the desired mixture.

Unsuccessful coating attempts before spraying

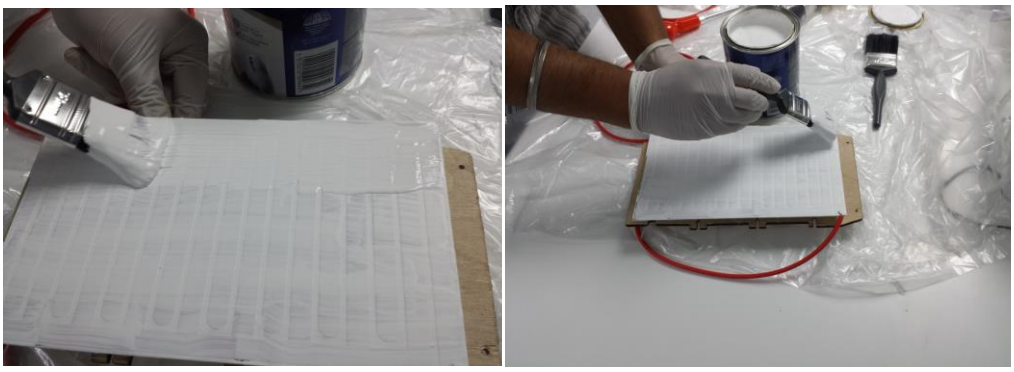


Figure 5-12 Coating attempts before spraying

Spraying was the method which provided uniform coating of the BT mixture. An image from the microscope in figure 5.7 confirm the coating to be uniform.

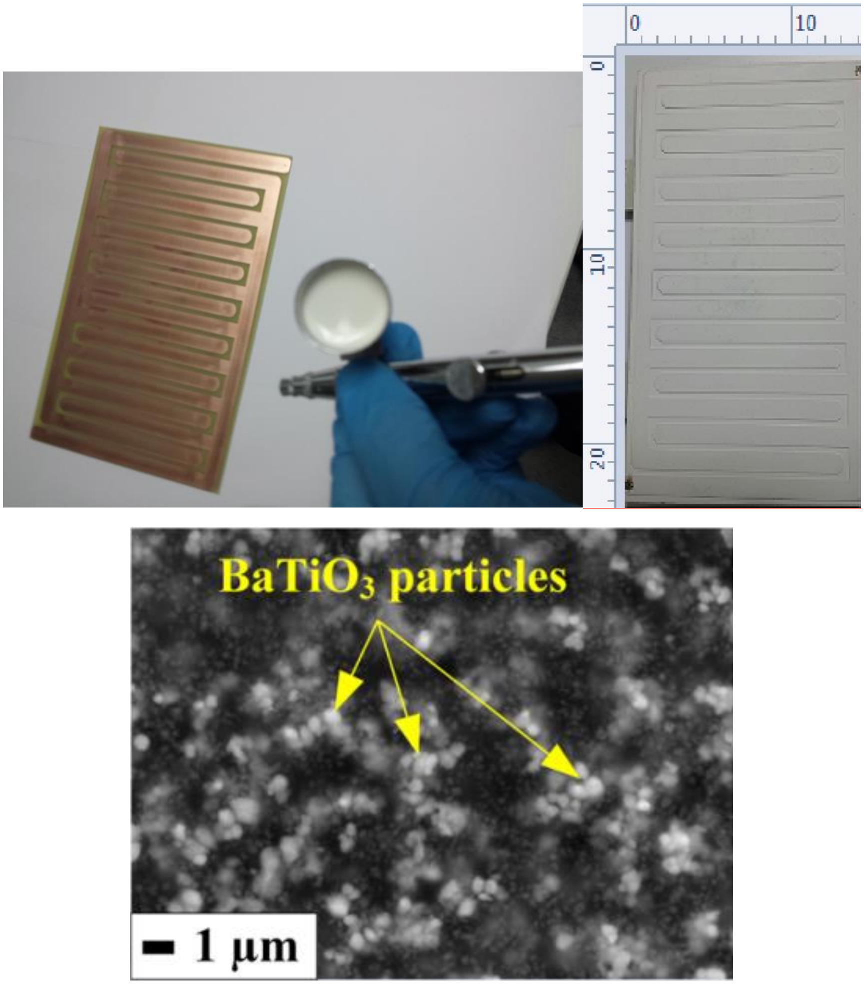


Figure 5-13 Spraying method of uniform coating

Base materials chosen for the experiments

Following figures depict the base materials used for experimentation. These were sourced and used in original form, with no alterations needed to the component. The aim was to source the right size, that is big enough to hold all the substrates.

Figure 5-14 Different base materials used in experimentation

Construction of the power supply

In power supply experiments, three configurations were needed to supply voltage; DC supply that can be switched on and off, DC supply for pick up and AC supply for release and AC supply only for pick and release.

For this, an AC-DC switching circuit was prepared. Following is the circuit diagram for the switching circuit

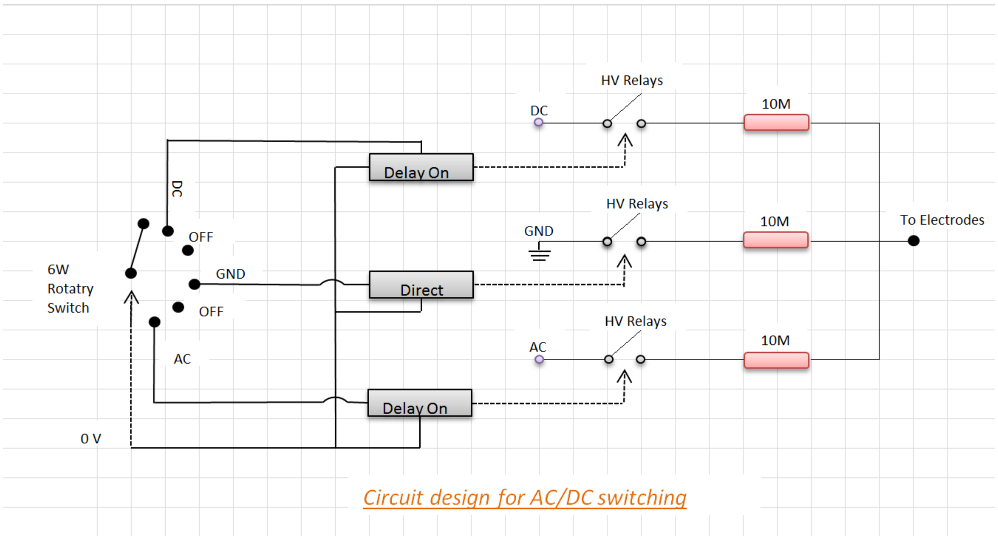
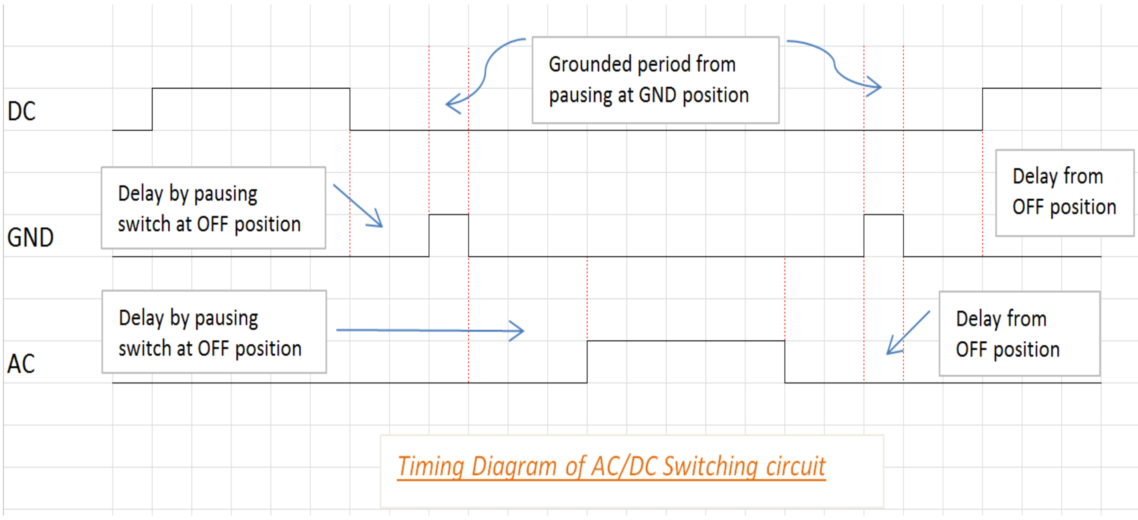


Figure 5-15 Concept Circuit Design for AC/DC Switching



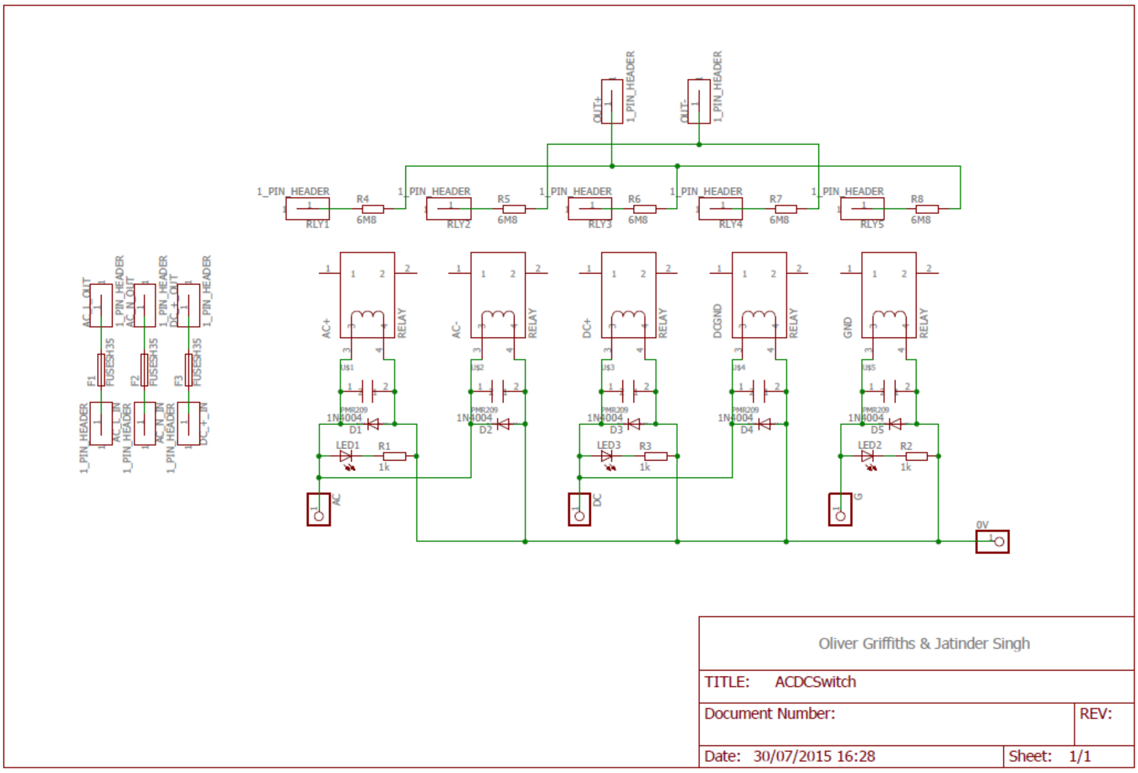
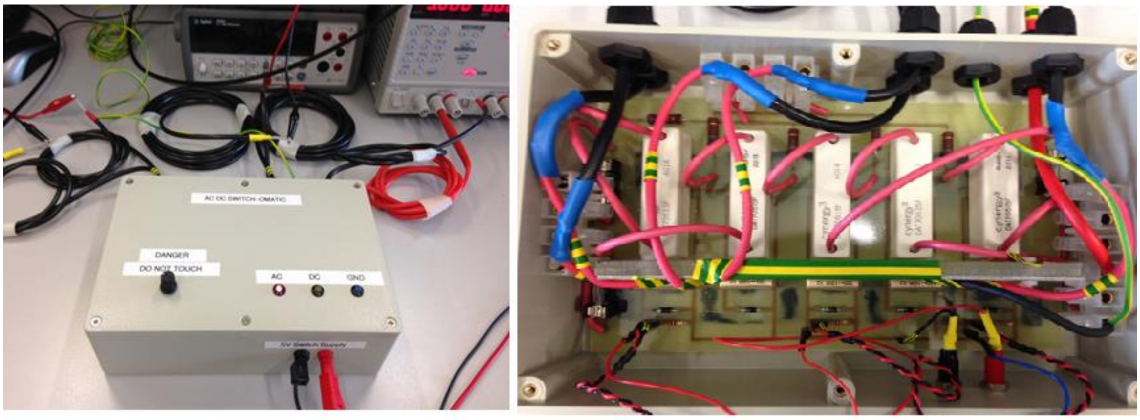


Figure 5-26 Switching and Timing Diagram for DC/AC Switching

Power supply switching circuit was constructed in the lab using the above circuit diagram. Following figures represent the final constructed circuit that was used for experimentation.



Switching circuit box **Switching circuit internal view**

Figure 5-17 Final Power Supply box

The switching circuit was used to switch the power supply from DC-AC as needed by the experiments. It was a single button used to switch between DC-GND-AC supply. There were LEDs displayed highlighted the particular supply turned ON at a particular time. This was connected to the main power supply, as below

Figure 5-18 DC and AC power supply

6. EXPERIMENTS AND RESULTS

6.1 Introduction

Preliminary Experiment results Standard deviation

A set of preliminary experiments were performed to establish the basics of electro-adhesion with respect to release time. An example of standard deviation experiments for base materials which consisted of 10 trials at 1700V is presented below

Material	Release time per trial (s)										Standard Deviation
ABS	9	8	8	8	7	7	6	5	7	7	1.077
Nylon	16	17	16	15	15	15	15	13	15	13	1.183
Polycarbonate	18	16	16	18	10	16	14	8	44	251	70.58392

Table 6-1Base materials results from different trials

Standard deviation is not an effective method of analysis of the results in this set of experiments presented above as assured pick up and assured release time is necessary to establish Standard deviation. Assured pick up can vary depending upon various parameters ie different substrates can be picked up at different voltages. Also, for experiments where the time to pick and release is less than one second, there may be human error involved in recording the exact time (up to a resolution in msec). For such experiments it was considered to take rounded value 1sec. Therefore, requirement for a new way of analysis, that can effectively provide a means to measure the desired outcome (assured pick up and release) and suggest repeatability and reliability was realised. This has been previously explored in chapter 5, where the efficiency equation presents a better method to evaluate experiments of R2 and was then used in results analysis in further chapter 6.6.

Experiments have been devised as per the parameter table described in section 5.2.3. The main aim is to study different parameters and to identify key parameters making an impact in the performance of Electro-adhesive gripper for pick and place of elastomers.

Only one parameter was varied at one time and rest of the parameters were kept constant. Selection of the key parameter is based on the research presented in the theory sections.

The experimental parameter was considered one at a time and only one column in the table above (number the table) was varied keeping other parameters constant. After completion of one set of experiments for each column the best performing material/configuration was selected for the gripper and the next column was then studied keeping rest of the parameters constant. Experiments were repeated for checking R2 results as per the efficiency equation mentioned in the section 5.2.2.

The substrates list for all experiments is constant as follows:

1. Nitrile
    a. gloves
    b. Small sheet of Nitrile
    c. Large sheet of Nitrile
2. Glass
    a. composite
    b. Pure glass
3. Polypropylene
4. HDPE
5. Polycarbonate

6.2 Experiments performed for Electrode analysis

In the theory, although there were different electrode structures identified for electro-adhesive grippers, two main electrode structures were identified: Concentric electrodes and interdigitated electrodes. These are shown as below in figure 6.1:

Interdigitated Structure of Electrodes

Concentric structure of Electrodes

Figure 6-2 Interdigitated and Concentric Electrodes Structure

These two electrodes were chosen as the correct structure for Electro-adhesive gripper. Hence experiments were devised to check their performance which will in turn help to choose the more appropriate configuration of electrodes for this application of material handling.

The table of parameters is as follows:

Electrodes	Dielectric	Base material	Power Supply
Concentric	Polyimide	Nylon	DC
Interdigitated	Barium Titanate Coating 1	Polycarbonate	AC
	Barium Titanate Coating 2	Plywood	
	Barium Titanate Coating 3	Polystyrene	
	Polyurethane		
	No Dielectric (bare electrodes)		

Constant
Varying

Table 6-3 Electrodes parameter table

As per the experiment methodology in chapter 5, it can be seen that two configurations of electrodes were used for the experiments (one at a time). This was to ensure that a comparative study is done and then the best electrode for further experiments is chosen. These are the varying parameters (yellow) in the experiments as shown above in table 6.2. Other parameters such as dielectric, base material and power supply (in orange) were kept constant as indicated in the table 6.2 above. Since this was the first set of experiments and the dielectric was not confirmed at this stage, 2 dielectrics: BT2 and Polyimide were used in the experiments (one at a time).

The results for comparative study of dielectrics and electrodes were as follows:

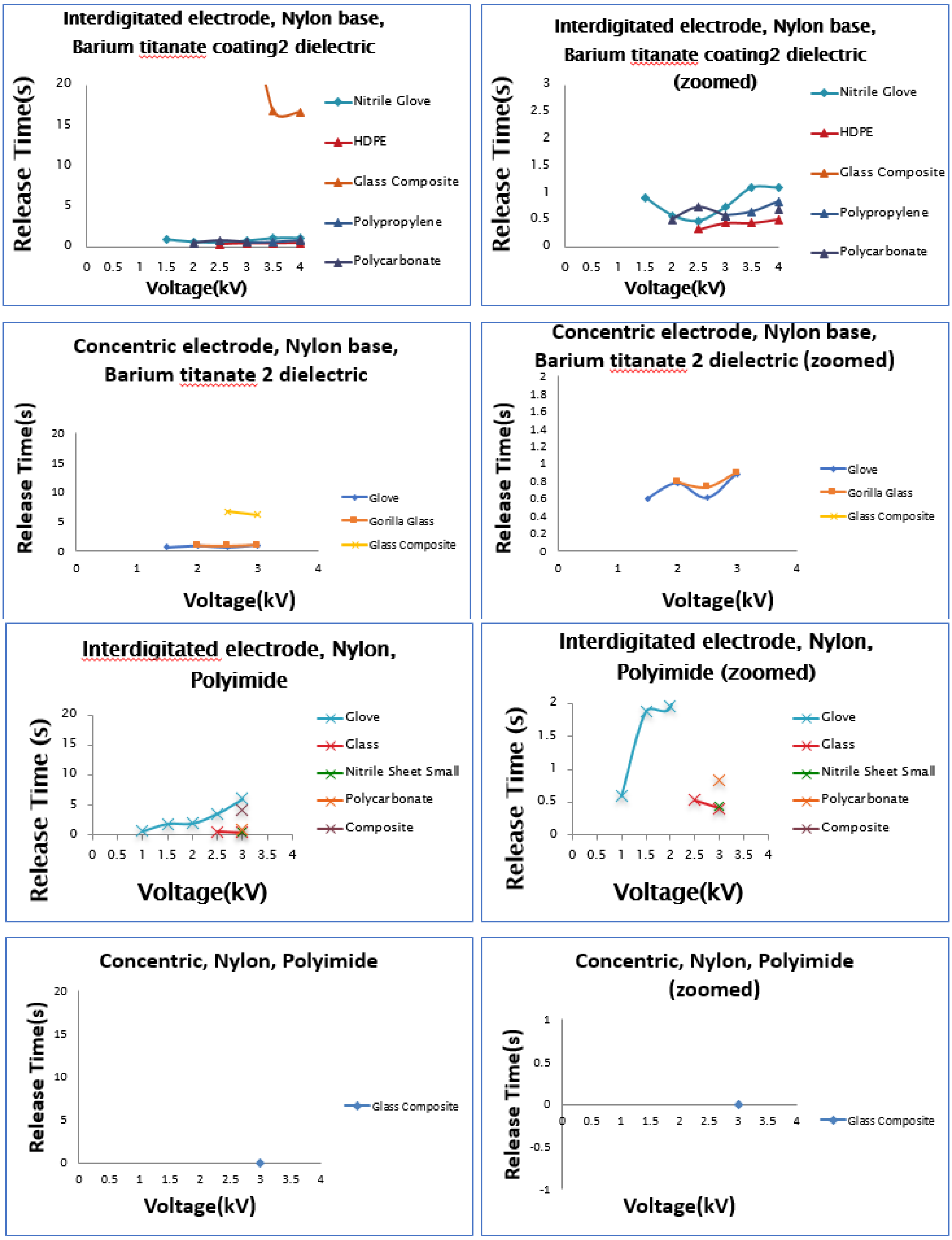


Figure 6-4 Results from electrodes experiments

Here it can be seen that not all substrates are picked up in every experiment. For example, in the experiments for concentric electrodes with Nylon base and Polyimide dielectric, only glass composite substrate is picked up. Also, it can be seen that in the above graphs, y axis is release time only. This assumes that the pickup was instantaneous and therefore only the release time needs to be measured. In Electro-adhesive gripper experiments, pick up is instantaneous, if it takes place at all, thus it is important to measure only the release time for R2 results.

R2 experiments:

Above experiments were repeated for R2 results and analysed using the efficiency equation. In the R2 experiments, Barium titanate coating 2 (BT2) was used as the dielectric, since this provided better results as can be seen in the above graphs (more flexible materials were picked up in case of BT2 coating). These were done in 4 sets: E1, E2, E3 and E4 as below:

Electrode	**Substrate**	**Results**			
		E1	**E2**	**E3**	**E4**
Concentric	Nitrile glove	Repeatable	Repeatable	Not Repeatable	Not Repeatable
	Nitrile sheet (Large)	Not Applicable	Not Applicable	Not Applicable	Not Applicable
	Nitrile sheet (Small)	Not Applicable	Not Applicable	Not Applicable	Not Applicable
	Gorilla glass	Not Repeatable	Not Repeatable	Repeatable	Repeatable
	Polycarbonate	Not Applicable	Not Applicable	Not Applicable	Not Applicable
	HDPE	Not Applicable	Not Applicable	Not Applicable	Not Applicable
	Polypropylene	Not Applicable	Not Applicable	Not Applicable	Not Applicable
	Glass composite	Not Applicable	Repeatable	Not Repeatable	Not Repeatable
Interdigitated	Nitrile glove	Repeatable	Repeatable	Repeatable	Repeatable
	Nitrile sheet (Large)	Not Applicable	Not Applicable	Not Applicable	Not Applicable
	Nitrile sheet (Small)	Not Applicable	Not Applicable	Not Applicable	Not Applicable
	Gorilla glass	Repeatable	Repeatable	Repeatable	Repeatable
	Polycarbonate	Repeatable	Repeatable	Repeatable	Repeatable
	HDPE	Repeatable	Repeatable	Repeatable	Repeatable
	Polypropylene	Repeatable	Repeatable	Repeatable	Not Repeatable
	Glass composite	Repeatable	Repeatable	Repeatable	Not Repeatable

Table 6-5 Electrodes R2 Results table

Key

(green)	Repeatable
(red)	Not Repeatable
(grey)	Not Applicable

From the R2 experiments conducted for electrodes, it can be seen in table 6.3 that Concentric electrodes are able to pick up only Nitrile gloves for half of the experiments performed (E1 and E2 show repeatable results for nitrile gloves whereas E3 and E4 results were not repeatable). For all other substrates, Concentric electrodes were not able to pick up the substrate, thereby making the experiments not applicable.

6.3 Experiments performed for Dielectric Analysis

In the theory, it was discussed that Electro-adhesive gripper works as a parallel plate capacitor, where dielectric plays an important role in charge accumulation which is in turn responsible for effective pick up of substrate. However, for R2 results, this is a trade-off between efficient pick up and release. If the charges are not settled in time, then the release is not instant and in a quick repetitive and continuous cycle, it can be a disadvantage to have too much charge accumulation. Below experiments were devised to check which configuration can provide the best outcome for this trade off.

The dielectric parameter table is as follows:

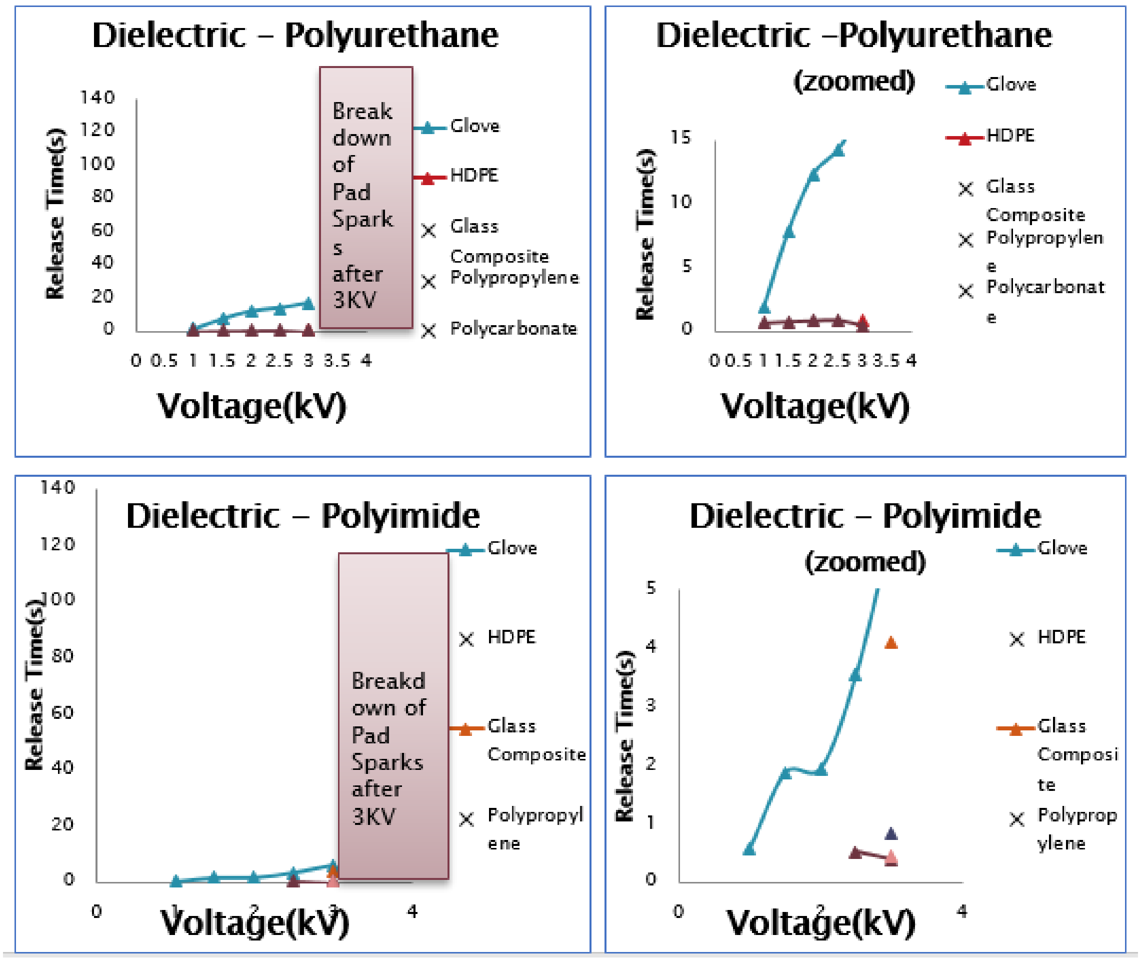
Electrodes	Dielectric	Base material	Power Supply
Concentric	Polyimide	Nylon	DC
Interdigitated	Barium Titanate Coating 1	Polycarbonate	AC
	Barium Titanate Coating 2	Plywood	
	Barium Titanate Coating 3		
	Polyurethane	Polystyrene	
	No Dielectric (bare electrodes)		

(orange)	Constant
(yellow)	Varying

Table 6-6 Dielectric Parameter table

The Dielectrics are the varying parameters (yellow) in these set of experiments. These were varied one at a time in the conducted experiments. Other parameters such as electrodes, base material and power supply (in orange) were kept constant as indicated in the table 6.4 above.

From the first experiments that were performed, following were the results:



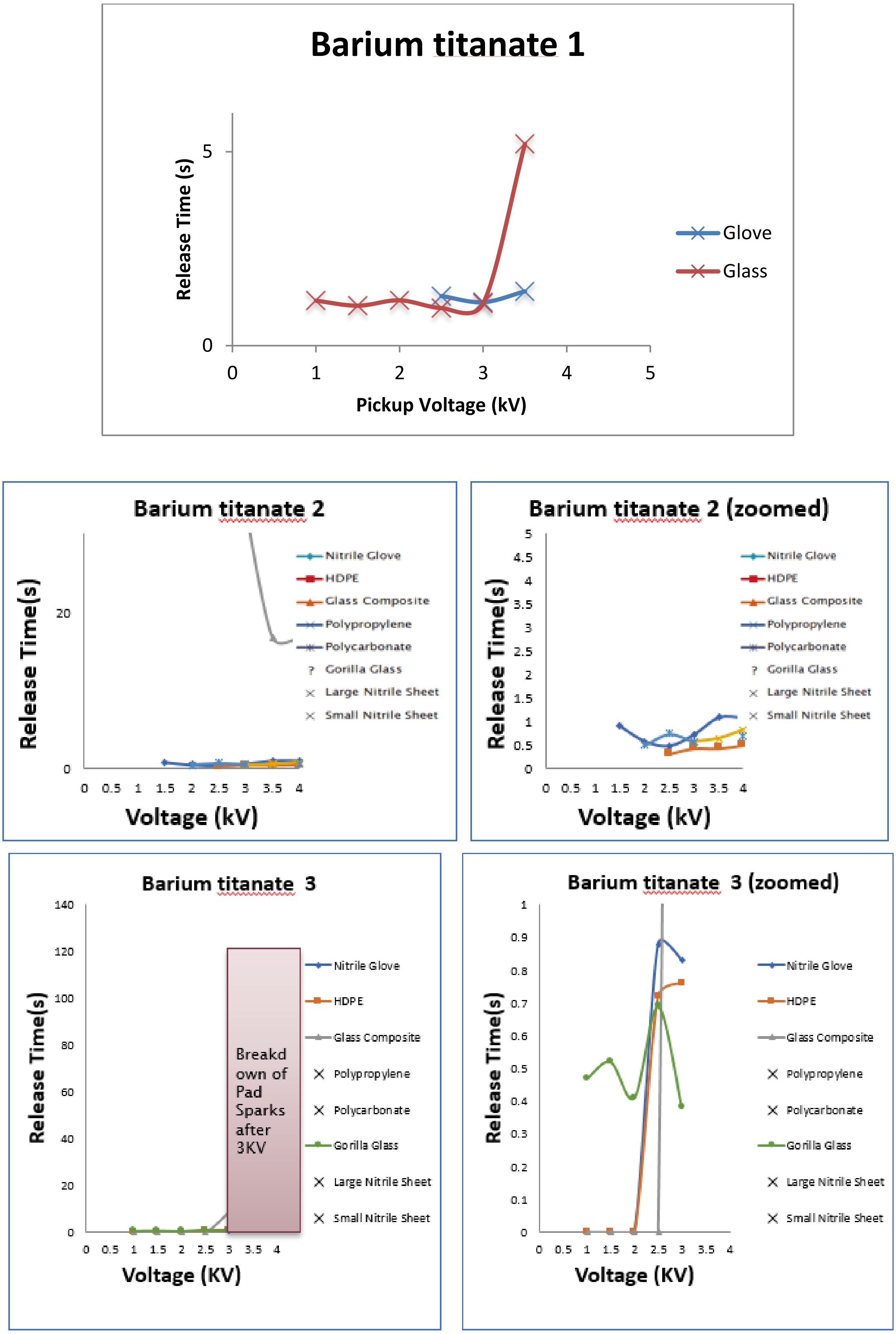


Figure 6-7 Result from dielectric materials experiments

Here, it can be seen in the above figure 6.2, dielectrics such as Polyimide, Polyurethane and BT3 were unable to withstand the high voltages of electro-adhesion experiments and therefore resulted in breakdown of electrode pads (thereby making the pads conductive and no longer safe for further use). BT1 and BT2 did not breakdown, however BT2 was able to pick up a larger number of substrates than BT1.

R2 experiments:

Above experiments were repeated for R2 results and analysed using the efficiency equation. These were done in 4 sets: D1, D2, D3 and D4 as below:

Dielectric	**Substrate**	**Results**			
		D1	**D2**	**D3**	**D4**
Polyimide	Nitrile glove				
	Nitrile sheet (Large)				
	Nitrile sheet (Small)				
	Gorilla glass				
	Polycarbonate				
	HDPE				
	Polypropelene				
	Glass composite				
Polyurethane	Nitrile glove				
	Nitrile sheet (Large)				
	Nitrile sheet (Small)				
	Gorilla glass				
	Polycarbonate				
	HDPE				
	Polypropelene				
	Glass composite				
BT1	Nitrile glove				
	Nitrile sheet (Large)				
	Nitrile sheet (Small)				
	Gorilla glass				
	Polycarbonate				
	HDPE				
	Polypropelene				
	Glass composite				
BT2	Nitrile glove				
	Nitrile sheet (Large)				
	Nitrile sheet (Small)				

	Gorilla glass	[green]	[green]	[green]	[green]
	Polycarbonate	[green]	[green]	[green]	[green]
	HDPE	[green]	[green]	[green]	[green]
	Polypropelene	[green]	[green]	[green]	[red]
	Glass composite	[green]	[green]	[green]	[red]
BT3	Nitrile glove	[grey]	[red]	[green]	[green]
	Nitrile sheet (Large)	[grey]	[grey]	[grey]	[grey]
	Nitrile sheet (Small)	[grey]	[grey]	[grey]	[grey]
	Gorilla glass	[grey]	[green]	[red]	[green]
	Polycarbonate	[grey]	[red]	[red]	[red]
	HDPE	[grey]	[green]	[red]	[red]
	Polypropelene	[grey]	[grey]	[red]	[red]
	Glass composite	[grey]	[red]	[green]	[green]

Table 6-8 Dielectric R2 Results table

Key

[green]	Repeatable
[red]	Not Repeatable
[grey]	Not Applicable

From the R2 experiments conducted on dielectrics, it can be seen in table 6.5, BT2 mixture was able to provide most repeatable and reliable results as it was able to pick up most substrates, marked as green (only nitrile sheets were not picked up). BT1 provided R2 results for only 2 sets of results for nitrile substrate, whereas for the rest, the results were not applicable (unable to pick up, as indicated by grey). BT3 was able to pick up more substrates than BT1 but most experiments did not provide R2 results (as indicated by red). Both Polyimide and Polyurethane provided inconsistent results (more red and grey than green), thereby providing less efficiency, possibly due to electrode breakdown.

6.4 Experiments performed for Base material analysis

As mentioned in the theory, base material plays an important role in the charge accumulation of the substrate. Although the base material may be viewed as something that simply holds the substrate before it is picked up by the Electro-adhesive gripper, yet, at micro level, it makes a difference to the charge orientation in the substrate and therefore influences its ability to be efficiently picked up and released.

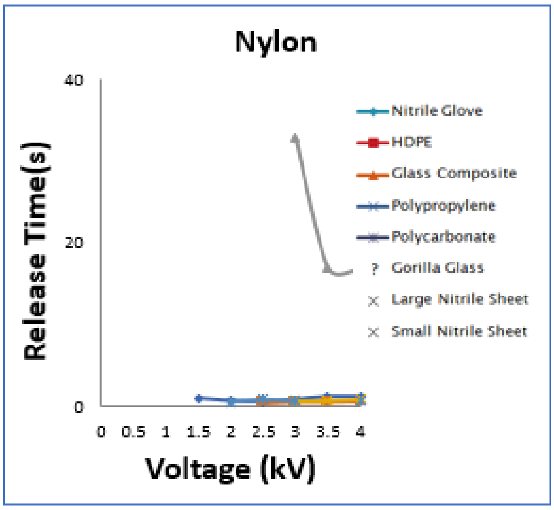
The base material parameter table is as follows:

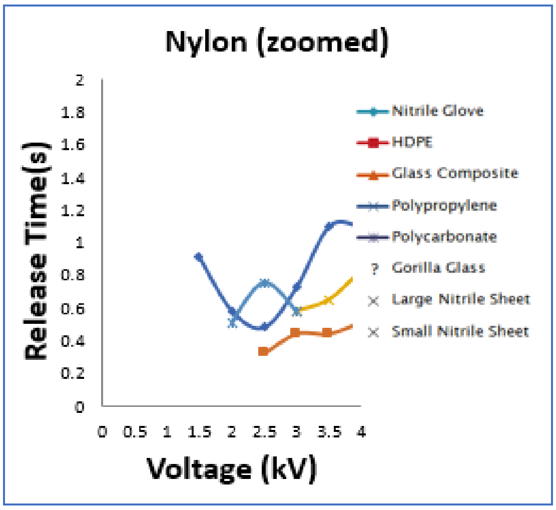
Electrodes	Dielectric	Base material	Power Supply
Concentric	Polyimide	Nylon	DC
Interdigitated	Barium Titanate Coating 1	Polycarbonate	AC
	Barium Titanate Coating 2	Plywood	
	Barium Titanate Coating 3		
	Polyurethane	Polystyrene	
	No Dielectric (bare electrodes)		

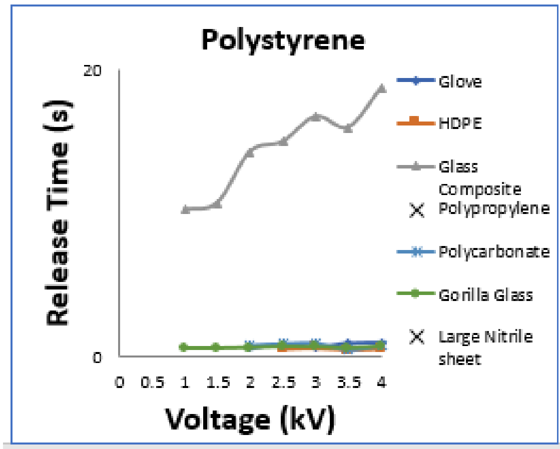
	Constant
	Varying

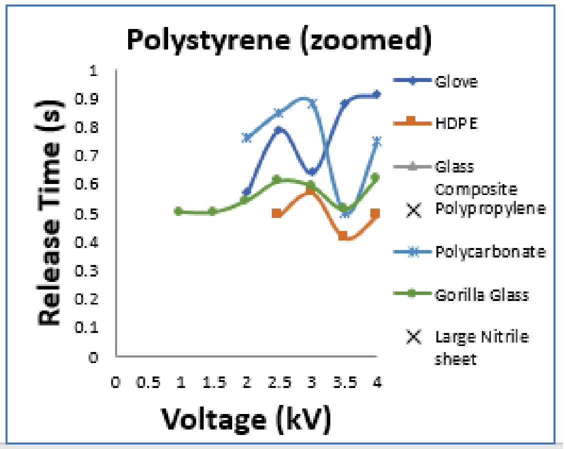
Table 6-9 Base material parameter table

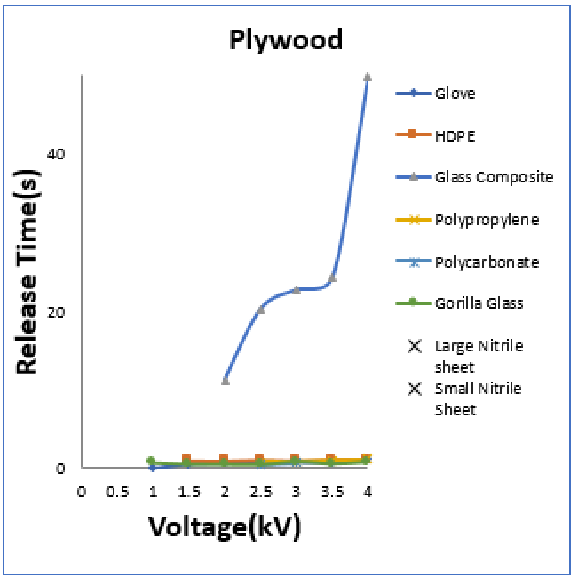
The Base material is the varying parameters (yellow) in these set of experiments. These were varied one at a time in the conducted experiments. Other parameters such as electrodes, dielectrics and power supply (in orange) were kept constant as indicated in the table 6.4 above.

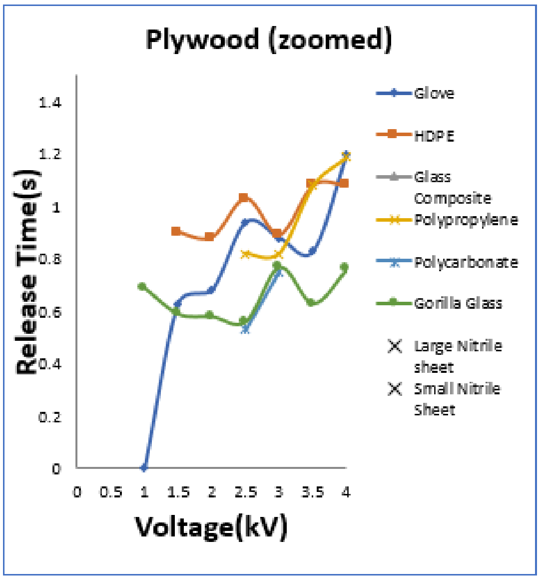

Nylon
Release Time(s)
Voltage (kV)
Nitrile Glove
HDPE
Glass Composite
Polypropylene
Polycarbonate
Gorilla Glass
Large Nitrile Sheet
Small Nitrile Sheet


Nylon (zoomed)
Release Time(s)
Voltage (kV)
Nitrile Glove
HDPE
Glass Composite
Polypropylene
Polycarbonate
Gorilla Glass
Large Nitrile Sheet
Small Nitrile Sheet


Polystyrene
Release Time (s)
Voltage (kV)
Glove
HDPE
Glass Composite
Polypropylene
Polycarbonate
Gorilla Glass
Large Nitrile sheet


Polystyrene (zoomed)
Release Time (s)
Voltage (kV)
Glove
HDPE
Glass Composite
Polypropylene
Polycarbonate
Gorilla Glass
Large Nitrile sheet


Plywood
Release Time(s)
Voltage(kV)
Glove
HDPE
Glass Composite
Polypropylene
Polycarbonate
Gorilla Glass
Large Nitrile sheet
Small Nitrile Sheet


Plywood (zoomed)
Release Time(s)
Voltage(kV)
Glove
HDPE
Glass Composite
Polypropylene
Polycarbonate
Gorilla Glass
Large Nitrile sheet
Small Nitrile Sheet

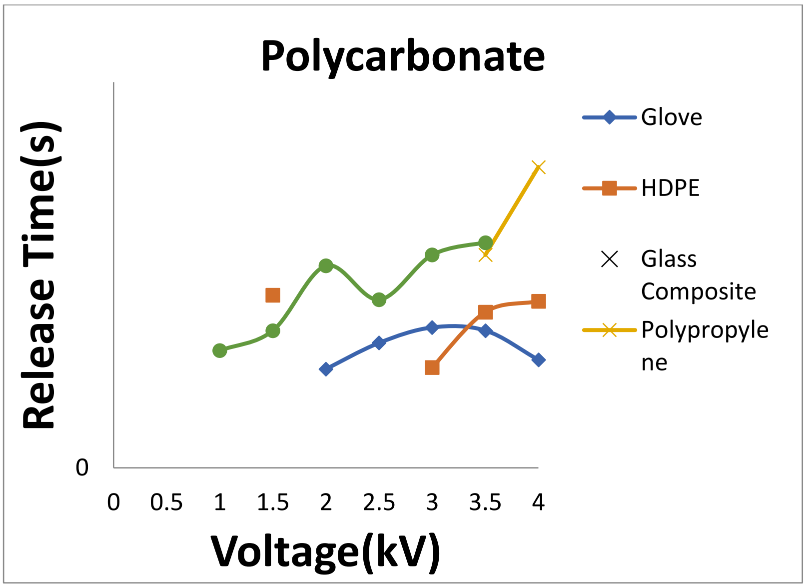


Figure 6-10 Results from Base materials experiments

R2 results:

Above experiments were repeated for R2 results and analysed using the efficiency equation. Experiments were conducted in iterations of BM1, BM2, BM3, BM4. Following was the result:

Base	**Substrate**	**Results**			
		BM1	**BM2**	**BM3**	**BM4**
Polystyrene	Nitrile glove				
	Nitrile sheet (Large)				
	Nitrile sheet (Small)				
	Gorilla glass				
	Polycarbonate				
	HDPE				
	PP				
	Glass composite				
Nylon	Nitrile glove				
	Nitrile sheet (Large)				
	Nitrile sheet (Small)				
	Gorilla glass				
	Polycarbonate				
	HDPE				
	PP				

	Glass composite	Green	Green	Green	Red
Plywood	Nitrile glove	Red	Green	Green	Red
	Nitrile sheet (Large)	Grey	Grey	Grey	Grey
	Nitrile sheet (Small)	Grey	Grey	Grey	Grey
	Gorilla glass	Green	Red	Green	Green
	Polycarbonate	Grey	Red	Red	Red
	HDPE	Grey	Red	Red	Red
	PP	Grey	Red	Red	Red
	Glass composite	Grey	Red	Red	Red
Polycarbonate	Nitrile glove	Grey	Red	Green	Green
	Nitrile sheet (Large)	Grey	Grey	Grey	Grey
	Nitrile sheet (Small)	Grey	Grey	Grey	Grey
	Gorilla glass	Grey	Green	Red	Green
	Polycarbonate	Grey	Red	Red	Red
	HDPE	Grey	Green	Green	Green
	PP	Grey	Green	Green	Green
	Glass composite	Grey	Red	Green	Green

Table 6-11 Base material R2 Results

Key

Green	Repeatable
Red	Not Repeatable
Grey	Not Applicable

From the R2 experiments conducted for base material, it can seen in the table 6.6, Nylon proved as the most successful outcome (comparatively most green results). Results achieved from Plywood were mostly non repeatable (as indicated by red cells) whereas Polycarbonate and Polystyrene were both inconsistent in providing results (more red and grey cells than green cells).

6.5 Experiments performed for Power supply

The type of power supplied to the Electro-adhesive gripper makes a difference to its ability to work as a parallel plate capacitor, thereby affecting its ability to efficiently provide R2 results in a pick-up and release cycle. As per theory, AC supply can be good for quick release of the substrate as not enough charges are allowed to accumulate in the electrodes acting as a parallel plate capacitor. However, if enough voltage is not supplied in the AC cycle, then there will not be sufficient charges generated to pick up the substrate. DC supply ensures substrate is always picked up, but it may cause too much charge accumulation, thereby making the release time longer. This forms a trade off. Therefore, type of power supply used becomes an important parameter to study in its influence on an Electro-adhesive gripper to perform its task.

The parameter table for power supply experiments is as follows:

Electrodes	Dielectric	Base material	Power Supply
Concentric	Polyimide	Nylon	DC
Interdigitated	Barium Titanate Coating 1	Polycarbonate	AC
	Barium Titanate Coating 2	Plywood	
	Barium Titanate Coating 3		
	Polyurethane	Polystyrene	
	No Dielectric (bare electrodes)		

	Constant
	Varying

Table 6-12 Power Supply parameter table

The Power supply is the varying parameters (yellow) in these set of experiments. These were varied one at a time in the conducted experiments. Other parameters such as electrodes, dielectrics and base material (in orange) were kept constant as indicated in the table 6.4 above

From the first experiments performed, following were the results:

When the experiments were conducted, it was found that using only AC power supply voltage for pick up and release cycle, no substrates were successfully picked up. This matches in line with the theory regarding AC supply not being able to provide enough charge to polarise the substrate and provide an adhesion for pick up. One of the key reasons of the result could be the frequency of the AC supply which was the limitation in this setup. Molecular polarizability is inversely proportional to the oscillating frequencies as shown in the equation below (Jackson, 1999).

$$\gamma_{mol} = \frac{1}{\varepsilon_0} \sum_j \frac{e_j^2}{m_j\, w_j^2}$$

xii Relationship of polarisation vs oscillating frequency

Where

γ is Polarizability, m_j is masses, $w_j$is oscillating frequencies (Jackson, 1999)

Therefore, the experiments were devised so that DC supply is always used in the pick-up cycle. For release, then three configurations were tested. First, AC supply was provided for the release cycle; second, complete power was switched off; third, the substrate was grounded with power switched off. Also, in the interest of time, only two substrates were tried: nitrile gloves and glass composite. This is because these two substrates are considered as the most important ones, based on previous experiments and they provide enough results to ensure that the power supply study can be completed.

Following were the results of these sets of experiments:

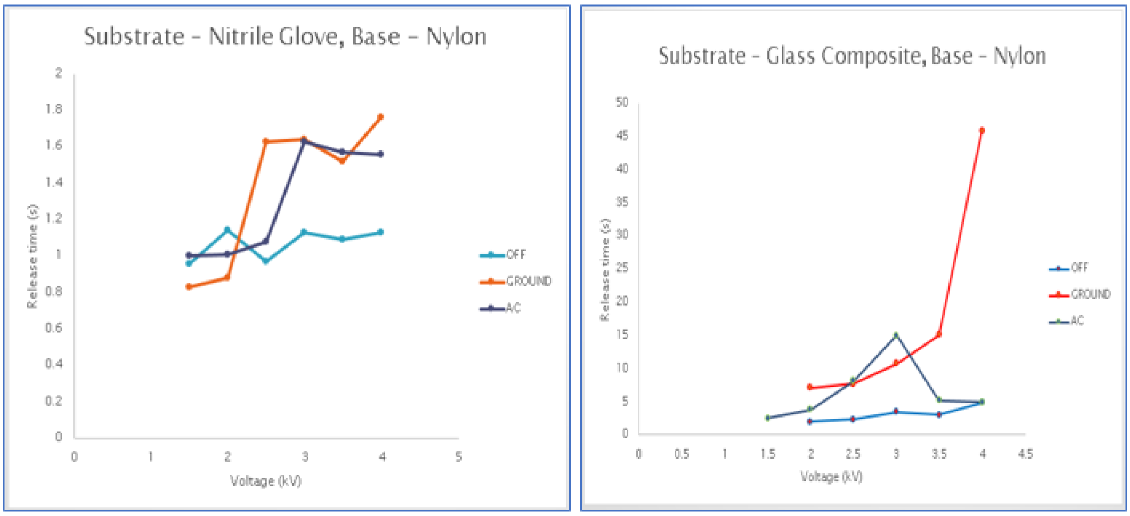


Figure 6-13 Results from DC and AC power source

R2 results:

Above experiments were repeated for R2 results and analysed using the efficiency equation. Experiments were conducted in iterations of PS1, PS2. Following result table was generated:

Power supply	**Substrate**	**Results**	
		PS1	**PS2**
AC for release	Nitrile glove	[red]	[red]
	Glass composite	[grey]	[red]
Substrate grounded for release	Nitrile glove	[red]	[green]
	Glass composite	[red]	[green]
Power supply switched off	Nitrile glove	[green]	[green]
	Glass composite	[green]	[green]

Table 6-14 Power supply R2 Results

1

Key

[green]	Repeatable
[red]	Not Repeatable
[grey]	Not Applicable

From the R2 experiments conducted on power supply, it can be seen in table 6.8 that the DC supply voltage for pick up and power switched off for release proved as the best configuration for electro-adhesive gripper, which provided R2 results for all experiments performed. In other cases, grounding the substrate for release cycle provided half of the results but was not repeatable for the other half. AC power supply for release cycle did not provide any repeatable results. It was not repeatable for 3 sets of experiments and not applicable for 1 (possibly due to electrode breakdown).

6.6 Results Analysis

Section 5.4 contains an exhaustive list of experiments that were devised to understand the effects of various parameters on the performance of an Electro-adhesive gripper in a pick and place application of flexible material. Experiments were performed multiple times, to check for repeatability and reliability as per the efficiency equation. This section provides the analysis of these results.

Experiments conducted on performance of interdigitated electrodes versus concentric electrodes show that interdigitated electrodes were more successful in providing successful R2 results for a larger number of substrates. Concentric electrodes are able to pick up only nitrile gloves, glass composite and gorilla glass. No other substrates were picked up with concentric electrodes. This agrees with the research done in theory section where interdigitated electrodes were identified to be a better configuration for Electro-adhesive gripper. Although by performing E1, E2, E3 and E4 repetitions, it was found that Nitrile sheets (small and large) were not picked up at all by either configuration of electrodes. E4 results for interdigitated electrodes also show that in case of Polypropylene and glass composite, interdigitated electrodes do not provide R2 results. Overall efficiency calculation as per the efficiency equation (section 5.2.2) was done and resulted in a value of 68.75% for the interdigitated electrodes and 15.62% for concentric electrodes. This proves that interdigitated electrodes are able to provide a larger force to pick up various flexible materials. Also, the release time was smaller in the configuration where interdigitated electrodes were used with barium titanate coating 2 and nylon acting as base material. This suggests that interdigitated electrodes are the best configuration for pick up and release.

Experiments conducted on performance of various dielectric materials show that Barium titanate coating 2 mixture when used as a dielectric, proves to be more effective in successful pick up of a larger number of substrates when compared to other dielectric materials. Other than Nitrile sheets (small and large) all substrates were picked up, as shown by D1, D2, D3 and D4 repetitions for barium titanate coating 2 mixture. Also, D4 for Polycarbonate and Gorilla glass showed non repetitive results, making the overall efficiency equal to 68.75% as per the efficiency equation. In comparison, for Barium titanate coating 1, the efficiency was calculated as only 6.25% since it was only able to pick up Nitrile gloves in D2 and D3; whereas for Barium titanate coating 3, the efficiency was calculated as 21.87%. Other dielectrics did not perform as well, with Polyimide giving efficiency of 21.87% and Polyurethane giving an efficiency of

28.12%. This agrees with our theory that dielectrics in liquid state prove to be better at even distribution of charge and avoidance of breakdown of electrodes due to leakage current. In this case, the mixture for Barium titanate coating 2 provided a higher efficiency. Other electrodes went through break down at high voltage due to leakage currents. This suggests that Barium titanate coating 2 mixture is the best dielectric for pick up and release of flexible material by an Electro-adhesive gripper.

Experiments conducted on performance of base materials show that Nylon provides the best results for an Electro-adhesive gripper, with a calculated efficiency of 68.75%. Lowest performing base material was plywood with an efficiency of only 15.62%, followed by Polystyrene with an efficiency of 31.25% and then Polycarbonate with an efficiency of 37.5%. Therefore, this suggests that Nylon is the best material for use as a base material component in an Electro-adhesive gripper for a pick and place application.

Experiments conducted on study of type of power supply reveal that the best method for quick discharge and therefore faster release time of substrate was to provide DC power supply in pick up cycle and switch off the power supply in release cycle. In case of the two substrates tried, this method provides 100% efficiency. Providing AC power in the release cycle provides 0% and grounding the substrate in the release cycle provides 50% efficiency. Also, it was found that only using AC power supply for pick up and release did not provide enough forces to pick up the substrate and therefore this method is not suggested as per the result analysis.

6.7 Conclusion: Suggestion for pick and place Electro-adhesive gripper

In conclusion to the result analysis, following table can be summarised for efficiencies achieved:

Experimental type	Material/ Configuration	Efficiency
Electrodes Analysis	Concentric	15.62%
	Interdigitated	68.75%
Dielectric Analysis	Polyimide	21.87%
	Polyurethane	28.12%
	Barium titanate coating 1	6.25%
	Barium titanate coating 2	68.75%
	Barium titanate coating 3	21.87%
Base material Analysis	Polystyrene	31.25%
	Nylon	68.75%
	Plywood	15.62%
	Polycarbonate	37.5%
Power supply	AC for pick up and release	0%
	DC for pick up and AC for release	0%
	DC for pick up and substrate grounded for release	50%
	DC for pick up and power supply switched off for release	100%

Table 6-15 Efficiency Results

From the results analysis, the best configuration for an Electro-adhesive gripper when used in a pick and place application of flexible material can be chosen as: **Interdigitated configuration of electrodes, coated with Barium titanate coating 2 mixture, substrate placed on a Nylon base material and DC power supply provided during pick up cycle and switched off during release. This answers research question 3.**

It is to be noted that the best configuration from above is also not able to provide 100% results and therefore further work can be done to tune the parameters further, in order to improve the efficiency. In all the experiments, Nitrile sheets (small and large) were not picked up, except for D2 in the case of Polyimide used as a dielectric. As D1, D3 and D4 experiment sets for this dielectric were unsuccessful in providing the desired outcome, this is still not considered as an ideal solution. One attribute to be considered is the size of the electrodes to be used for the application. We believe that for our best configuration selected above, if the size of electrodes is varied and experiments subsequently done for optimal selection of size, then desired outcome can be achieved for these substrates as well, thereby increasing the overall efficiency. This remains as further research work to be done.

7. CONCLUSION AND FURTHER WORK

Above research was an endeavour to find and analyse the most suitable gripping solution that can be used for material handling in an industrial setup. As discussed, automation in an industrial setup, provides many advantages such as providing fast, repeatable and reliable results and eliminating human error. In this study, automation of handling widely used materials was considered, such as nitrile gloves, composite gloves, polycarbonate sheets, polypropylene sheets and high-density polyethylene sheets. These materials have a wide application in daily use and therefore are handled in large quantities in their production and packaging industries. It was noted that most areas of the material handling in these industries was human based and therefore automation of material handling can help in making these industries more productive, as replacing humans by robotic arms provides advantages such as efficiency, fast operation, repeatable and reliable results.

However, handling of such materials poses many challenges as mentioned in section 2.2, such as ply separation, avoiding contamination of object when picked and placed, achieving correct orientation while placing the object, tuning to different loads, achieving speed and accuracy and finally, in providing repeatable and reliable results in an industrial setup. The operation cycle consists of pick up cycle (with ply separation from a pile of objects) and a release cycle (in desired orientation). Thus, the aim of this research was defined in terms of 3 main research questions

RQ1: Which technique is most suitable for handling of commonly used material and what are the key components that constitute the chosen technique when deployed in a pick and place application of commonly used material?

RQ2: What are the key parameters that influence the pickup and release time of the chosen technique when deployed in a material handling application?

RQ3: What are the components that make the novel gripping solution that can be deployed in a pick and place application of commonly used materials?

To answer RQ1, literature review was conducted to present a comparative study between the various gripping solutions or end effectors present in the market and their suitability in material handling. The gripping solutions were organised in four main categories; Impactive, Contiguitive, Astrictive and Ingressive technologies. Each of these technologies were individually studied and it was found that astrictive gripping technology was most suited for current application of material handling, since it was non-intrusive, did not contaminate the object to be handled, was tuneable to handle various loads and was able to perform ply separation from a pile of material objects. In Astrictive technology, electro-adhesion was considered as the most appropriate technology, thereby answering our RQ1 to find the most suitable technology that can be deployed for handling commonly used materials in an industrial setup.

This focused the basis of future chapters and defined the scope of this research study. In order to address RQ2, it was important to first establish the principles of electro-adhesion and the physics involved in this technology. This was done in chapter 3 (section 3.2), where the key equations governing the electro-adhesion phenomenon were stated. This chapter presented the difference between the behaviour of insulators and conductors in the presence of electric field. This micro level phenomenon was important to understand as electro-adhesion is a micro level phenomenon. Thus, the difference in electron distribution and behaviours of insulators/dielectrics in presence of electric field was important to understand the phenomenon of polarization, which was established as the governing law of electro-adhesion. It was established that polarization of a material was directly proportional to the electric susceptibility of the material, permittivity of free space and the applied electric field. It was also noted that the electric susceptibility is directly proportional to the dielectric constant (or relative permittivity) and therefore it was concluded that if the dielectric constant is high, then the insulator exhibited a higher polarization. In conductors, although dielectric constant is considered high, yet there is no polarization seen due to free movement of electrons, therefore conduction eclipses the process of polarization in conductors.

Polarisation was considered an important phenomenon to understand electro-adhesion, since it established the amount of charge accumulation that will take place in an electro-adhesive experiment. Charge accumulation on the dielectrics causes the adhesive property of an Electro-adhesive gripper, therefore higher the polarisation of dielectrics, higher is the ability of an Electro-adhesive gripper to pick up objects. This establishes the pick-up cycle of an Electro-adhesive gripper.

For the release cycle, section 3.2.2 listed the relaxation time that defines the amount of time taken to release the object from the grip of the Electro-adhesive gripper. Here methods of depolarisation were discussed such as removing the applied voltage, grounding of object and applying AC voltage in release cycle. It was noted that while charge accumulation was important for pick up, but excessive charge accumulation can cause a larger release time as depolarisation will take longer. This poses a trade off when choosing materials for dielectrics.

Further this chapter, established the theory of parallel plate capacitor as the basic working principle of an Electro-adhesive gripper, where the object (or substrate) is placed between 2 plates of electrodes that are coated with dielectric material and subjected to high electric field (in KV range). Due to the insulating layer of dielectric plated on the electrodes, no current is allowed to pass and therefore a large density of charge accumulation takes place on the surface of the electrodes. This high concentration of charge caused polarization of the substrate that was placed in its vicinity, which caused adhesion of the substrate to the electrode plates, thereby achieving successful pickup of object by the Electro-adhesive gripper. Here, contact vs contactless pickup was also discussed, where it was established, through literature review that a faster pickup is achieved when the substrate is in contact with the electrode plates. The force calculation formula was also presented, which can be used for load calculations and tuning the Electro-adhesive gripper to pick-up various objects.

In the end of chapter 3, failure causes of the Electro-adhesive gripper were listed. These are important to understand the limitations of the gripper and what factors must be considered when constructing an Electro-adhesive gripper. It was found that an Electro-adhesive gripper can breakdown due to the following reasons:

1) If air gaps exist between the dielectric layer and the electrode, then breakdown can occur at a lower voltage due to conduction through air (as it has dielectric constant). This suggests that dielectric must be correctly and evenly deposited on the surface of the electrode.

2) Uneven charge distribution present due to non-uniform electrode structure can cause corona discharge which can be responsible for Electro-adhesive gripper breakdown. This suggests that electrodes must be correctly etched without sharp edges.

3) Electrical breakdown in solid dielectrics can occur due to thermal breakdown, suggesting that liquid dielectrics may be better for current application of high voltage and repetitive usage.

4) If the dielectric is exposed to voltages higher than its dielectric strength, then breakdown occurs suggesting that appropriate dielectrics must be chosen with enough dielectric strength.

Once the theory of electro-adhesion was established, chapter 4 further presented the key components of an Electro-adhesive gripper and listed current applications of electro-adhesion, which presents a proof of concept. The key components were identified as the substrate (object to be picked up), the electrodes (plates that are connected to high voltage source), the dielectric (insulator deposited on the electrodes that allows high concentration of charge accumulation), the base material (material on which the substrate is placed), and the power source (which provides the electric field for polarization and charge accumulation). Each of these components was further researched as per the theory established in previous chapters. A list of commonly used materials was made that can be used for further Electro-adhesive gripper experiments. These include commonly occurring polymers such as polycarbonate, HDPE, polypropylene and nitrile and composite/pure glass. As already established, the ability of these substrates to be picked up by an Electro-adhesive gripper depends on their dielectric constant and polarizability. Literature review suggested that polar polymers such as polycarbonate show lower polarizability due to small charge accumulation, therefore are harder to pick-up. Whereas non-polar polymers such as HDPE have higher charge accumulation, thereby demonstrating higher abilities to be easily picked up by an Electro-adhesive gripper.

Further, research was conducted on the types of electrode arrangements that can be used in an Electro-adhesive gripper setup. Several arrangements such as jagged, rectangular, semi-circular and interdigitated electrodes were listed, out of which literature review suggested that Interdigitated electrodes proved to achieve best results in an Electro-adhesive gripper. Similarly, a theory on dielectrics was presented, where it was established that either non-polar polymers or liquid dielectrics deposited on the electrode structure would prove as the best alternative for Electro-adhesive gripper application. Dielectrics properties of high molecular polarizability and high dielectric strength were considered the key factors when making a choice of materials to be used as dielectric. Keeping these criteria in mind, a list was prepared comprising of polymers such as polyimide, polypropylene, polyurethane and in liquid dielectrics, barium titanate mixture was chosen as the basis for further experimentation. Here, it was also stated that for non-conductive substrates, bare electrodes could be used (no dielectric layer) but this area needs to be further concluded by experimentation.

Although the base material, directly does not contribute to the theory of parallel plate capacitor, it was considered component of an Electro-adhesive gripper, since at micro level, base material can have an impact on the spacial orientation of the charges of the substrate, thereby affecting the substrates ability to get polarized. Therefore, it was found that properties of materials such as dielectric strength, relaxation time and specific conductivity play a vital role in influencing performance of Electro-adhesive gripper. Here a list of base materials was created comprising of Nylon, polystyrene, polycarbonate, plywood, out of which nylon was researched to be the best candidate due to its rapid relaxation time and hygroscopic nature. Since, no current literature review was found identifying base material as a key component of Electro-adhesive gripper, this theory can only be validated by further experimentation.

Different types of power supplies were researched such as AC or DC or a combination, that can be used to provide energy to an Electro-adhesive gripper in the pickup and release cycles. Here, theory suggested that DC power supply is the most suited form of power source, since it ensures sufficient energy is provided for polarization to take place in the pick-up cycle. However, in the release cycle, AC power supply may be more helpful for depolarisation of substrate.

Hence, this chapter established the key components and parameters that influence the performance of an Electro-adhesive gripper when used in an industrial application of material handling. These form the basis of experimentation, which was used to validate the theory and establish the most suitable component configuration.

With the above theory in mind, experiments were devised to find the optimal and most suitable technique that can be deployed in material handling chapters 5 and 6 were used to answer RQ3 and to prove findings of theory presented in above sections. As was presented in the theory there are 4 main components of an Electro-adhesive gripper and for each of these components, different materials can be used. Here, first experiment ideology was established, where it was stated that experiments were organised in a way such that only one component of the Electro-adhesive gripper was varied, while keeping others constant.

This allowed us to study the effect of one component in detail and understand its influence on Electro-adhesive gripper. Once material for one component was established, it was fixed for other experiments and then the next component was studied. This process of experimentation allowed us to narrow down the most suited material that provided best results for all listed substrates.

In order to compare results of experiments, an efficiency equation was devised. An experiment of an Electro-adhesive gripper can be deemed as efficient, only if it is repeatable and reliable (as in an industrial setup continuous and efficient operation is required). The efficiency equation is universal and simplistic equation that can be used to analyse results of any repetitive experiments. Here efficiency is defined as a ratio of number of trials with desired outcome and the total number of trials conducted where desired outcome is a parameter K defined as per equation (equation x.). Thus, it is directly proportional to the assurance that the substrate was successfully picked up and released and inversely proportional to the time taken in each case. Through experimentation, it was found that interdigitated electrodes provided higher efficiency of operation (68.75%) as compared to concentric rings (15.62%). This ties with the theoretical findings presented in the study of electrode arrangement. Thus, it can be concluded that interdigitated electrodes provide a higher and even charge accumulation on their surface that is important for Electro-adhesive gripper in picking up and releasing the substrate.

Barium titanate coating 2 was found to provide maximum efficiency (68.75%) when compared to other dielectrics (polyimide 21.87%, polyurethane 28.12%, barium titanate coating 1: 6.25% and Barium titanate coating 3: 21.87%). This proves the theory of liquid dielectrics providing better results as they form a uniform coating on the electrode (avoid formation of air gaps). Also, this material has higher dielectric constant and therefore exhibits higher molecular polarizability, thereby increasing the overall charge accumulation. Other dielectric materials exhibited breakdown at higher voltages and did not support pickup of all substrates. Bare electrodes were not considered for experimentation due to their unsafe nature of operation as there is no insulating layer to prevent short circuit of electrodes.

Experiments on base material confirmed that Nylon provided the best results with 68.75% efficiency (polystyrene 31.25%, plywood 15.62% and polycarbonate 37.5%) and for power supply, DC pickup and power supply switched off for release was found as the best configuration with 100% efficiency. No substrates were picked up when AC voltage was used. Similarly, configuration of DC for pickup and AC for release provided no results (0% efficiency).

Thus, the most suitable configuration of Electro-adhesive gripper for material handling comprises of interdigitated electrodes, with Barium titanate (coating type 2) used as dielectric to coat the electrodes and substrate placed on nylon acting as base material and using DC power supply for pickup cycle with power supply switched off for release cycle.

This experimental result is valid for all substrates chosen for experimentation except for large sheet of nitrile, which will form part of further study. Here, we think, varying the size of electrode surface can be explored to achieve successful pickup but since size of electrodes was kept during current experimentation, pickup was not achieved. Since, the small nitrile sheet was picked up, we are confident that above configuration (with increased size of electrodes) can still be used for a larger sheet as well.

There can be other parameters that influence the performance of Electro-adhesive gripper such as environmental conditions of temperature, pressure and humidity. These were currently out of scope and can form basis of further study.

Also, fine tuning of identified Electro-adhesive gripper configuration forms part of further study, which can be an important study for using Electro-adhesive gripper in other applications such as waste management which forms part of further work.

8. SUMMARY AND RESEARCH CONTRIBUTION

1. The current research focussed on automation of handling commonly used materials such as elastomers (Polypropylene, Polycarbonate, HDPE and Nitrile) and Glass
2. Due to their wide application, these materials are mass produced and industries handle large volumes of such materials on a daily basis
3. Current production and packaging industries deploy human labour, that makes the handling of commonly used materials risk and error prone since the efficiency of operation is dependent upon the speed and accuracy of human operators employed
4. Therefore, use of robotic grippers in place of human operators not only reduces operational costs but also offers higher efficiency, accuracy and speed of operation when compared to their human counter parts
5. As discussed in section 1.2, handling of such materials poses certain requirements such as ply separation (pick up single materials from a large pile), non-contamination operation, creation of effective grip of material and smooth transportation from one point to another, correct orientation of material when released, provision of repeatable and reliable results, ensuring efficiency of operation, faster and safe operation of the robotic gripper and arm used.
6. In this context, the research endeavoured to find the best possible gripping solution for material handling and 3 research questions were established (as mentioned in section 1.4)
7. In a comparative study of various available gripping solutions, electro-adhesion technology (astrictive type gripper) was found to be most suited for material handling as mentioned in section 2.4, table 2.6.
8. In Chapter 3, parameters affecting performance of an electro-adhesive gripper were established such as:
    a. Looking at the micro level atomic orientation of conductors and insulators, the **electrons in conductors are free** (not bound to the atom) whereas **in insulators, strong bonds exist**. Due to having

no free electrons, insulators behave differently to conductors when placed under the influence of electric field, thereby exhibiting **molecular polarizability**.

b. Polarisation in insulators is therefore considered a shift in average equilibrium positions of charges of an insulator when placed in an electric field. This results in **charge accumulation**.
c. Polarisation is directly proportional to the **electric susceptibility** (measure of ease with which a dielectric material is polarised in response to electric field) and applied electric field
d. Electric susceptibility is directly proportional to the **relative permittivity (dielectric constant**)
e. Therefore, higher the dielectric constant, larger is the polarisation ability of the dielectric (insulator)
f. In theory, permittivity of conductors is very high, but due to conduction, polarisation effects are not realised
g. Molecular arrangement of polymers also effects their ability to get polarised and overall charge accumulation. Non-polar type polymeric material (such as polycarbonate) demonstrates larger charge accumulation when compared to polar types (such as polypropylene and polyethylene) due to molecular arrangement.
h. A larger charge accumulation on dielectric ensures a successful pick up of material by an electro-adhesive gripper
i. **Relaxation time** is defined as the amount of time taken for the accumulated charge to decay (resettle to equilibrium) once the electric field in removed.
j. A small relaxation time ensures that the material is successfully released (when needed) from the grip of the electro-adhesive gripper.
k. Electro-adhesive grippers work as **a parallel plate capacitor**, where charge accumulation on the surface of the dielectric (placed on electrode pads) is experienced due to their polarisation that occurs when the electrodes are supplied with high voltage, there-

by exerting force of attraction between the substrate and the electrode pads.

l. By carefully choosing the correct parameters, enough forces can be generated by the electro-adhesive gripper, allowing for pick up of various loads.

9. Based on the above theory, chapter 4 further elaborated on components of electro-adhesive gripper as explained in section 5.2.3. Here, literature review concluded with the following factors regarding individual components:
   a. Interdigitated electrodes arrangement, represented as a number of positive and negative electrodes arrangement next to each other in a comb like structure can provide best results when used in an EAG application
   b. Use of liquid dielectric, deposited evenly on the electrodes, exhibits even charge distribution and is less prone to breakdown due to leakage current and air gaps.
   c. Polymers were identified as possible materials to be used as dielectrics due to flexibility, cheap cost and ease of tailoring for specific applications.
   d. Bare electrodes (no dielectrics used) can be used for picking up non-conductive loads, however this area of research remains inconclusive due to insufficient results.
   e. At micro level, Base material can have an impact on the special orientation of charges of the substrate, thereby affecting its ability to get polarised and effectively picked up by the gripper.
   f. Nylon can act as a good base material due to rapid relaxation time and hygroscopic nature but this area of research needs to be further explored (due to lack of sufficient literature)
   g. DC power source is more effective in generating enough charges needed for pick up of loads whereas AC power supply may not generate enough charge accumulation.

h. In order to ensure relaxation time is reduced to a minimum, different techniques can be tested such as grounding of substrate in release cycle to settle the charge accumulation, applying AC power source in release cycle or simply switching off the DC power supply.

10. Based on the above literature review, experiments were devised and results were compared using the efficiency equation to establish the most suitable configuration of electro adhesive gripper.
11. Following was the most suitable gripping solution providing 68.57% efficiency:
    a. Interdigitated Electrodes
    b. Liquid dielectrics: Barium titanate mixture (ratio 2:1) deposited evenly on the electrodes
    c. Nylon used as base material
    d. DC power supply for the pick-up cycle
    e. Switch-off of the power supply in release cycle

Research contribution

In order to ensure suitability to the actual industry and gather important real-world data, the research was conducted in conjunction with AA Robotics (Ayelsbury) and robotic lab at MERI, Sheffield Hallam University.

This contribution is novel because it is a c study of the components that make up a novel gripping solution for the pick and place of flexible material and the parameters that influence it.

The research presented a comprehensive study on the types of grippers available in the current market and analyses their suitability when used in handling flexible material. Further it narrowed down the best possible gripper configuration suitable for the handling of flexible material and explores how a novel gripping solution can be made. Extensive study was done to understand the components that make up an electro-adhesive gripper, with suggestions made on different types of materials that can be used and parameters of these materials involved along with electro-adhesive theory, that influence its performance. A patent was successfully filed to capture the best components (configurations involving barium titanate solution) that make the dielectric material of an electro-adhesive gripper. Also, suggestions (with experimental back up) have been made to reduce the release time of a gripping solution, making it more effective when used in a pick and place application. This research contributes to identifying parameters that reduce release times, since literature review suggests that research in this area is lacking.

The research also presents a universal efficiency equation that can be used to assess the use of any gripping solution in any application. In this specific place, gripping solution is assessed for pick and place of flexible material and assessed for repeatability and reliability (quick pick up and release times). Exhaustive experimentation is presented to support the claims and therefore recommendations are made where the researched gripping solution can be used for the advancement of electro-adhesive technique in the real-world industrial applications.

Suggestions have been made for configuring the gripping solution to tune it to be used in handling different types of materials/ objects, thereby making it possible to be used in applications where sorting of materials or selective pick up is needed. This presents future applicability to waste management of non-ferrous materials, where a patent was also successfully filed.

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APPENDIX A

A.1 Glove production and packaging

Wearing protective equipment is an important consideration for many work places where there is use of bare hands and this is important for maintaining work consistency. More than 25% of injuries at work place are hand and arm injuries (Ansell, 2014). Gloves come under the personal protective equipment (PPE) where they are mainly used for hand protection. 2.3% growth has been recorded in hand and arm protection sector which is because of the frequent use of disposable gloves (Tutt, 2014). Also gloves find widespread use in the medical and food sector, where they are used for reducing contamination. This has resulted in the expansion of the glove industry and therefore has been a key area of research for automated production processes.

Nitrile gloves, a kind of elastomer, are part of the first experimental setup and form the main focus of our initial investigation. These mainly provide protection from chlorinated solvents such as trichloroethylene and perchloroethylene. Their properties allow them to work even after exposure to such solvents on a very prolonged time period. Along with such solvents they can also be used when working with oils, greases, caustics, acids and alcohols. (Adminstration, 2003)

Key stages of glove production (Ambitex, 2013)

1) Washing – Washing the first stage of glove packaging process makes sure the glove is clean and without any holes. Two types of washing are done. First, the online washing where the glove goes through five step process along the assembly line mainly going through tank of water, acid and alkaline, which further leads to the removal of the gloves and being washed manually in a process called offline washing

2) Coagulation – Gloves (with formers) are then dipped into a coagulant tank at around 140 degrees consisting of calcium nitrate and calcium carbonate. The solution allows latex or synthetic to adhere but not bind to the glove. Gloves are then put into oven at 210 – 250 degrees for 2 minutes for proper strength.

3) Application – Gloves are dipped into a tank of latex or synthetic compound.

4) Dripping – Dripping being an important stage to ensure that the gloves have even surface. The excess compound is restored back in coagulation stage.

5) Gelling – Gelling process solidifies the gloves when they are put in an oven at 210 to 250 degrees and begin to solidify. It is an important process as it impacts the physical properties of the glove.

6) Leaching – In leaching process gloves are dipped into 160 degree water tanks for 2 minutes. This process extracts proteins and other residuals to lower the potential for an allergic reaction.

7) Beading – After leaching the cuff of the glove is rolled to give it durability and make it stronger when stripping it.

8) Slurry – Powdered gloves are then put through a wet process for about a minute for even powdering. From this process, the gloves are then again dried at 200 degrees for 2 minutes.

9) Stripping – The gloves are ready to be stripped from the formers. Currently the stripping is done either manually or in semi- automatic way.

10) Testing – Gloves have to go through testing to ensure compliance with ASTM and FDA standards

11) Packaging – Gloves are then packed into boxes manually. Currently the process of packaging is done manually in a clean manufacturing environment.

Sheffield Hallam University

Faculty of Arts, Computing, Engineering and Sciences	***For Office Use Only*** ***File Reference:*** ***File Date:*** ***Review Date:*** ***Type of Activity:***

Risk Assessment / Method Statement / Sequence of Work Form **RAMS3** (July 12)

Written By: Jatinder Singh	**Sign: Jatinder Singh**	**Date:** 02/04/14
Approved By: (Line Manager/Supervisor)	**Sign:**	**Date:**

Activity / Project Title (Course): PhD (Electrostatic gripper for Elastomers)

<u>Examples of Common Hazards</u> (Please Tick all that apply) ✓

Machinery / tools		**Entanglement**		**Dust**		**Falling Objects**		**Lighting**		**Striking Object**	
Chemical Hazard		**Cutting Accident**		**Electrocution**	✓	**Fire**	✓	**Manual Handling**		**Toxic Gases**	
Climate		**Lasers**		**Explosion**		**Flooding**		**Noise**		**Traffic**	
Material Ejection		**Display Screens**	✓	**Fall from Height**		**Lifting Equipment**		**Abrasion**		**Slip/Trip Hazards**	
N-I Radiation		**Vibration**		**Other**		**(please specify)**					

Using the list above and your knowledge of the activity, select the SIGNIFICANT hazards

Significant Hazards	Number of Persons at Risk	Probability	Severity	Risk Rating

1) Electrocution (use of mains power equipment) **2) Electrocution (HV use)** **3) Arcing** **4) Display Screens**	1 1 1 1	2 2 2 3	5 5 4 1	10 10 8 3

Substances / materials to be used: Include substances produced as a by-product and identify Risk Phrases from MSDS	**Risk Phrase Code**	**Workplace exposure limit (WEL)**
Electrostatic Plate **1) Copper** **2) Polyimide** **3) Latex (Glove)**		
Are less hazardous substances available? Yes / No		

If 'Yes' reasons for not using them?		

Sequence of Work / Method Statement (Please use additional sheet if required)

1) Power (5kV) given to electrostatic plate
2) Electrostatic plate moves up and down (platform made and automated for lifting and dropping purpose)
3) Electrostatic plate makes contact with the glove and the adhesive forces attract the glove
4) The glove is lifted up
5) Power Supply is shut off to see if the glove is dropped (adhesive forces are nullified as the power is shut off)

(*High Voltages (kV) are essential to this technology and lower voltages cannot be used*)

Control Measures using PPE

(Tick all that apply)

Ear protection ☐	**Harness or line** ☐	**Overalls/Lab Coats** ☐
Eye protection ☐	**Face Protection** ☐	**Respirator** ☐

Other PPE required	

A.2 Risk Assessment form

Control Measures:	**Safety Phrase Code:**
Refer to **Table 2** for an interpretation of the Actions and Timescales required relative to the above individual Risk Rating/s. *Electrocution (HV use)* Faraday Cage has been built up to isolate the setup inside the cage and protect the environment from electric discharge. All the metal parts will be grounded for protection from any leakage of charge. Cage will be checked by qualified SHU electrical experts before use to ensure maximum safety. *Electrocution (Use of mains powered equipment)* Power supply is having a 50 MΩ safety resistor for extra safety. The main HV power source has been PAT tested by the supplier. There is a ground on the power source as well so the neutral of the source will be connected to the ground for extra safety. The equipment needs to be PAT tested by University. *Arcing* The main power source will be shut immediately in case of arcing. If arcing leads to fire, the fire alarm will be setoff and everyone in the lab will be alarmed to go out of the lab immediately	Refer to **Table 4 /** MSDS

Relevant Regulations

(Please Tick as Applicable) ✓

☐ Control of Substances	✓ Electricity at	☐ Local Exhaust	☐ Lifting Operations &
☐ Manual Handling regula-tions	☐ Noise at Work regs	☐ Personal Protective Equipment	☐ Ionising & Non- ionising Radiation

Skills and Competencies

Do all the persons involved in this activity have the skills and competencies required to carry out the activity? - If YES please Tick ✓

If NO please indicate below the skills and competencies to be acquired as part of the activity.

(Please use additional sheet if required)

✓

Resources Required e.g. Plant, Equipment, Tools, etc. (Please use additional sheet if required) 1) Power Supply (For Stepper Motor) 2) Power Supply (For electrodes) 3) Laptop 4) Field Meter

Emergency Procedures (Please use additional sheet if required) Contact a member of staff immediately. Green signs indicate how to contact a local first aider. For medical emergencies ring 888. 1) Shut the power source. 2) In case of fire setoff the fire alarm and everyone in the lab will be alarmed to leave the lab immediately.	**Safety Phrase Code:** Refer to **Table 4 /** MSDS

Waste Disposal Procedures (Please use additional sheet if required)

-------------------N.A----------------------

Additional Information (Please use additional sheet if required)

1) Arduino board is connected to the laptop
2) Stepper motor is given a voltage of 10V and 1Amp
3) Power (5kV) given to electrostatic plate

4) Program is downloaded in the Arduino board to make the electrostatic plate move up and down
5) Electrostatic plate moves up and down (platform made and automated for lifting and dropping purpose)
6) Electrostatic plate makes contact with the glove and the adhesive forces attract the glove
7) The glove is lifted up
8) Power Supply is shut off to see if the glove is dropped (adhesive forces are nullified as the power is shut off)

	Date:
Date Copy of RA/MS filed with Relevant Technical Team Leader / Advisor	**Date:**
Received / Approved By (Relevant Technical Team Leader / Advisor)	**Name:**

NOTE: Please attach any other information that you think may be relevant to this activity e.g. Handouts, Travel Arrangements, Accommodation, Site Contacts, Mobile & Landline Phone Numbers, etc.

Table 1 - Risk Rating Analysis Matrix					
	Probability (Likelihood)				
Severity (Hazard Consequence)	**1 Very Unlikely** (Freak event – No known history)	**2 Unlikely** (Unlikely sequence of events)	**3 Possible** (Foreseeable under unusual circumstances)	**4 Likely** (Easily foreseeable- Odd incident may have occurred)	**5 Very Likely** (Common occurrence – Aware of incidents)
1 Negligible (No visible injury – No pain)	**Trivial** **1**	**Trivial** **2**	**Accepta-** **3**	**Accepta-** **4**	**Accepta-** **5**
2 Slight (Minor cuts, bruises – No long term effects)	**Trivial** **2**	**Acceptable** **4**	**Acceptable** **6**	**Moderate** **8**	**Moderate** **10**
3 Moderate (Heavy bruising, deep flesh wound. Lost time accident)	**Acceptable** **3**	**Acceptable** **6**	**Moderate** **9**	**Substantial** **12**	**Substantial** **15**
4 Severe (Lost time accidents and major injuries)	**Acceptable** **4**	**Moderate** **8**	**Substantial** **12**	**Substantial** **16**	**Intolerable** **20**
5 Very Severe (Long term disability or death)	**Acceptable** **5**	**Moderate** **10**	**Substantial** **15**	**Intolerable** **20**	**Intolerable** **25**

Table 2 - Interpretation of the **Actions** and **Timescales** required relative to the **Risk Rating** identified using the above Analysis Matrix.

Risk Rating	Action and Timescale
Trivial **1 to 2**	No action is required to deal with trivial risks and no documentary records need be kept (insignificant risk).
Acceptable **3 to 6**	No further preventative action is necessary but consideration should be given to cost-effective solutions or improvements that impose minimal or no additional cost burden. Monitoring is required to ensure that the controls are maintained.
Moderate **8 to 10**	Efforts should be made to reduce the risk but the costs of prevention should be carefully measured and limited. Risk reduction measures should normally be implemented within three to six months, depending on the number of people exposed to the hazard.
Substantial **12 to 16**	Work should not be started until the risk has been reduced. Considerable resources may have to be allocated to reduce the risk. Where the risk involves work in progress, the problem should be remedied as quickly as possible and certainly within one to three months.
Intolerable **20 - 25**	Work should not be started or continued until the risk level has been reduced. While the control measures should be cost-effective, the legal duty to reduce the risk is absolute. This means that if it is not possible to reduce the risk, even with unlimited resources, then the work must not be started or must remain prohibited.

Table 3 - Approved Risk Phrases

Risk Code	Risk Phrase
R1	Explosive when dry
R2	Risk of explosion by shock, friction, fire or other source of ignition
R3	Extreme risk of explosion by shock, friction, fire or other source of ignition
R4	Forms very sensitive explosive metallic compounds
R5	Heating may cause an explosion
R6	Explosive with or without contact with air
R7	May cause fire
R8	Contact with combustible material may cause fire
R9	Explosive when mixed wth combustible material
R10	Flammable
R11	Highly flammable
R12	Extremely flammable
R14	Reacts violently with water
R15	Contact with water liberates extremely flammable gases
R16	Explosive when mixed with oxidising substances
R17	Spontaneously flammable in air
R18	In use may form flammable/explosive vapour-air mixture
R19	May form explosive peroxides
R20	Harmful by inhalation

R21	Harmful in contact with skin
R22	Harmful if swallowed
R23	Toxic by inhalation
R24	Toxic in contact with skin
R25	Toxic if swallowed
R26	Very toxic by inhalation
R27	Very toxic in contact with skin
R28	Very toxic if swallowed
R29	Contact with water liberates toxic gas
R30	Can become highly flammable in use
R31	Contact with acids liberates toxic gas
R32	Contact with acids liberates very toxic gas
R33	Danger of cumulative effects
R34	Causes burns
R35	Causes severe burns
R36	Irritating to the eyes
R37	Irritating to the respiratory system
R38	Irritating to the skin
R39	Danger of very serious irreversible effects
R40	Possible risk of irreversible effects
R41	Risk of serious damage to the eyes
R42	May cause sensitisation by inhalation
R43	May cause sensitisation by skin contact
R44	Risk of explosion if heated under confinement
R45	May cause cancer
R46	May cause heritable genetic damage
R48	Danger of serious damage to health by prolonged exposure
R49	May cause cancer by inhalation
R50	Very toxic to aquatic organisms
R51	Toxic to aquatic organisms
R52	Harmful to aquatic organisms
R53	May cause long term adverse effects in the aquatic environment
R54	Toxic to flora
R55	Toxic to fauna
R56	Toxic to soil organisms
R57	Toxic to bees
R58	May cause long term adverse effects in the environment
R59	Dangerous for the ozone layer
R60	May impair fertility

R61	May cause harm to the unborn child
R62	Possible risk of impaired fertility
R63	Possible risk of harm to the unborn child
R64	May cause harm to breastfed babies

Table 4 - Approved Safety Phrases

Safety Code	Safety Phrase
S1	Keep locked up
S2	Keep out of reach of children
S3	Keep in a cool place
S4	Keep away from living quarters
S5	Keep contents under....(specify appropriate liquid)
S6	Keep under....(specify inert gas)
S7	Keep container tightly closed
S8	Keep container dry
S9	Keep container in a well ventilated place
S12	Do not keep the container sealed
S13	Keep away from food, drink and animal feeding stuffs
S14	Keep away from....(incompatible materials identified by manufacturer)
S15	Keep away from heat
S16	Keep away from sources of ignition - No smoking
S17	Keep away from combustible material
S18	Handle and open container with care
S20	When using do not eat or drink
S21	When using do not smoke
S22	Do not breathe dust
S23	Do not breathe gas/fumes/vapour/spray(appropriate wording to be specified by manufacturer
S24	Avoid contact with the skin
S25	Avoid contact with the eyes
S26	In case of contact with eyes, rinse immediately with plenty of water and seek medical advice
S27	Take off immediately all contaminated clothing
S28	After contact with skin, wash immediately with plenty of....(specified by the manufacture)
S29	Do not empty into drains
S30	Never add water to this product
S33	Take precautionary measures against static discharge

S35	This material and its container must be disposed of in a safe way
S36	Wear suitable protective clothing
S37	Wear suitable gloves
S38	In case of insufficient ventilation, wear suitable respiratory equipment
S39	Wear eye/face protection
S40	To clean up floor and all objects contaminated by this material use...(to be specified by the manufacturer
S41	In case of fire and/or explosion do not breathe fumes
S42	During fumigation/spraying wear suitable respiratory equipment (appropriate wording to be specified)
S43	In case of fire use...(indicate the precise type of fire fighting equipment. If water increases the risk add - never use water)
S45	In case of accident or feeling unwell, seek medical advice immediately(show label where possible)
S46	If swallowed seek medical advice immediately and show this container or label
S47	Keep at temperature not exceeding....C(specified by the manufacturer)
S48	Keep wetted with......(specified by the manufacturer)
S49	Keep only in the original container
S50	Do not mix with.....(specified by the manufacturer)
S51	Use only in well ventilated areas
S52	Not recommended for interior use on large surface areas
S53	Avoid exposure - obtain special instruction before use
S56	Dispose of this material and its container to hazardous or special waste collection point
S57	Use appropriate containment to avoid environmental contamination
S59	Refer to manufacturer/supplier for info on recovery/recycling
S60	This material and/or its container must be disposed of as hazardous waste
S61	Avoid release to the environment
S62	If swallowed, do not induce vomiting; seek medical advice immediately and show container or label