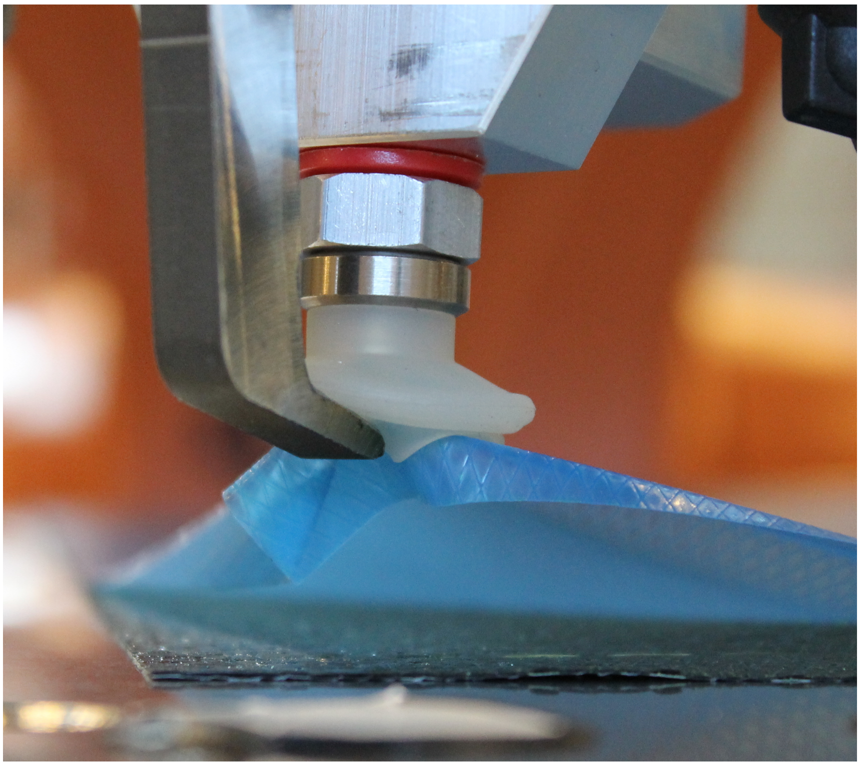
Development of an automated robotic cell to remove the baking paper from the Carbon fibre ply

Development of a pick and place solution for composite manufacturing



Project Report

Group VT4 d-f19

Aalborg University
Department of Materials and Production

This project is written in Share LaTeX, the figures is generated in draw.io. The CAD software has been used in this project is Fusion 360.

AALBORG UNIVERSITY
STUDENT REPORT

Department of Materials and Production
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Development of an automated robotic cell to remove the baking paper from the Carbon fibre ply

Theme:
Development of a pick and place solution for composite manufacturing

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Abstract:

There is an increasing demand on composite materials and specifically Carbon fibre composites. However, many operation related to production of composite materials is carried out manually and the developed automation solutions are demanding for a high initial cost and they are not flexible and suitable for production of the small size components. Therefore, there is a demand for a more cost effective and flexible solution in all industries which benefits composite materials for their production. In this project the developed end-effector by RoboTool A/S has been assembled and mounted on a robot and a fixture has been developed to hold the Carbon fibre ply down as the robot remove the baking paper from it. However, in order to develop a reliable process it is a need to recognise influential parameters. Therefore. two-way ANOVA has been used as an statistical analyser to examine the significance of the effect of the considered variables; suction cup position and feeding air pressure namely on the response of the experiment. It has been concluded that the interaction between suction cup position and the feeding air pressure has a significant effect on the response of the experiment and the design of the end-effector has to be altered to be able to remove the baking paper totally.

Contents

Preface

This project report is developed by Rahim Ataollahi Eshkoor. The project has been developed during spring 2019.

Thanks to the AAU project supervisor: Morten Kristiansen, other partners who involve in the project Flexdraper and employees at the laboratory.

Motivation

The motivation for this project was to develop an automated robotic solution for removing the baking paper from the Carbon fibre plies which is carried out manually today. Therefore, this project will includes analysis the developed end-effector by the RoboTool A/S for this goal and development of a fixture and design an experiment to find the influential parameters.
Reading directions Here, the important information for the reader to understand the report are collected.

Appendices

Here are the lists of appendices attached with the project:

A. Drawing of the fixtures

B. Pneumatic diagrams

C. Schematics

Aalborg University, June 3, 2019

Preface

Chapter 1

Introduction

This project is a part of a bigger project, FlexDraper (Kristiansen et al. 2016), which its aim is to develop an automated robotic pick and place solution for draping the prepreg carbon fibre plies on a mould and manufacture composite based products. With the introduction of this concept the required manual labour for production will be reduced. One step of the production process of composite based products is to remove the baking paper from the carbon fibre ply. Therefore, the goal of this project is to make an automated robotic solution to remove totally the baking paper from the pre-cut prepreg carbon fibre plies. This chapter is going to provide a brief description of composite materials and automation in manufacturing composite based products and explain the motivation for doing this project. Furthermore, this chapter will contain an initial problem statement.

1.1 Composite Materials

A composite material is a combination of two or more material which has superior properties than constituent materials. The constituent materials are not soluble in each other and the combination is in macroscopic level (Shubhra & Alam 2011). The constituent materials are categorised in two categories; matrix and reinforcement namely. The matrix category has different functions such as the distribution of load among reinforcement and forming the product. An example of the matrix can be epoxy resin or other types of resins. The matrix is generally continues (Kaw 2005). However, the reinforcement category provides the load carrying capability to the composite material. High specific stiffness and specific strength make the composite materials an attractive material to be used in different structures from ancient time til now.

Composite materials have been implemented to the aerospace industry from the Second World War due to the efforts of aerospace community members. They were able to produce composite materials with higher specific stiffness and strength than conventional material. However, this alone was not enough to make the composite material an attractive choice for the other markets such as commercial transportation. Due to the energy crises and mark up of fuel price in 1970, enough motivation for substitution of heavy metal parts with light composite parts has been created (Miracle et al. 2001). It is possible to control the properties of the composite material via manipulation of the volume fraction and change of the reinforcement type and material. (Miracle et al. 2001). Each part in the composite has its own function and role. Matrix has different functions:

1- To bind the fibres together and transfer the load to the fibres by adhesion and/or friction. 2- To provide rigidity and shape of the structural member. 3- Fibres isolation, thus fibres can act separately, as the result is slow or no crack propagation. 4- Protection of fibres against chemical and mechanical damages. 5- Affect on performance characteristics such as ductility and impact strength. 6- To provide finish colour and surface finish for connections. The reinforcement part is in charge of providing strength and stiffness to the structure. (Tuakta 2005). Figure 1.1 illustrates some example of how the continues fibre can be arranged in a composite structure.

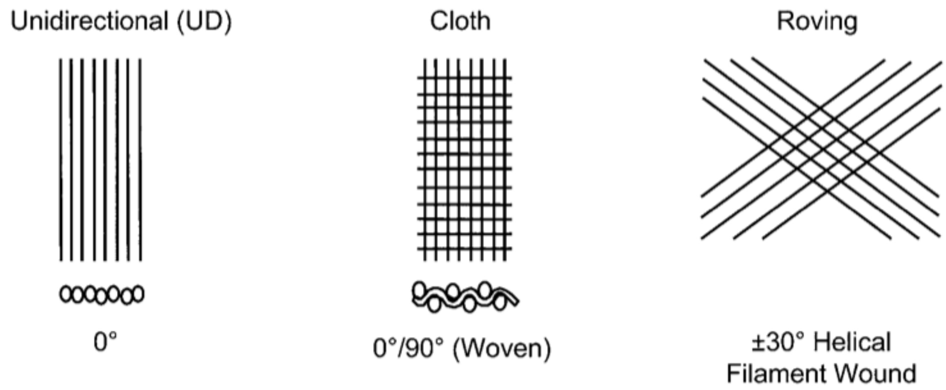


Figure 1.1: Examples of fibre arrangement in composite structures. (Campbell 2010)

One of the reinforcement which can be used in composite based products is Carbon fibre.

1.2 Carbon Fibre Composites

Carbon fibre composites have the carbon fibre as reinforcement in their structure. carbon fibres have shown excellent mechanical properties such as high specific strength and stiffness. These characteristics make them a replacement for conventional equivalent materials. Aerospace is highly interested in composite with carbon fibre as reinforcement due to their properties. Figure 1.2 shows the dramatic growth of using carbon fibre composites in the aerospace industry.

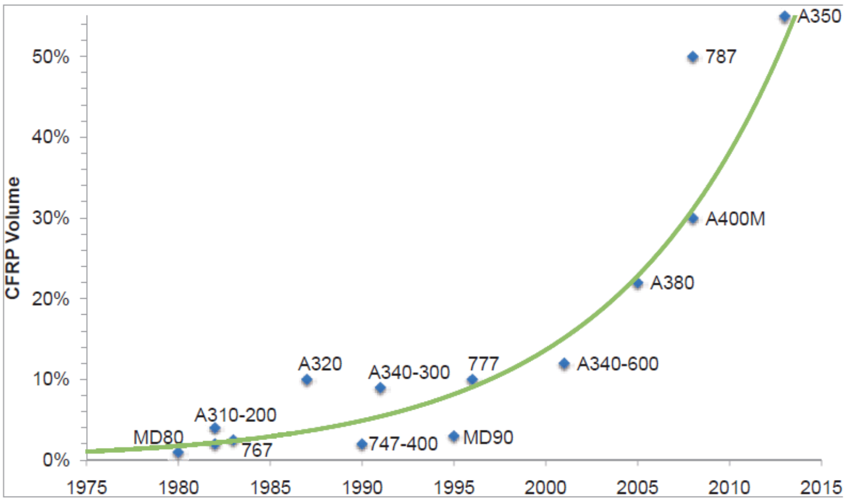


Figure 1.2: Development of carbon fibre reinforced plastic in aircrafts (Angerer et al. 2010)

Boeing and Airbus using lots of components made of composite materials to manufacture the aircrafts such as Airbus A350 and Boeing 787. Many other industries such as wind energy, transportation, building, and sports also use composite materials due to their properties such as resistance to corrosion and low-density (Angerer et al. 2010).

Carbon fibre provides a higher degree of freedom in design of the car and performance and lets to reduce more weight which leads to less fuel consumption. The demand for the carbon fibre composites in the automotive industry is growing and it will be for the next 20 years. It has been estimated that the consumption of carbon fibre will increase by 10% annually (Björnsson et al. 2018). Carbon fibre is an expensive material, about five to six times of the steel price. However, the price of carbon fibre for the automotive applications will be reduced for about half of the current price in a conservative scenario until 2030 (Heuss et al. 2012). In all the industries which benefit of carbon fibre composites automation has an important role in increasing the production capability and reducing the required manual labour especially in high wage countries such as Denmark.

1.3 Automation in Manufacturing Composites

The use of composite material in different sectors is increasing and therefore, demand for manufacturing them is higher now. In some industries such as the automotive industry the costs are important. Therefore, rational and cost-efficient manufacturing methods are highly appreciated. An important part of the cost-efficient manufacturing based on composite materials is deemed to be the automatic manufacturing processes (Dirk et al. 2012). The processes which has to go through to manufacture a composite based components are shown in Figure 1.3.

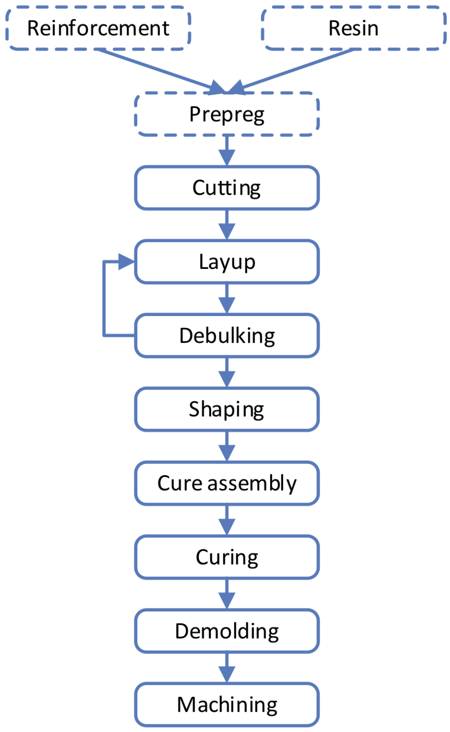


Figure 1.3: The manufacturing process of a composite based component (Björnsson 2014)

Automation in composite manufacturing is limited to some automatic and semi-automatic solutions. They have limited variety and the solutions need high capital investment (Grant 2006). Grant (2006) carried out a comparison between metal and composite components fabrication in the aircraft manufacturing and yielded that the number of automated processes for composite manufacturing is limited. Mallick (1997) mentioned in his research that many of the composite manufacturing processes are done manually especially in the aerospace industry. More analysis of the automation in composite manufacturing will be presented in Chapter 2.

1.4 Terma History

Terma is one of the stack holders in the FlexDraper project and is also the industrial part of this project. The information of this section has been extracted from Wikipedia.com (2019) and Terma A/S websites (Terma.com 2019). Terma A/S is a Danish company founded by brothers Orla and Svend Aage Jørgensen in Aarhus in 1949. In the beginning, the company was producing and selling thermometers and manometers for ships and a variety of metal components. The number of employees at that time was fewer than 10 employees. Later in the same year, it has been bought by Thorkild Juncker and he changes the path of the company to produce and selling the electronic measuring instruments. In the meantime, he employed a Norwegian engineer which could develop a competitive radar in terms of price and quality.

Terma under the ownership of Juncker grew and increased the number of employees to 120. It Developed radar- computer- and air defense systems and sold them to the

European market. In 1980, The Thomas B. Thrige foundation bought the majority of the share of the company. Terma has bought some other companies which were active in the aerospace and defense fields. Terma has grown enough to be the leading supplier company for the only launched Danish satellite, Ørsted satellite, to space.

Terma has been grown and now it has offices in different countries. Today, Terma is one of the strategic partner companies in designing, manufacturing and supplying of the components for the F-35 joint strike fighter. This company has over 1400 employees worldwide. However, the headquarter is located in Lystrup near Århus,

1.5 Summary

In this chapter, a small introduction on composite material and automation in composite materials fabrication has been provided. It has been explained that the demand for composite materials is rising and new technologies to fabricate composite materials are needed. In addition, a short history of the Danish company Terma has been provided since Terma is the biggest aerospace company and also the most benefited company from this project in Denmark.

1.6 Initial Problem

As it was mentioned the demand for composite materials and specifically carbon fibre composites, which means also more demand for the cost efficient and flexible automation in composite fabrication. The FlexDraper project has been defined based on this need. The goal of the FlexDraper is to use automated robotic solution to layup of the carbon fibre plies on a mould. However this project can be break down to following steps:

1 Removing the baking paper from the fibre ply.

2 Pick and place the fibre on the mould.

3 Remove any flaw from the lay-up.

In this project the main focus in on the first step, and therefore the initial problem statement is as follows:

"How can the removal of the baking paper from the Carbon fibre ply be automated?"

Chapter 2

Analysis

In this chapter, more detail about prepreg composite materials and automation in manufacturing of components made of composite materials will be provided. The gripping technologies will be investigated since the aim of this project as a part of Flexdraper project is to grip the baking paper and remove it totally from the carbon fibre ply.

2.1 Prepreg Composites

Prepreg term is used for pre-impregnated fibres with a matrix. This matrix can be either a thermoset matrix or a thermoplastic matrix. The typical method to produce a prepreg is to pass the fibres between resin films or through resin bath by the use of some rollers. (Crossley et al. 2013). The application of prepreg materials is mainly in high quality and high-cost applications such as aerospace industry. Most of the aircraft components are made of prepreg fibres today. These materials are available in a wide range of fibre and matrix selection. Prepreg provides a uniform and high level of material quality and fibre density. (Astrom 1997) The fibre material and reinforcement type mostly define the rigidity of a prepreg, and tack is defined as the stickiness ability of the two prepreg plies together (Putnam et al. 1995). The tack level has to be in a range that the baking paper can be easily separated from the ply and also keep the lay-up together (Crossley et al. 2013).

These two characters of a prepreg material affect the automated handling of these materials. The prepreg unidirectional materials are highly sensitive to damage due to their anisotropic properties. Therefore they are packed in within rigid and stiff baking papers to increase the rigidity of the ply (Buckingham & Newell 1996). It is important to take care of the direction of peeling off the baking paper to avoid any damage to ply or misalignment of the fibres in the ply (Björnsson et al. 2013). However, in order to peel off the baking paper from the ply it is necessary to overcome the tack. Tack is necessary to keep the plies fixed during the layup. The tack or stickiness ability depends on the following factors (Putnam et al. 1995):

- Resin
- Fibre
- Processing conditions during manufacturing
- The environmental conditions

- The prepreg storage history

Therefore, any change in one or more of these factors can alter the tack of the ply. Based on the type of manufacturing the required care for tack is different. If the layup is performed manually, the tack value can be flexible as the operator flexibility can compensate that. However, in automated manufacturing, high care should be paid to the tack value since the automation methods are not that flexible to be responsive to any tack value. (Crossley et al. 2012). Crossley et al. (2012) investigated the effect of increasing temperature on the tack value and found that the tack value does not always reduce as the temperature increased. In another research Crossley et al. (2011) pointed out that laying the first ply on the mould is probably the most difficult one as the mould surface is usually smooth and covered by a release agent.

2.2 Automation

Some of the automated solutions which have been used in the manufacturing of composite structures are Automatic Tape Laying (ATL), Advanced Fibre Placement (AFP) and fully automated cells for Resin Transfer Moulding (RTM) (Grant 2006).

In order to answer the demand for composite products and reduce the cycle time, the demand for automation has been increased generally in composite products manufacturing. Lay-up and forming processes are considered the main bottlenecks for the continues fibres. In aerospace, the prepreg fibres are the generally used material to make the components and due to the lack of an alternative, it seems it will be staying for the next generation at least. The main automation method has been used for making components out of prepreg fibres are ATL and AFP (Björnsson et al. 2013). It has been mentioned by Hallander et al. (2013) that the main problem is that AFP is expensive and its cycle time is high. The ATL has been developed more than the AFP and it has higher speed.

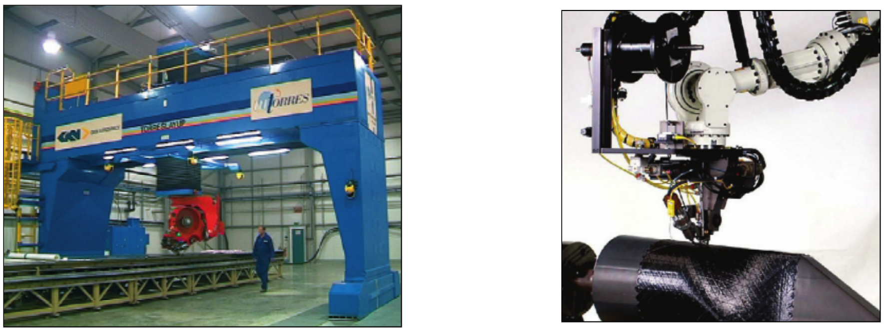
ATL and AFP are the commercially available automated solution in the market. These can handle complex cutting and laying operations. In these solutions usually, the ply in the contact point with mould is pressed to the mould to stick to it. The challenge at this point is that almost at the same time the baking paper is also removed from the ply. Here, the adhesion between baking paper and ply is undesirable since it will resist the separation of ply and backing paper. As the results, it can cause the separation of the ply from the mould. (Björnsson et al. 2013)

Although ATL and AFP are considered efficient at the manufacturing high-performance components, some difficulties have been reported regarding the lay-up process especially due to change of prepreg tack value (Repecka 1988, Shirinzadeh et al. 2004).

It has been mentioned in the last section that the tack value depends on different parameters and one of them was the environmental condition. Therefore, a highly regulated environment is needed to keep the tack value in a range that an automatic solution can handle it. In addition, it is always required to have a highly skilled operator to monitor the lay-up process all the time and intervene if required (Crossley et al. 2013). These have limited the use of these solutions mostly to the aerospace industry. In following subsections these methods will be described.

2.2.1 AFP

AFP is one of the advanced and automatic methods for fabrication of the composite structures. Both the gantry style and robotic setups can be used in this method. In the robotic setup, a robot carries the AFP head (Frketic et al. 2017). These setups are depicted in Figure 2.1.



(a) **(b)**

Figure 2.1: a) Gantry style AFP b) Robotic style AFP. (Frketic et al. 2017)

This lets the method to be highly controllable and repeatable. However, this method is almost confined to the continues fibres. AFP places one ply at a time and this lets to make very complex and customised components. Each ply can have a different orientation to answer the loads. This method uses bands which comprises of multiple tows and the width of each tow is typically between $\frac{1}{8}$ into $\frac{1}{4}$ in. In order to be able to make more customised components, these tows are usually individually controlled. In other word they can be started and cut at different points. This reduces the amount of scrap in the fabrication (Frketic et al. 2017).

2.2.2 ATL

ATL is a well developed composite components fabrication. It has been developed over the past 26 years. ATL machines start the fabrication by depositing some prepreg onto the mould and then following a defined CNC path to form the component and at the end, it cuts the tape automatically. However, this method is mostly used for flat surfaces or surfaces with a single curvature (Frketic et al. 2017).

If the goal is to create a non-flat surface another step has to be added and the main challenge is that the laminates have a tendency to wrinkle if the curvature is large. This method is also possible to be used in both Gantry style and robotic setup where a robot holds the head. The width of the tape that is used in this method is between 75 mm to 300 mm. The current tendency toward ATL is to make smaller scale projects which smaller robot can be used and therefore it is more accessible to small companies. (Frketic et al. 2017) In figure 2.2 shows the ATL machine used in different setups.

(a) (b)

Figure 2.2: a) Gantry style ATL b) Robotic style ATL. (Frketic et al. 2017)

2.2.3 Pick and place

A pick and place technique with the use of a robotic arm has been proposed by Angerer et al. (2010). This method benefits a robotic arm with different end effectors to handle the different tasks such as cutting and placing (Angerer et al. 2010, Lindbäck et al. 2012). This methods is not in industrial level yet and has been only used in a laboratory level. This method can replace other methods namely AFP and ATL. However, it is not a mature technique and the main time-consuming process in this method is removing the baking paper from the ply (Frketic et al. 2017, Lindbäck et al. 2012). More development in this area needs to make this method a suitable industrial technique.

As mentioned in above subsections, automation for the fabrication of composite structure is employed in different industries specifically aerospace. For the sake of automation, the design has to be simple. However, change in design can cause major cost and due to this, the composite materials are not used in their full potential. A more flexible method is a requirement to be able to use composite materials in more shapes without causing a substantial cost (Frketic et al. 2017).

2.3 Gripping Technologies

In order to pick and place objects, it is needed that the object has been picked up and then placed it down in a controlled manner. The object in the composite manufacturing can be a prepreg ply (Newell et al. 1996). It has been mention in section 1.6 that one of the tasks in the FlexDraper project is to remove the Baking paper from the prepreg Carbon fibre plies and this task is the main focus of this project. In order to achieve this goal, it is necessary to use grippers. Grippers are generally divided into two categories: contact grippers and non-contact grippers. In the contact grippers, the gripper touches the material while in non-contact gripper there is no contact between the gripper and the material. In Figure 2.3 division of the grippers based on the above-mentioned criteria can be seen.

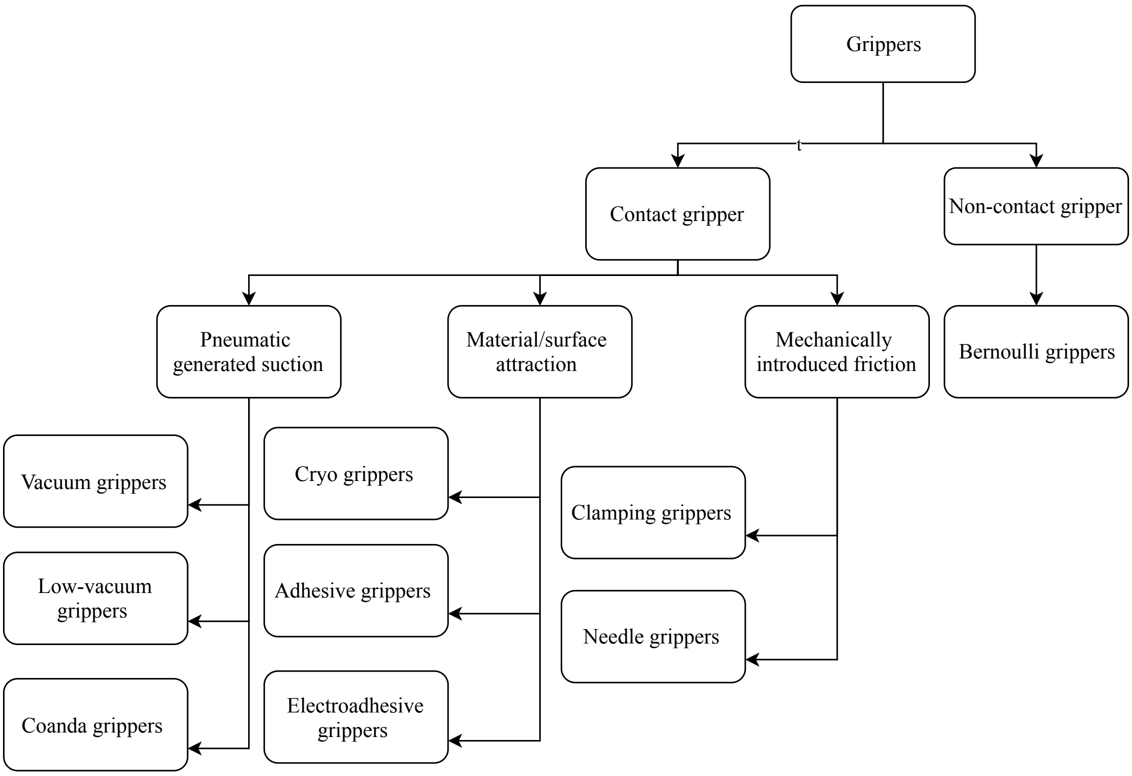


Figure 2.3: Categorising gripper based on their type (Björnsson 2014)

In the following, the working principle of each gripper type will be described and the advantages and disadvantages of them in regard to composite manufacturing will be mentioned.

Bernoulli Gripper: is a noncontact gripper which benefits from the under-pressure created by flowing a high-speed air between the gripper and the object (Dini et al. 2009). The material will be lifted due to the pressure difference and it will float under the gripper. The working principle of this gripper has been illustrated in Figure 2.4. The positive point is that there is no physical contact and therefore the possibility of the contamination or damage of the object due to the contact is less. However, the control of the orientation of the object is harder and also flexible objects can deform due to the air flow (Ozcelik et al. 2003).

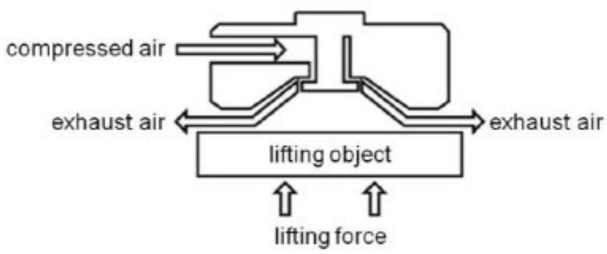


Figure 2.4: Working principle of a Bernoulli gripper (StÃŒhm et al. 2014).

Vacuum gripper: is a gripper based on the Venturi principle. In this gripper, compressed air is directed into a nozzle and due to a decrease in the cross section of the nozzle the airspeed increased and the static pressure decreased. As the air passed the nozzle, it expands and a vacuum will be generated and therefore the air from the vacuum connection will be sucked. Figure 2.5 shows a schematic of vacuum gripper. The compressed air from inlet A introduced to the Venturi nozzle B and due to the created vacuum, the air will be sucked in from port D. Then the compressed air and sucked air will be ejected from silencer C.

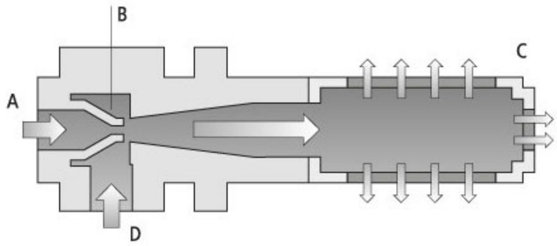


Figure 2.5: Schematic of a Vacuum gripper (schmalz.com 2018)

This method is widely used in the industry to handle objects from different materials, The main challenge for using this kind of gripper is that they are built based on the high suction and low flow rate. Therefore they are not suitable for the objects with porosity. The objects made of flexible materials can be deformed and sucked into the vacuum cup (Taylor 1995)

low-vacuum gripper: is an alternative to the vacuum gripper. As it was mentioned above the disadvantage of the vacuum gripper is that they do not fit to the task of picking the objects that air pass through them. Therefore the low vacuum grippers have been developed and they provide a lower under-pressure but they compensate it with higher flow rate which let to pick up the porous and breathable objects (Lien & Davis 2008). However, if the object is highly flexible, porous, or breathable, still there is the same issue as there were with the normal vacuum grippers.

Coanda gripper: is a type of gripper and is considered an alternative to the normal and low vacuum grippers. The Coanda grippers utilise the Coanda effect to create a secondary air flow which is used to pick up the objects (Lien & Davis 2008).

Cryo gripper: This type of gripper works based on spraying a liquid on the object surface and then make contact between the liquid and a cold gripper and let the liquid to freeze. Since the liquid has frozen on both gripper and object, the gripper can pick up the object (Stephan & Seliger 1999). The release function of the object is faster than the pickup process as the release process is usually done by blowing air in the contact zone of the object and the gripper (Stephan & Seliger 1999). This method is not suitable for the composite materials since there is a risk of exposing the material to the moisture and also contaminate the material.

Adhesive gripper: In this kind of gripper, a sticky surface comes to contact with the object which has to be picked up. This type of gripper is not suitable for the manufacturing of composite structures as there is the risk of contamination of the composite materials (Taylor 1995)

Electroadhesive gripper: Usually, the high voltage applied on the gripper surface creates an attraction between the object and the gripper(Kolluru et al. 1995, Monkman et al. 1989). The main advantage of electrostatic grippers is that they do not damage the object and they neither contaminate the object. In addition, they provide the fast pick up and drop off operations. However, the high voltage needs insulation of the system from the surrounding. This cause the system to be complex(Kolluru et al. 1995).

Clamping gripper: This type of gripper uses a mechanical clamping force to hold the object and lift it. The clamping force causes friction between gripper and object and does not let the object to fall. The drop off the object is easy on this type of gripper since it just needs to open the gripper and it is most suitable to lift objects which both sides are accessible (Taylor 1995). The disadvantage of this type of gripper is that there is a high risk of damaging the material.

Needle gripper: This type of gripper is inserting some needles in the object and therefore there is induced friction between the object and the gripper. This induced friction helps to lift the object and dropping process is done by retracting the needles. The main disadvantage of this gripper is the damage that it causes to the object (Stephan & Seliger 1999).

Table 2.1 shows the summary of the evaluation that has been done above. In this table columns except the last one are the general requirements for the tasks in this project. A green colour cell means that the gripper considered passed the requirement and red colour cell means the gripper failed in regard to that requirement and at the last column is the result of the analysis and show whether a gripper can be used. If a cell in last column is green, it means that gripper is suitable for this project otherwise it cannot be used in this project. Based on the table the suitable grippers for this project are vacuum, low-vacuum, Coanda and elctroadhesive gripper.

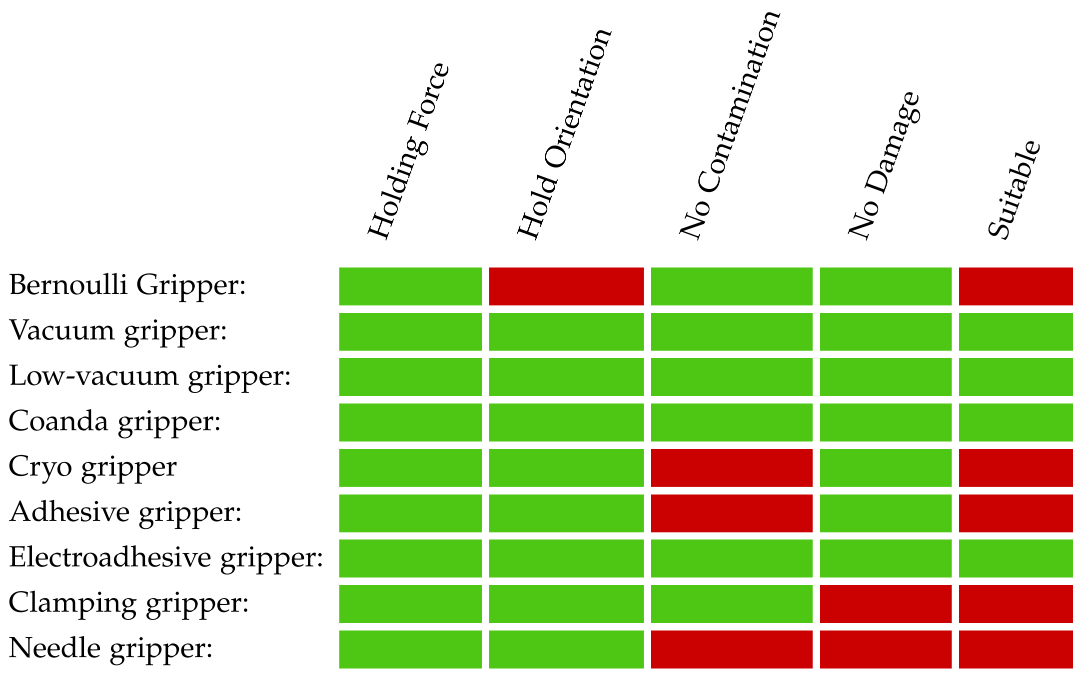


Table 2.1: Summary of the evaluation of the grippers for the tasks in this project

2.4 Proposed gripping tool

In order to remove the baking paper from the Carbon fibre ply, a gripper has been developed previously by Borg (2019) and handed into the author to be used in this project. The gripper has to detach the baking paper from the Carbon fibre ply and then remove it totally from the carbon fibre ply. Figure 2.6 illustrates a 3D drawing of the proposed gripper.

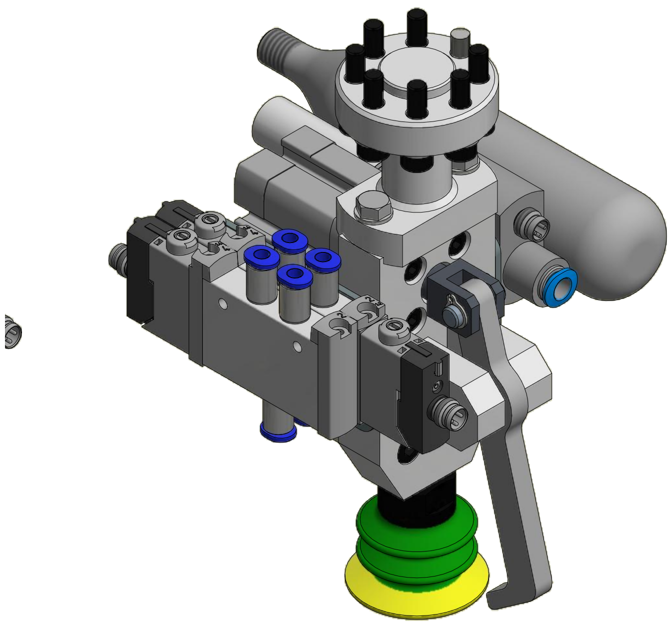


Figure 2.6: 3D model of the proposed gripper (Borg 2019)

The gripper has been facilitated with a compact design. Its features are a vacuum ejector to provide suction to lift the object, a finger to clamp the lifted object and a liquid Nitrogen tank, which will be used to cool the ply and increase its stiffness and reduce the tack.

Therefore, the proposed gripper is a mix of vacuum gripper and the clamping gripper. Although it uses Nitrogen to cool the ply, it is far from a Cryo gripper. in the following paragraphs, the reasoning behind this choice has been analysed and discussed. Before that, it is necessary to know the requirements that have to be met by the gripper. The requirements are:

- Bringing no damage to the ply
- Introducing no contamination
- To be able to remove the baking paper from the ply totally

Based on the above requirement and the analysis has been done over different gripper types in the previous section, this type of gripper seems suitable for detaching the baking paper from the ply. It has been featured with a vacuum gripper. Therefore the first two requirements will be respected since based on the analysis of gripper types the vacuum gripper introduce no damage and no contamination to the object. With respect to the third requirement, it deemed that the finger clamping mechanism can assure the user that the baking paper will not slide off the suction cup as it was mentioned by Björnsson et al. (2013).

Figure 2.7 shows the process that have to be carried out to remove the baking paper from the Carbon fibre ply.

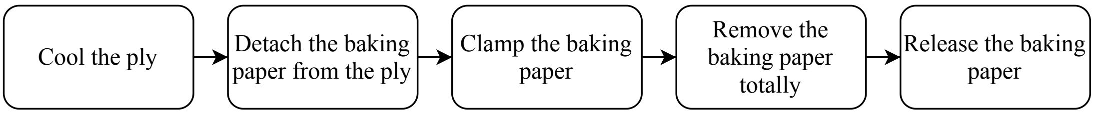


Figure 2.7: The processes of removing the baking paper from the Carbon fibre ply

At this point is good to check if the designed end-effector can carry out the mentioned processes in Figure 2.7. In order to assure that the detaching of the baking paper and the ply happens, a channel has been considered to spray liquid Nitrogen over the baking paper through the suction cup. It will cool down the object and make the carbon fibre ply stiffer and less flexible. This helps to keep the design compact. After reached to required cooling temperature the flow of liquid Nitrogen will be blocked. The flow of Nitrogen will be controlled by a pneumatic valve. Then another pneumatic valve will activate the vacuum ejector and due to created suction the baking paper will be detached from the ply by the suction cup

After the detaching has happened a clamping mechanism will be engaged in order to assure that the baking paper will not slide and being released due to the existence of tack. After removing the baking paper from the ply and reaching to the releasing point of the baking paper the clamping and vacuum ejector will be disengaged and let the baking paper fall off. The whole gripper will be mounted on a KUKA robot to carry out the task. KUKA robots are industrial robots and are highly accurate and therefore the results obtained by using them are reliable.

2.5 Summary

The demand for components made of composite material is increasing and a cheaper and more flexible method is required to be able to answer the demand. Therefore, special consideration has been set to the pick and place concept to be used in the manufacturing of products made of composite materials. The developed tool by Robot tool A/S has been analysed and it showed that it has the potential to be used in the removing of the baking paper from the Carbon fibre ply.

Chapter 3

Problem formulation

As the market for the composite structures and specifically carbon fibres is growing, demand for a more flexible and less costly solution is rising. The FlexDraper project has been developed based on this needs of the market. One of the tasks of the FlexDraper project is to remove the baking paper from the prepreg Carbon fibre ply Based on this and the analysis, the following problem statement is formulated.

"How can the baking paper be removed from both sides of the prepreg carbon fibre ply in an automated pick and place concept?"

3.1 Limitations

1. The gripper has been designed and developed on the forehand and delivered to the author to do the experiment with it.
2. The amount of prepreg to do the experiment with are limited.
3. The tack value of the prepreg plies is not known since the supplier does not provide this value, due to it is very uncertain
4. A robot has to be used to do the experiments.
5. An Epoxy certificate is needed to work with composite materials.

To fulfill this problem statement, the following objectives have been developed.

3.2 Objectives

1. A fixture has to be designed to facilitate the removal of the baking paper from the prepreg carbon fibre ply.
The design of the fixture has to be done based on the product development methodology.
2. To Carry out the assembly and connections of the equipment and develop a control interface and remove the design issues.
Although the gripper has been developed in advance, it has not been used before and therefore some challenges may be faced during assembly and use.
3. An experiment has to be designed systematically to find the influential parameters on the removal of baking paper from the prepreg carbon fibre ply.
It is important to find the influential parameters to make the process robust and reliable.

4. To develop an automated robotic cell to remove the baking paper from both sides of the Carbon fibre ply totally.

Chapter 4

Development of the fixture

This chapter will focus mainly on the development of a fixture to be able to hold the Carbon fibre ply down as the baking paper is peeled off from it. In order to develop the fixture, the concept generation principles will be followed.

4.1 Design Process

In order to develop a product, some general steps have to be gone through. These steps have been illustrated in Figure 4.1. This project will follow these steps to be able to reach to a mature design which can be used in the industry.

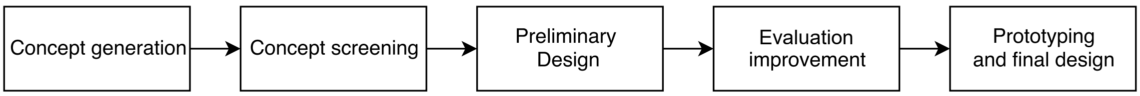


Figure 4.1: The course of a general design process. (Slack et al. 2010, p. 118)

4.2 Concept Generation

This section will mainly focus on the concept generation. the concepts that are generated. Based on the Ulrich & D.Eppinger (2004) a five-step methodology can be used to develop new concepts. These five steps have been shown in Figure 4.2

Step 1: Clarify the problem

It is important to have a clear understanding of the problem and divide it into sub-problems. In order to develop a general understanding of the problem, it is necessary to be familiar with the processes to identify the customer needs and develop the target product specifications and results of these two steps. There are some problems which are complex and handling them as one problem it is difficult. Therefore it is useful to break them down to some simpler and easier sub-problems. All the problems, however, cannot be divided into sub-problems since some of them are extremely simple and breaking them down will not introduce any benefit. The mission here is to develop a fixture. Based on the analysis in section 2.3, the suitable gripping methods to hold the carbon fibre ply in its place are; Non-contact, adhesive, vacuum and Electroadhesive griping technologies. the nature of the object plays the most important role in the selection of a gripping method (Moulianitis et al. 1999, p.15). The composite ply is partly rigid, the

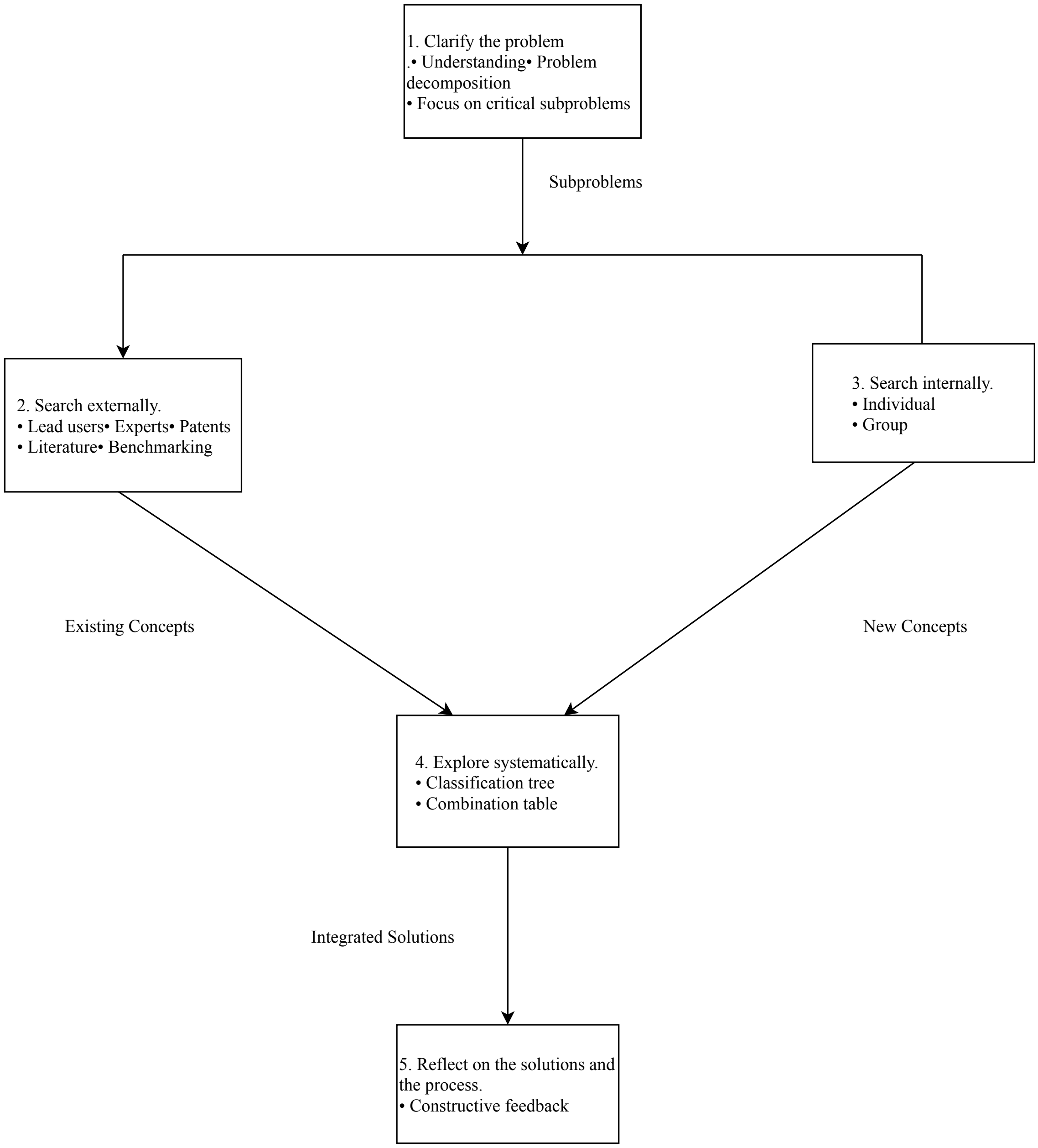


Figure 4.2: The fivestep concept generation method. (Ulrich & D.Eppinger 2004, p. 120)

surface is similar for all the plies and is flat and not breathable. The goal is to hold the ply down by one side as the baking paper is removing from the other side. The weak and strong side of the different end-effectors strategies, which are applicable for this task, are elaborated as follows:

- The Non-contact (Bernoulli gripper) is gentle to the material and deliver a high holding force, but the object is floating so any external force can bring new orientation to the object.

- The adhesive solution can either be chemical or mechanical such as glue or velcro. These solutions are more suitable for small forces or if the use of maintenance on the end-effector is less critical.

- The stick/pin can make a mechanical lock, so it is very strong but it makes small holes from the needles which may result in damage of the ply.
- The suction can adapt to surfaces of different curvatures and will deliver a high force for surfaces with small or none breathability.
- Electroadhesive griper is a very flexible gripping technology which can handle different sizes and shapes easily. However, it is a complex system.

These grippers can hold an object from one side. However, In addition to holding the ply down during the process, there are some other requirements which have to be respected and the selection has to be done based on these requirements. The requirements are as follows:

- It has to bring no or minimal damage to the carbon fibre ply.
- It has to be flexible in terms of handling different shapes and sizes of the carbon fibre ply.
- It has to bring no contamination to the carbon fibre ply.
- It has to hold the orientation of the ply.

The Bernoulli gripper is not able to keep the object fixed since the object is floated into the air. This will cause a high uncertainty on the path that the robot arm has to go through and therefore this type of gripper is not suitable for this application, The adhesive gripper is fast to grip the object. However, there are two issues related to this type of the gripper: (i) This is useful when the amount of required force is known and limited, which is not the case here. (ii) The releasing of the object requires an additional mechanism. Therefore, this type of gripper is not fitting the application too.

The stick/pin can hold the object fixed and the required time for gripping and releasing is considerably small. Nevertheless, the risk for damaging the object or introducing contamination to the object is high. Hence this type of gripper is neither suitable. Electroadhesive griper is a very suitable gripping technology which introduces no damage to the object and can handle different shapes and sizes. However, it needs an isolated area and high voltage which make the design complicated. The vacuum gripper is fast and able to hold the object fixed. In addition, it introduces minimum damage and no contamination to the object. According to this analysis of each gripper technology, the chosen one will be the vacuum gripper technology.

Since the function of this product is simple. It will not be therefore divided into sub-problems.

Step 2: Search Externally

The initial search for ideas can be internal and external. The initial external search will be to investigate if any existing solutions can be used (Slack et al. 2010, p. 120). The external search is to see if existing solutions or sub-solutions exists, why a search in the sub-suppliers for the composite industry is relevant. The search has shown there is a solution around this industry. The used solution is the vacuum table which is producing by different companies around the globe. This solution sounds promising for performing the task. Since an existing solution has been found, There is no need to follow the next steps of concept generation methodology and this solution can be used.

Based on the existing solution, a vacuum table which can satisfy the following requirement will be fabricated.

- It has to be flexible in terms of installation on different work tables and handling different shapes of plies.
- It has to be as compact as possible to reach to the required vacuum as fast as possible.
- It has to have a cross-sectional size which the draping frame can sit on it and the holes cover the operational area of the draping frame which means the operational area of the fixture has to be 41.5 cm in length and 34.5 cm in width as it is the operational area of the draping frame.
- it has to be made of a material which brings no contamination to the plies.

With consideration of all the requirements, a fixture has been developed and the rendered version in a CAD program can be seen in Figure 4.3.

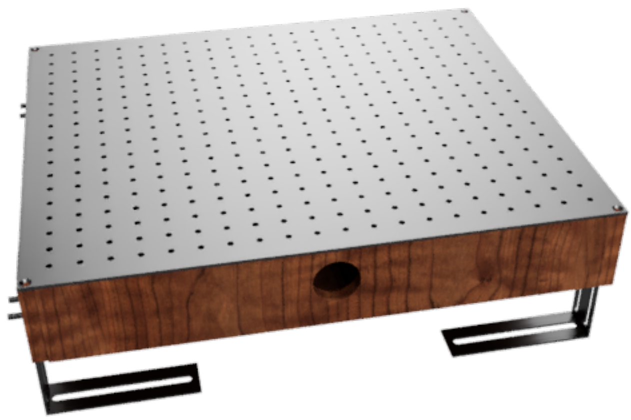


Figure 4.3: The developed fixture.

The top plate of the fixture has been made from the stainless steel to insure about the rigidity and also no contamination requirement. The material choice for the bottom and the lateral plates is not critical issue since they have no direct contact with the plies and the only requirement is to be able to withstand the force created due to the vacuum. Five millimetre deemed to be a suitable dimension for the diameter of the suction holes. The reason for choosing this dimension is that a bigger diameter can case damage to the ply as the ply may be sucked in which cause the damage to the fibres. A smaller diameter, from the other side, may not produce enough force to keep the ply down as the end-effector remove the baking paper from the ply. The produced force by each hole can be calculated as follows:

$$F = \Delta P \pi \frac{d^2}{4}$$

where d is the diameter of the hole. the total amount of force which will be imposed to the ply by n holes will be equal to:

$$\text{Total Force} = n \Delta P \frac{d^2}{4} p$$

In this project, since one of the requirement was to be able to handle different shapes of plies and it has deemed the smallest length of a ply will not less than two centimetre. therefore it has been decided that the distance of the holes from each other to be about two millimetre. This provides a flexibility to handle any ply with any shape. If the covered area by the ply is smaller than the effective area of the fixture, the extra holes has to be blocked to let the vacuum being generated and created force can hold the ply down. The fixture has been facilitated with modular legs which let to install the fixture on any table. The only pieces of fixture which may need to be changed are the installation legs. The legs can be easily unscrewed from the fixture and changed with a new set which are designed for the new table if the table specifications is out of the range that current legs can support. The current designed legs can support a table with maximum thickness of 11 cm and a width of 45.5 cm. The technical drawing of the fixture can be found in the appendix A.

Chapter 5

Proof of concept

In this chapter, the concept will be tested to gain more insight into the developed concept and check some assumptions. The developed end-effector has been assembled and mounted on a KUKA robot and each component has been tested to verify the assumptions that have been made during the development. However, based on these tests some modifications have been introduced into the developed concept.

5.1 Proof of Fixture

The first step in the proof of concept is to make sure each of the parts is working individually properly.
Purpose:
The aim is to investigate the functionality of the developed fixture.
Procedure:
In order to test the fixture, it has been connected to a vacuum cleaner and an A4 paper has been set on the top plate of the fixture as it can be seen in Figure 5.1 and the uncovered holes with paper have been blocked. then the vacuum cleaner was turned on and tried to remove the paper from the table.

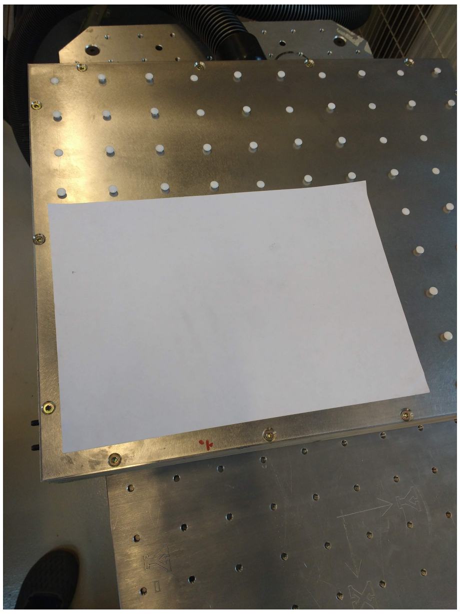


Figure 5.1: Setup of the fixture test

Results and discussion:
The experiment showed that the fixture is able to hold the paper down although with increasing the applied force it was possible to take off the paper from the fixture. However, since the amount of required force is not known and later on is possible to use a vacuum pump or vacuum ejector based on the needs instead of vacuum cleaner, the fixture considered working properly.

Conclusion:
The fixture is working and it deems to be suitable for the task.

5.2 Test of Suction Cups

The next component is the suction cup.
Purpose:
The aim is to investigate the suitability of the suction cups for the tasks in this project. In another word, The suction cups will be tested to check whether they can produce enough force to detach the baking paper from the Carbon fibre plies and since the baking paper is a flexible material, they are able to handle this material.
Procedure:
The author has been limited to three suction cups, which are shown in Figure 5.2. Two green suction cups are made of Polyurethane 60. The model number is Piab-BX35P and author has no access to the technical data related to the red suction cup. The green suction cups are made of Polyurethane 60. The red suction cup is more flexible than the green suction cups. Therefore, it has been used in this project and it deemed that it may respond better with handling of a highly flexible material.

Figure 5.2: Three suction cups that have been used in this test.

Two type of tests will be carried out over these suction cups.

1 Weight carrying test.
This test will show measure force each suction cup can handle.

2 Handling flexible object.
This test will check the capability of the suction cups in handling a flexible object.

The end-effector has been installed on a KUKA robot. During the mounting, it has been realised that the diameter of the mounting area of the end-effector needs to be reduced by 1 mm to be able to mount and demount the end-effector easily on the robot. In addition, the electrical connection has been established and the shematic of electrical diagram can be found in appendix C. However, the pressure of feeding air for the vacuum ejector has been set to vary between 3 bar and 7.5 bar with a step of 0.5 bar. the measurement for each pressure has been replicated 3 times to assure about the accuracy of the measurements. The next test is to investigate whether they are suitable for the job of handling a flexible material. For this purpose, an A4 paper has been picked up by the suction cup when the feeding air pressure to the vacuum ejector was 7.5 bar.
Results and discussion:
The graph in Figure 5.3 shows the average load carried by each suction cup. The Piab-BX35P with green sealing lip suction cup has the highest load carrying capability with maximum load carrying of 5 kg and the red suction cup has the minimum load carrying capability with the maximum carried load of 2.2 kg. The graph also shows that the maximum load carrying capability for the suction cups happens between 4 bar and 4.5 bar.

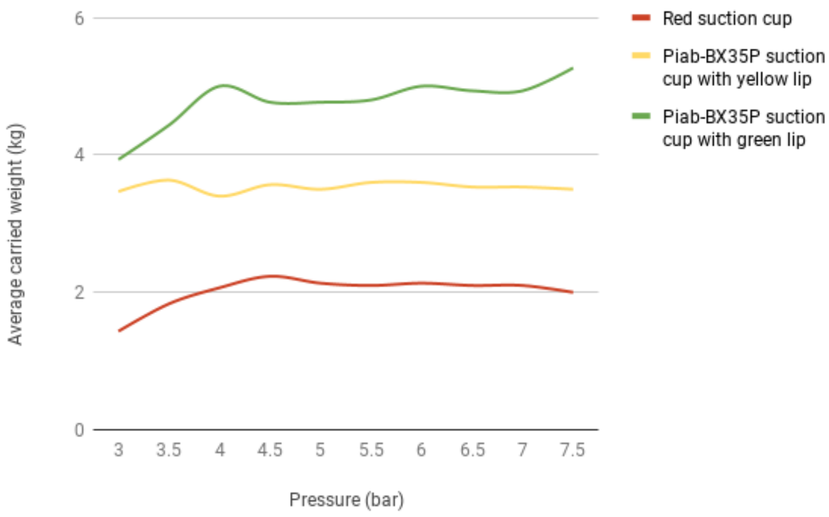
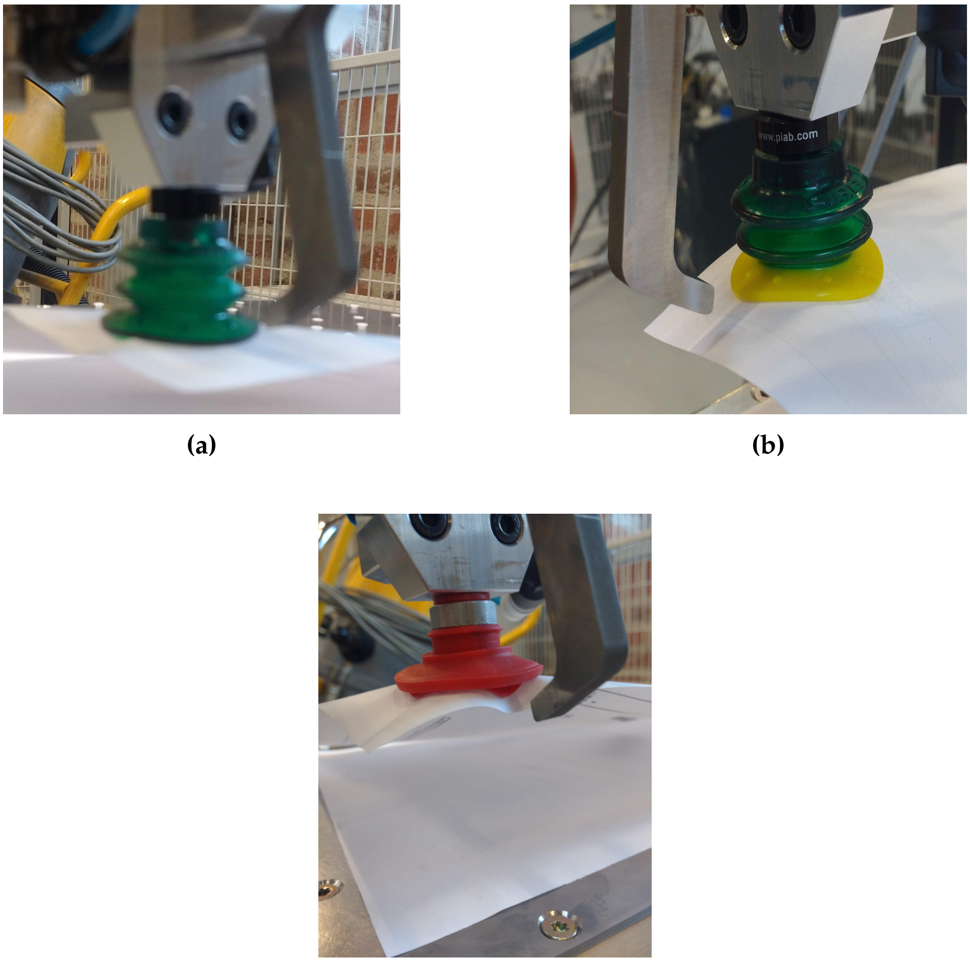


Figure 5.3: The load carrying capability of suction cups.

Since the amount of load which has to be carried is not known and it has been considered to be less than the carrying load capability of the suction cups, all of them considered promising in the handling of the task. Figure 5.4 shows the results of the second test. As can be seen in Figures 6.11(a) and 6.11(b), none of the Piab-BX35P suction cups collapsed when held the paper. In contrast, the red suction cup collapsed as can be seen in Figure 5.4(c).



(a) (b)

(c)

Figure 5.4: Test of suction cups

The other observation from the Figure 5.4 is if the suction cup does not collapse, the finger cannot clamp the object to the suction cup and therefore the suction cup will be rejected from the use in further investigations. Based on this argument the only remained suction cup for further investigation is the red suction cup.

Conclusion:

All the suction cups regarding to the first test which is the load carrying capability are considered acceptable since the amount of load which the suction cup has to cope with is not known. However, in the term of handling a flexible and light object, only the red suction cup showed appealing and it has been concluded that the stiffness of the suction cup has affect on the collapsing of the suction cup as it handles the object. In order to be able to clamp the object by the finger it is necessary the suction cup collapses as it holds the object.

5.3 Liquid Nitrogen

Before any talk about this test, it is necessary to point out a modification that has to be done during the assembly. In the developed design for the end-effector, only one

pneumatic valve with one inlet port has been considered to control the feed of the liquid Nitrogen and the compressed air to the vacuum ejector. Since they are two different material, they need different inlet ports to be fed to the system through them. Therefore, another pneumatic valve has been added to the design to overcome this issue. Therefore the pneumatic diagram of the design has been modified and can be seen in appendix B.
Purpose:
The aim of testing this feature is to check whether the liquid Nitrogen provides enough cooling effect that can be used in the project.
Procedure:
For this purpose the liquid Nitrogen has been sprayed over a thermometer for a set of time spans and the temperature has been measured. The liquid Nitrogen has been sprayed over the thermometer for 30 s, 60 s, 120 s, and 240 s.
Results and discussion:
The measured temperatures are tabulated in Table 5.1

Time (s)	Temperature (^oC)
0	22.7
30	22.5
60	21.5
120	19.6
240	17.4

Table 5.1: Measured temperatures

Based on the data in the table, it is clear that the liquid Nitrogen cannot cause a big temperature difference and this is due to the fact that the used hose to attach the Nitrogen tank to the end-effector is long and Nitrogen gets warm as it reached to the end-effector and cannot provide effective cooling.
Conclusion:
It has been concluded that with the current setup using of liquid Nitrogen as a coolant is not beneficial for the project since it is not providing an effective cooling effect in a short time.

5.4 Test of the Concept

Purpose:
As each feature has been tested and they work well individually, it is the time to check if they work also properly together.
Procedure:
Since the carbon fibre is an expensive material, the number of samples are limited, and work with prepreg Carbon fibre needs Epoxy certificate, the first stage of this investigation has been continued with the A4 papers. If this step was successful in the next step the carbon fibre will be used. At the beginning, two A4 paper have been piled on each other over the fixture. Then it has been attempted to separate them from each other. IN occasion of succession in this step, then the experiment will be repeated with the actual material, which is the pre-cut prepreg carbon fibre ply. During the test in this stage the air feeding pressure to the vacuum ejector was fix and equal to 5 bar and to create

vacuum inside the fixture a vacuum cleaner has been used in the beginning and have been changed to two vacuum cleaner later and at the end a vacuum pump has been used.

Results and discussion:

It can be seen in Figure 5.5 the solution is able to separate the A4 papers from each other and clamp the top one with the finger.

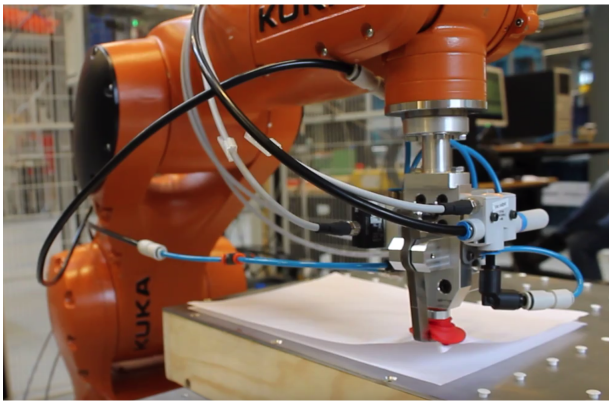


Figure 5.5: Paper separation test

Since this step was successful, the same test has been carried out over the plies. The results showed that the Vacuum table is not able to hold the ply down when a vacuum cleaner is used as a vacuum maker. The pressure inside the vacuum table has been measured and the vacuum cleaner has reduced the pressure inside the vacuum table from 1033.1 mbar to 981.9 mbar. Based on these results, another vacuum cleaner has been added to the setup. The measured pressure in this setup was 853.3 mbar and the test results showed that the vacuum table is able to keep the ply down as the end-effector detach the baking paper from the ply. The second setup can be observed in Figure 5.6.

Figure 5.6: Setup with two vacuum cleaner

Since this setup showed that the solution is promising, it has been decided to replace the two vacuum cleaner with a vacuum pump for the rest of the investigation. The vacuum pump is able to make an even stronger vacuum than the two vacuum cleaner and since there was no need for a big flow, the vacuum pump gets priority to the vacuum ejector.

In a test, it was founded that the vacuum pump can reduce the pressure inside the vacuum table to 678.3 mbar in 5 seconds. It has been considered fast enough for this task. Figure 5.7 shows the measured pressure inside the vacuum table when the vacuum pump is used. This shows that the vacuum pump has produced even a greater vacuum than the two vacuum cleaner created.

Figure 5.7: Measured pressure inside of vacuum table while using a vacuum pump for 5 second

It has been tested to check the solution again and assure that the vacuum table can hold the ply down as the end-effector detach the baking paper from the ply. Figure 5.8 shows that the vacuum table is able to hold the ply down as the gripper separate the baking paper from the ply. However, in this stage, the clamping process has not been checked not to damage the Carbon fibre plies.

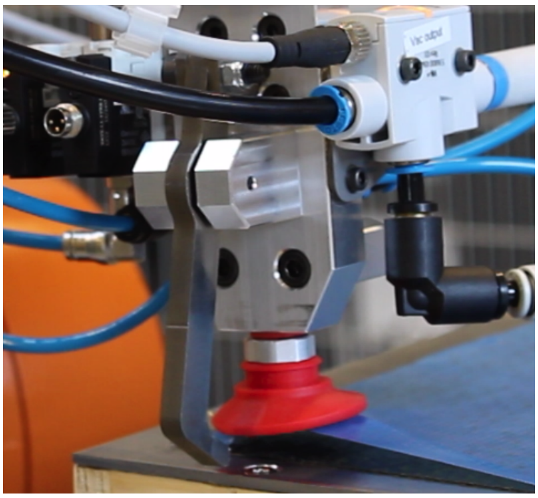


Figure 5.8: Detaching of the baking paper from the ply

Conclusion:
Based on the results, it can be said that the proposed solution is feasible. However, there are still some challenges that have to be answered before being able to make it industrial ready solution. One of the challenges is that in some cases the end-effector instead of detaching baking paper from the ply it has separated the baking paper and ply from the other cover of ply, This can be seen in Figure 5.9.

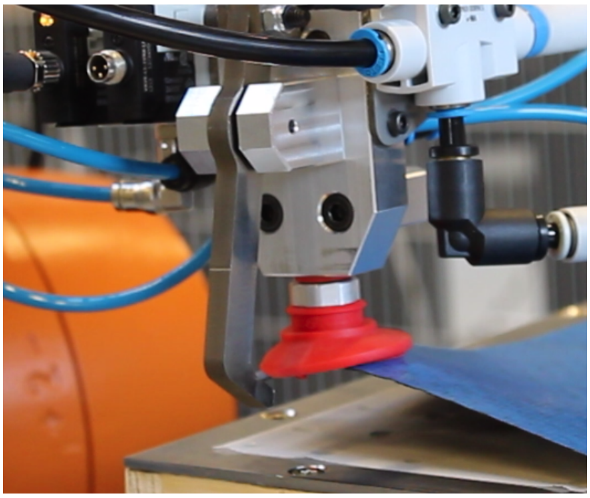


Figure 5.9: Detaching of the baking paper and the ply from the other cover of ply

and in some other cases, it has been observed that the vacuum table cannot hold the ply down as the gripper was detaching the baking paper. Therefore, a deeper investigation is needed to find out the influential parameters and based on that define a more reliable detaching process. It has also observed that the liquid Nitrogen has not an effecting cooling influence and therefore, there is not a benefit to use the liquid Nitrogen in the current configuration of setup. It is possible to make a new configuration for the setup, but it is time-consuming and the requirement for cooling has not been confirmed. Hence, it has been decided to carry out the investigation further without using the liquid Nitrogen.

5.5 Summary

In this chapter, the functionality of each feature of the concept has been investigated individually and later the functionality of their combination has been checked. It has been realised that the suction cup has to be flexible in order to collapse when it lift up the baking paper and the liquid Nitrogen in the current setup is not working as it has been expected. The pneumatic diagram of the setup has been modified and finally it has been concluded that the solution is promising and more investigation is needed to find the influential parameters.

Chapter 6

Design of Experiment

It has been concluded in the previous chapter that there is a need to do further investigation on the detaching of the baking paper from the Carbon fibre ply to find the influential parameters.

Therefore, this chapter will focus on to design a set of experiment to distinguish some influential parameters. In order to define whether the influence of a parameter is significant, a statistical analysis has to be done. The statistical method which will be used in this chapter to do the analysis is ANOVA method.

6.1 Design of an Experiment Principles

In this section, different principles which are used in the design of an experiment will be introduced based on the book of Design and Analysis of Experiments (Montgomery 2013). The first principle is there are two types of inputs which contribute to the outcome of each experiment. They are controllable and uncontrollable inputs. The controllable input parameters are those that are under the control of the practitioner in an experiment such as the feeding air pressure. The uncontrollable input parameters are those that cannot be modified in an experiment such as the ambient temperature. The uncontrollable input parameters have to be recognised and therefore realised how they may affect the outcome of the experiment. The outcome of the experiment is called response which can be in the form of a numerical measurement or binomial. In an experiment, the controllable input parameters are modified to optimise the response. Figure 6.1 illustrates the relationship between the input parameters and the response.

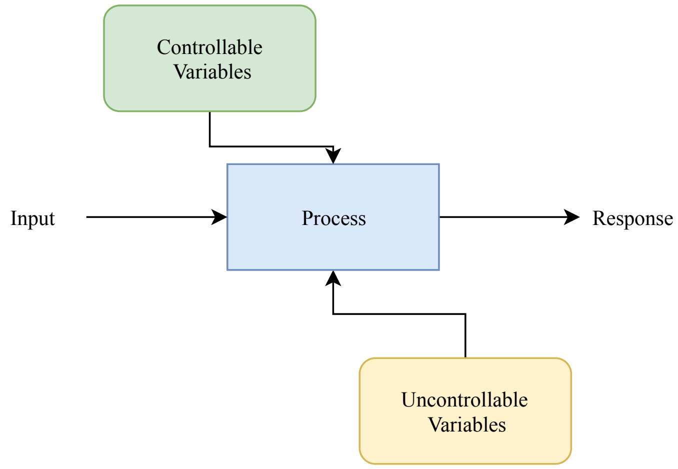


Figure 6.1: Relationship between the process parameters and response of the process

Among the controllable input parameter, some will be chosen to be modified and these parameters are called variable. If the number of the variable is more than two then the interaction is something that should be considered. Interaction is a situation when the concurrent effect of variables on the response is not linear and additive. In this study some of the controllable parameters are:

- Position of the suction cup
- Feeding air pressure
- Suction cup material
- suction cup size

Ambient temperature and the tack value of the plies have been considered as the non-controllable parameters.

Some other concepts are hypothesis testing and blocking. Hypothesis testing will be used in order to find influential input parameters. In hypothesis testing, two statements will be investigated by the help of statistical methods to determine whether a parameter is influential. The two statements are null and alternative. The null statement is true when the parameter has no big effect on the response and the alternative is true when the parameter has a significant influence on the response. Blocking is a method to prevent any undesired change on the input parameters. An example for blocking is to use the same equipment in the experiments to avoid any effect on the results due to change of the equipment.

The last concept is replication. The aim of replicating an experiment over and over is to be able to minimise the role of the element of chance. These concepts are the fundamental principles of the design and analysis of experiment.

6.2 ANOVA Test

This sections content is mainly based on Gurchetan Singh (2018). In order to reject the null hypothesis and accept the alternative, it is necessary to do a statistical analysis. Through the statistical analysis is possible to say whether an input parameter influence over the response is significant. One of the statistical method to investigate this is the ANOVA method.

ANOVA checks if the means of the groups are different from each other. Through this, it is possible to find significant factors. In ANOVA two type of mean values are used; Grand mean μ and separate sample mean μ_i. Grand mean is the mean of all the observations together while a separate sample mean is the mean for each sample group. If the separate sample means has no significant difference, it means the null hypothesis is valid. The alternative hypothesis can be valid on the other hand if at least one of the separate sample means is significantly different from others.

In ANOVA there are some values which have to be calculated. Here the calculation method for values of a two way ANOVA will be presented,

Sum of Squares of each factor: It is easier to explain the calculation by an example. If there is two group within factor one; a and b, then the Sum of Squares of factor one is equal to

$$\text{Sum of Squares of factor one} = \sum_{1}^{j}(\mu_{1,a} - \mu)^2 + \sum_{1}^{j}(\mu_{1,b} - \mu)^2$$

where j is the number of the observations in a group. and the same method will be used to calculate the sum of squares of the other factors

Sum of Squares Within(Error): If the score value for i^{th} observation in group a for first factor is $S_{i,1,a}$ and there are three groups within second factor; e, f, and g, the Sum of Squares Within(Error) will be calculated as follows:

$$\begin{aligned}\text{Sum of Squares Within(Error)} = {} & [\sum_{i=1}^{j}(S_{i,1,a} - \mu_{2,a,e})^2 + \sum_{i=j+1}^{k}(S_{i,1,a} - \mu_{2,a,f})^2 \\ & + \sum_{i=k+1}^{l}(S_{i,1,a} - \mu_{2,a,g})^2] + [\sum_{i=1}^{j}(S_{i,1,b} - \mu_{2,b,e})^2 \\ & + \sum_{i=j+1}^{k}(S_{i,1,b} - \mu_{2,b,f})^2 + \sum_{i=k+1}^{l}(S_{i,1,b} - \mu_{2,b,g})^2]\end{aligned}$$

where l is the number of observation in total and j is the number of observations in sample group of e. **Sum of Squares Total**: If the score value for i^{th} observation is S_i, the value will be calculated as follows:

$$\text{Sum of Squares Total} = \sum_{i=1}^{j}(S_i - \mu)^2$$

where j is the total amount of the observations.

Sum of Squares Both Factors: This value will be calculated in the following way:

$$\begin{aligned}\text{Sum of Squares Both Factors} = \text{Sum of Squares Total} - [&\text{Sum of Squares Within(Error)} \\ & - \sum_{i=1}^{2}\text{Sum of Squares of factor i}]\end{aligned}$$

where i is the factor number.

Degree of Freedom: the degree of freedom for the sum of squares of each factor is equal to the number of the groups within the factors minus one. and for the sum of squares within (Error) is equal to the summation of the number of observation in each individual group within second factor minus one. The degree of freedom for the sum of squares for both factor is obtained by multiplying the degree of freedom for sum of the first factor to the degree of freedom for sum of the second factor.

The degree of freedom for the sum of squares total equals the accumulation of all the aforementioned degree of freedoms.

Mean Square: for each parameter is equal to the value of that parameter divided to the degree of freedom of that parameter.

F Score: For sum of square of each factor and sum of square of both factor is equal to its mean square divided to the mean square of the sum of squares within (error).

Interpretation: After calculation of the F scores for each, is time to interpret the meaning of this F scores. For this, it is necessary to read the critical value of F for each factor from the F distribution table which can be found in the book of design and analysis of experiment (Montgomery 2013). If the F score is greater than the critical value then the null hypothesis is not valid.

6.3 Tests

In order to investigate the effect of position of the suction cup and feeding air pressure to the vacuum ejector on the success of the foil detaching process, a series of experiments have been carried out. Three positions have been selected for the suction cup and also three different pressure values for feeding air have been chosen based on the load carrying tests of the suction cups. The three feeding pressures are three, four and five bars while the suction cup will be located in three different positions as shown in Figure 6.2.

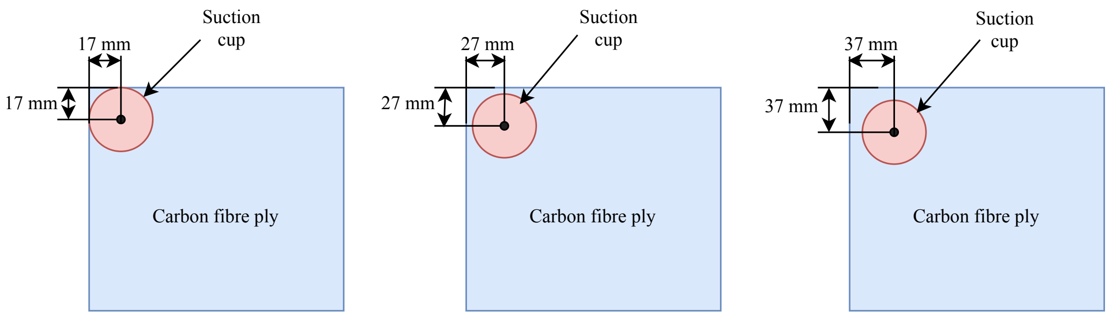


Figure 6.2: Different positions of the suction cup

The test has been conducted randomly to avoid any sensory discrimination. The result considered as successful if the foil has been detached from the Carbon fibre although it may not be lifted up otherwise it has been considered a failure. Each test has been replicated 3 times. Higher number of replication provides more accurate results (Gauch Jr 2006). It was not, however, possible here to carry out the experiment with a greater number of replication since the number of samples were limited and therefore three replication has been chosen. The results of experiments have been summarised in Table 6.1. In this table P means pass and F means fail.

		Pressure (bar)								
		3	3	3	4	4	4	5	5	5
	1	F	F	F	F	P	F	P	F	P
Position	2	P	F	P	F	F	F	P	F	F
	3	F	F	F	P	F	F	F	F	P

Table 6.1: Results of the experiment

The first step of doing statistical analysis is to establish the null hypothesis. In this investigation effect of two independent variables over the success of the experiment will be studied. Therefore three null hypotheses have to be considered.
Hypothesis 1: The position of suction cup has no significant effect on detaching of the baking paper from the prepreg carbon fibre ply.
Hypothesis 2: The feeding aire pressure to the vacuum ejector has no significant effect on detaching of the baking paper from the prepreg carbon fibre ply.
Hypothesis 3: The interaction of feeding air pressure and the position of the suction cup has no significant effect on the detaching of the baking paper from the prepreg carbon fibre ply.

Since the effect of two independent variables is going to be investigated, a two way ANOVA test has been chosen to be used as the tool for the analysis of the results of the experiment.

In order to be able to do the statistical analysis, it is necessary that the distribution of the results is normal. Since the results for this test are percentage, they do not have a normal distribution and a function has to be used to transfer the distribution to the normal distribution. In order to change the distribution from percentage to a normal distribution, square roots and arcsin functions can be used together (Manikandan Jayakumar 2012). Therefore, the square roots and arcsin function has been used in this study to convert the distribution of the results from percentage to normal.

The result of the ANOVA test has been shown in Table 6.2. As it can be seen on the table the F_{crit} values for the position and feeding pressure is greater than the F values for these two parameters. This means that these two factors have no significant effect on the success of the experiment individually. Their interaction influence on the result, however, is statistically significant.

	Sum of Squares	Degree of Freedom	Mean Square	F	Fcrit
Sum of Squares of factor one	0.19	2	0.095	0.27	3.55
Sum of Squares of factor two	1.37	2	0.68	1.94	3.55
Sum of Squares Both Factors	6.06	4	1.51	4.29	2.93
Sum of Squares Within(Error)	6.35	18	0.35		
Sum of Squares Total	13.96	26	0.54		

Table 6.2: ANOVA analysis results

6.4 Change of Suction Cup

In the previous experiment it has been observed that though the end-effector is able to detach the baking paper from the carbon fibre ply, it was not able to pick it up. Therefore some further analysis and experiment have been conducted to establish a fundamental understanding of the process of picking up the baking paper.

Figure 6.3 shows one of the successful attempts to detach the baking paper from the ply. In this attempt, the end-effector was moved straight up after the detaching. As it can be seen in the figure the baking paper has been picked up until it reached a certain level and then it will fall off due to the interaction of different forces and deformation of the baking paper. The yellow line in the figure shows the border between the detached area and undetached area. This border acts as a hinge.

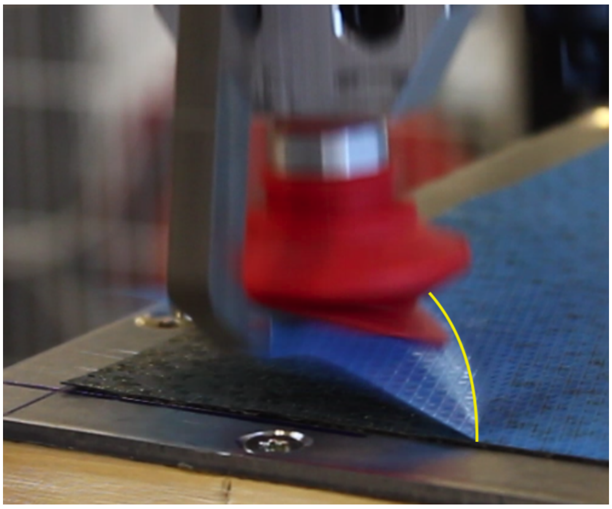


Figure 6.3: Detaching the baking paper from the carbon fibre

Since different forces are involved in the process, it is necessary to analyse them. five different forces are acting on the baking paper.

- Weight W: The first force is the weight of the part of the baking paper which has been detached.
- Dynamic force F_d: Due to the acceleration of the end-effector.
- Friction F_f: This hinders sliding of the baking paper against the suction cup and comes to consideration during the horizontal movements.
- adhesion force F_ad: This force is due to the tack. This force is a distributed force and increases as the area which should be detached increases.
- Pulling force F_p: The pulling force introduced by the suction cup.

The free diagram of the baking paper on the onset of detaching is similar to Figure 6.4. Since it is going to detach the baking paper from the ply, F_p has to be greater than the adding up of the other two forces shown in Figure 6.4.

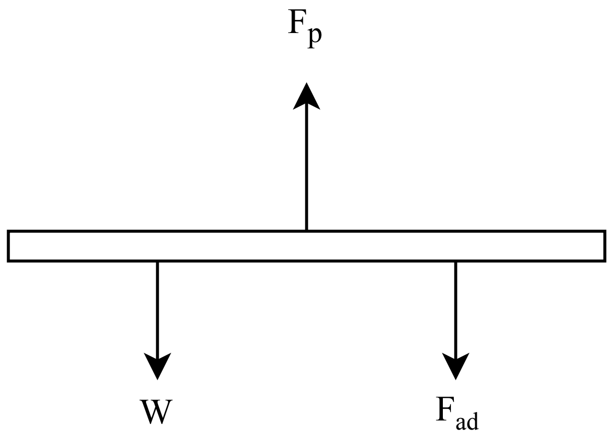


Figure 6.4: Free diagram of the baking paper on the onset of detaching

Therefore the equation is as follows:

$$F_p > F_{ad} + W$$

When the detachment happened and the end-effector moves upward dynamic force will be added to the diagram due to the acceleration of the end-effector. Therefore the free diagram of the baking paper changes to Figure 6.5.

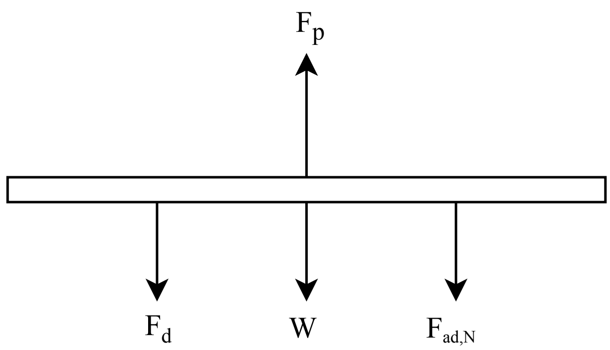


Figure 6.5: Free diagram of the baking paper after detaching

Based on the new diagram the equation will be updated as:

$$F_p > F_{ad,N} + W + F_d$$

As the end-effector goes higher the right side of the equation will become greater and the left side is whether constant or more realistic it reduces. Therefore there is a point that the right side of the equation is greater than the left side and it is where the baking paper falls off. The main reason for the decrease of F_p is the leak of air due to the deformation of the baking paper. First of all the baking paper will wrinkle as it detaches from the ply and sucked in the suction cup. these wrinkles provide some channels that air can leak through them. Secondly, as the end-effector moves upward the contact area between the suction cup and the baking paper from a horizontal surface change to a sloped surface. The suction cup can compensate this slop in some degree by opening the folds as it can be seen in Figure 6.4. After a specific degree, however, the contact between the suction cup and the baking paper fails at some points and air easily leaks through and reduce the F_p remarkably. This results in the total release of the baking paper.

In order to confront the reduction of F_p, it is not possible to prevent the wrinkle of the baking paper. However, it is possible to tilt the end-effector with some degree. In this way, the suction cup can follow the surface of the baking paper for a longer time and therefore it can lift the baking paper higher than before. It can be seen in Figure 6.6 That the suction cup could pick the baking paper up to a certain level and hold it there.

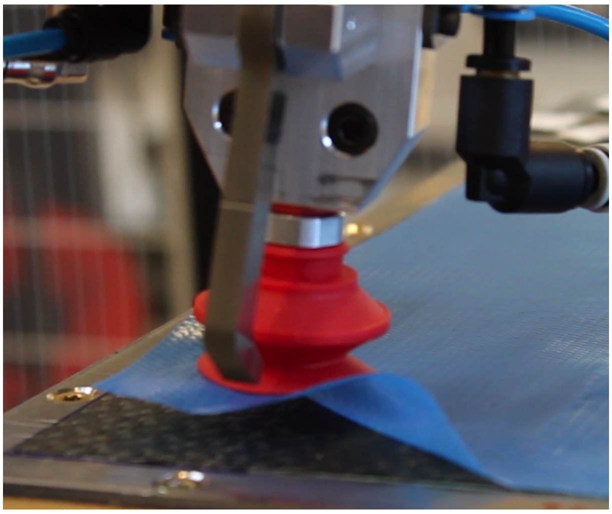


Figure 6.6: Picking up the baking paper with a tilted end-effector

However, the suction cup is not following the surface of the baking paper totally and it will have a considerable amount of air leakage which causes total unfold of the suction cup. Since the suction cup opens its folds to compensate with the tracking of the surface of the baking paper, it is impossible to clamp the baking paper between the finger and the suction cup. If the finger is activated, it will hit the suction cup and as the aftermath of this impact the baking paper will be released and fall off.

If the suction cup has a bigger radius, this can be even a greater issue since the baking paper surface will have stronger deformations. Based on this observation it has been decided to use a suction cup with a smaller diameter. In the meantime, the amount of force which has been generated by suction is dependent on the suction cup diameter based on equation 6.1.

$$F = \Delta PA = \Delta P\pi\frac{d^2}{4} \tag{6.1}$$

where d is the diameter of the suction cup and ΔP is the pressure difference. Therefore a smaller suction cup means a smaller amount of force, which has to be noticed.

Since the smaller suction cup due to its smaller volume need less vacuum to collapse and the amount of leaked air will be less, the suction cup will be mostly collapsed when it reaches to the point where the finger has to be activated to clamp the baking paper. The more collapsing is due to the smaller suction cups has a smaller volume and therefore with a smaller vacuum can collapse.

Some experiments with a smaller suction cup. SMC ZPT80HBN-B16, have been carried out. Figure 6.7 shows the result of one of these experiments. As it can be seen the suction cup is still collapsed and reduces the chances that the finger may hit the suction cup.

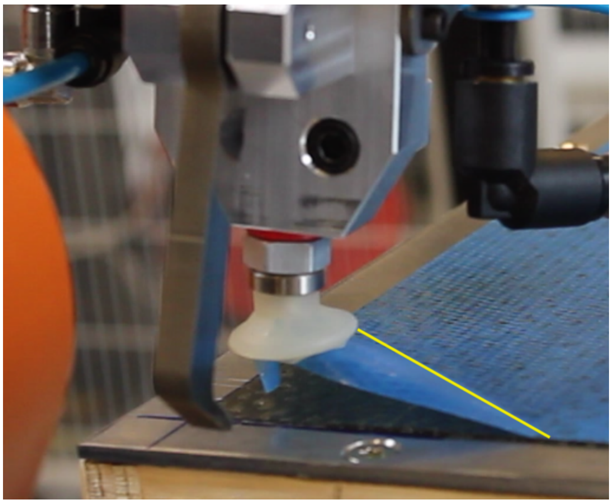


Figure 6.7: Picking up the baking paper with a smaller suction cup

The several experiments which have been conducted by the use of the smaller suction cup, shown that the smaller suction cup is more stable to detach and pick the baking paper. However, tries for clamping the baking paper were not successful since the finger was hitting the edge of suction cup most of the time and failed to clamp the baking paper. The main reason is that the finger has been designed to work with a bigger and a fully collapsed suction cup. Therefore, there is not enough clearance between the suction cup and the finger and the finger hits the edge of the suction cup and also due to the leakage the suction cup is not fully collapsed and this is also a reason that there is not enough clearance. This can be seen in Figure 6.8.

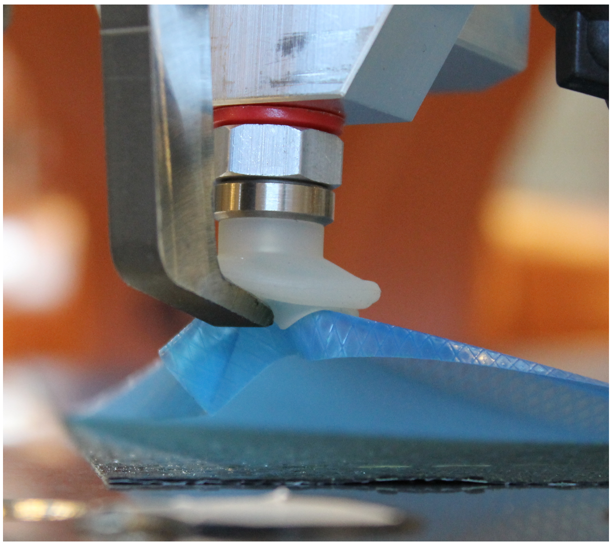


Figure 6.8: A close-up image from the finger and suction cup when the finger was activated

This shows that the design has to be changed in a way that the finger can clamp the baking paper. This will be the topic of the next section.

6.5 Clamping mechanism

As it has been mentioned in the previous section the clamping mechanism has to be improved. In order to find a better solution, the mechanism has been redesigned in a CAD software, Autodesk Fusion 360, in a form of a conceptual design. With a conceptual design in a CAD software, it is possible to see the limitations better and make a better decision. In the CAD program different design has been tested to see whether it is possible to make the clamping mechanism works without introducing a dramatic change in the whole end-effector.

One of the scenarios was to change the tip of the finger path with changing the distance of the rotation centre of the finger to a closer distance to the base of the tool. The design showed that the distance cannot be changed in a big span. If the distance reduced from 20 mm to less than 17 mm, the tip of the finger will interfere with the suction cup and it will prevent the suction cup to work. Therefore, the maximum possible change is 3 mm and this is not enough to cause the tip of the finger goes under the suction cup and clamp the baking paper. Figure 6.9 shows when the distance of the rotation centre of the finger is on 15 mm and finger is in the opening position. As can be seen in the figure, though the finger is on the opening position, the tip of the finger has been positioned below the suction cup. Since in this design the suction cup has been considered in the collapsed mode, in the reality the finger will hit the middle of the suction cup and will cause the malfunction of the suction cup.

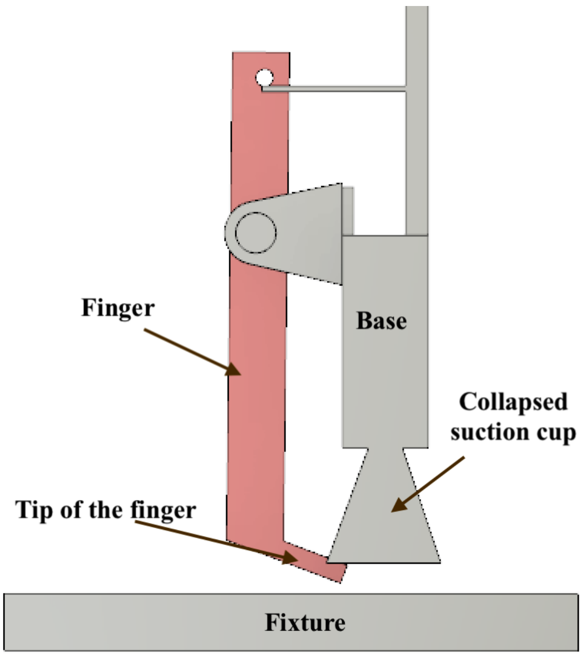


Figure 6.9: Position of finger at opening when the rotation center is in 15 mm

Second scenario that has been investigated it was to increase the length of finger and decrease the angle of the tip of the finger with the body of the finger. This shows that it will improve the mechanism slightly. However, Its path may not assure the clamping happens. The length of finger can be increased by 7 mm and the angle has been reduced from 110 degree to 90 degree. Figure 6.10 shows the finger in the clamping position and as can be seen the finger still do the clamping on the far edge of the suction cup and due to unpredictable deformation of the baking paper and the suction cup, there is a big risk of failure without introducing further changes in the design.

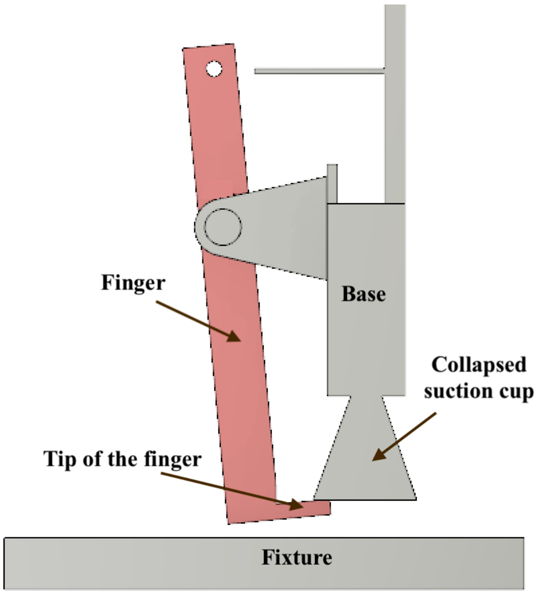
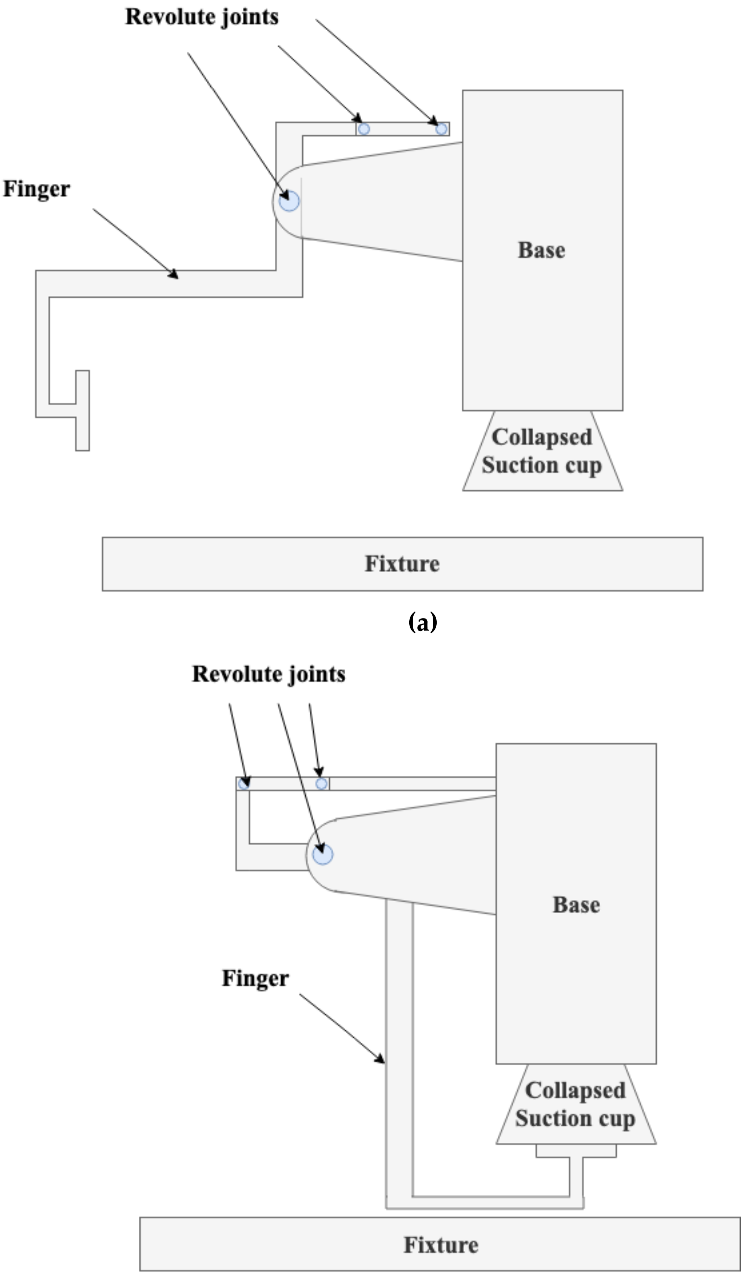


Figure 6.10: Longer finger with less angle with the tip at a closing position

One of the limitations in the last two scenarios is that the finger may come in contact with the fixture if it has a greater length. Therefore, a new mechanism has been considered. In the new mechanism the tip of finger at the opening position will have a considerable distance from the fixture. Thus it is possible to have a longer finger and even a longer finger tip. Figure 6.11 illustrate a schematic of this mechanism at the open and close position of the finger. However, for having such a mechanism it is necessary to have a travel distance of more than 10 mm for the pneumatic piston.



(b)

Figure 6.11: Finger positions in the new mechanism a) Open position b) close position

This generally shows that without a dramatic change in the design it is not possible to have a reliable clamping mechanism which can remove the baking paper from the ply.

6.6 Summary

In this chapter the significance of the suction cup position and the feeding air pressure parameters have been investigated and it has shown that their interaction has a significant effect on the response. A new and smaller suction cup has been used and it showed the process is more stable with a smaller suction cup. However, the clamping mechanism has to be redesigned and therefore the design of the end-effector has to be changed dramatically.

Chapter 7

Conclusion

The main objective of this project was to develop an automated robotic solution to remove the baking paper from the carbon fibre ply.

The components of the gripping tool have been assembled on a KUKA robot and the connection between the gripping tool and a Backhoff PLC has been established. During the assembly, two design issues have been recognised and they have been addressed. The diameter of the mounting part of the tool on the robot was too fit to the robot and mounting and dismounting of the tool could be a difficult and time-consuming process. Therefore the diameter has been reduced by 1 mm. The other issue was that one pneumatic valve with one inlet port has been considered to work with both compressed air for feeding the vacuum ejector and the liquid Nitrogen, while it has to be considered that they are two material from two different sources and they have to have separate inlet port. This has been addressed by adding another pneumatic valve.

The product development methodology has been followed to develop a fixture to hold the Carbon fibre ply down as the baking paper is removed. During the external search for a solution, it has been realised that there is a solution already in the market. Therefore a fixture based on the existing solution has been developed to answer the requirement of this project. the primary tests have shown the functionality and feasibility of the proposed solution.

An experiment with two variable; feeding air pressure and suction cup position has been carried out and its results have been analysed by two-way ANOVA to investigate the significance of each variable. It has been concluded that each variable individually has no significant effect while their interaction has a significant effect which shows that these two variable have an effect on each other.

The last objective of this project is to develop an automated robotic cell to remove the baking paper from the Carbon fibre ply. In order to achieve this goal different suction cups have been used and it has been concluded a small and flexible suction cup can be beneficial for this project since the small suction cup provides fewer channels that the air can leak through and it needs less vacuum to collapse. However, it was not possible to clamp the baking paper with the finger to remove it from the ply totally. Further investigation inside the CAD program showed that the design needs a dramatic modification in order to be able to clamp the baking paper.

Chapter 8

Direction of future work

This chapter revolves around the ideas for how the investigation can be improved if the project will be continued. Below, a discussion as well as a motivation for the proposed improvements will be given.

- **Gripping tool modification** It has been observed that the clamping mechanism of gripping toll is not working properly and it needs a dramatic modification. Therefore, the design modification is considered as a future work which has to be done.
- **Investigate further the influence of different parameters**

  In this Project two of the parameters have been investigated and the results have been analysed by the two-way ANOVA. However, there are other parameters such as suction cup size, which has to investigate their effects and also the effect of their interactions with the two investigated parameter.
- **Investigate the use of sensors or a vision system** In order to have a fully automated robotic cell it is necessary to employ sensors or a vision system to inform the robot about the new incoming plies.
- **Investigate the use a vision system for quality control** A vision system can be used to avoid the engagement of the clamping process and alerting the operator in the occasion of a failure such as picking up both baking paper and the ply. Therefore the ply will not be damaged and proper action can be performed by the operator.

Chapter 9

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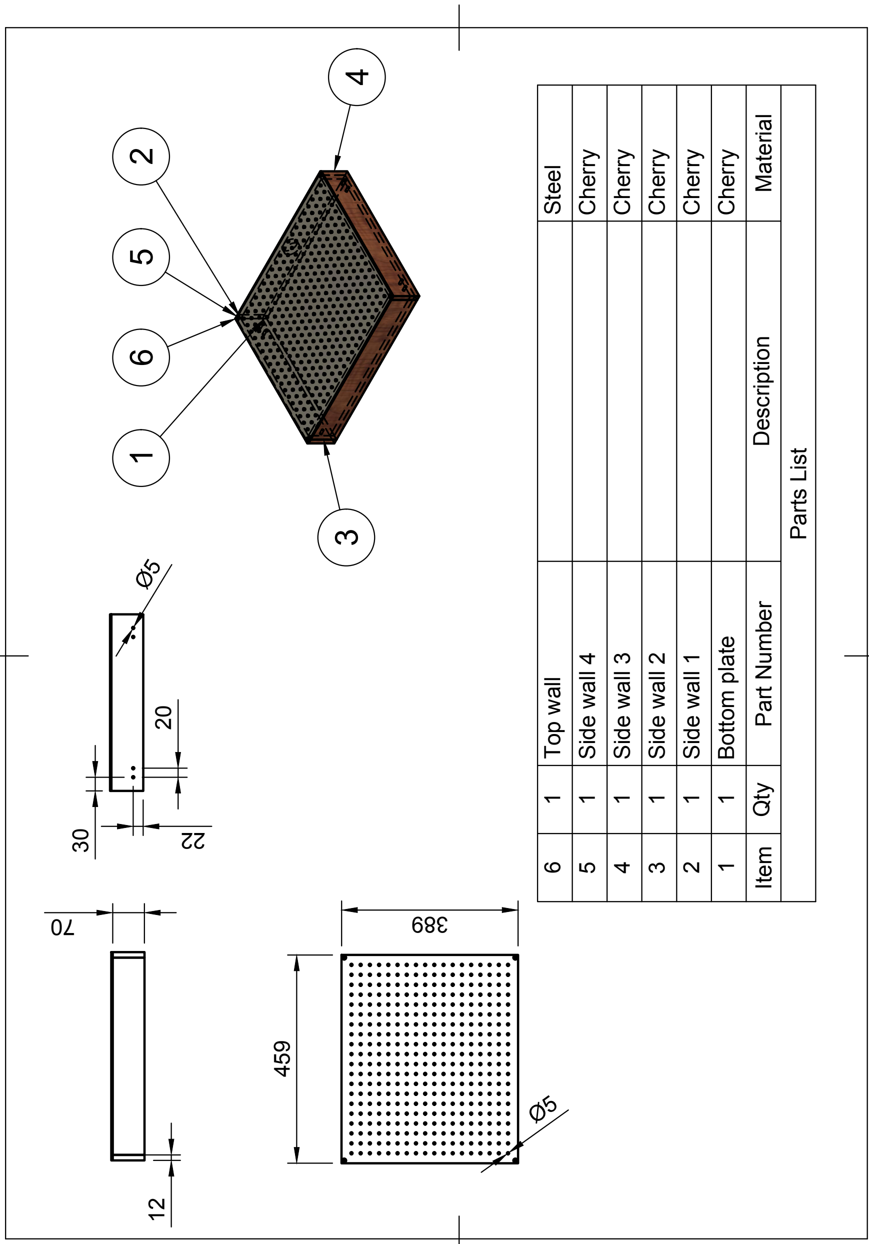
Appendix A

Drawing of The Fixture



Item	Qty	Part Number	Description	Material
6	1	Top wall		Steel
5	1	Side wall 4		Cherry
4	1	Side wall 3		Cherry
3	1	Side wall 2		Cherry
2	1	Side wall 1		Cherry
1	1	Bottom plate		Cherry

Parts List

Figure A.1: Drawing of the Fully assembled fixture.

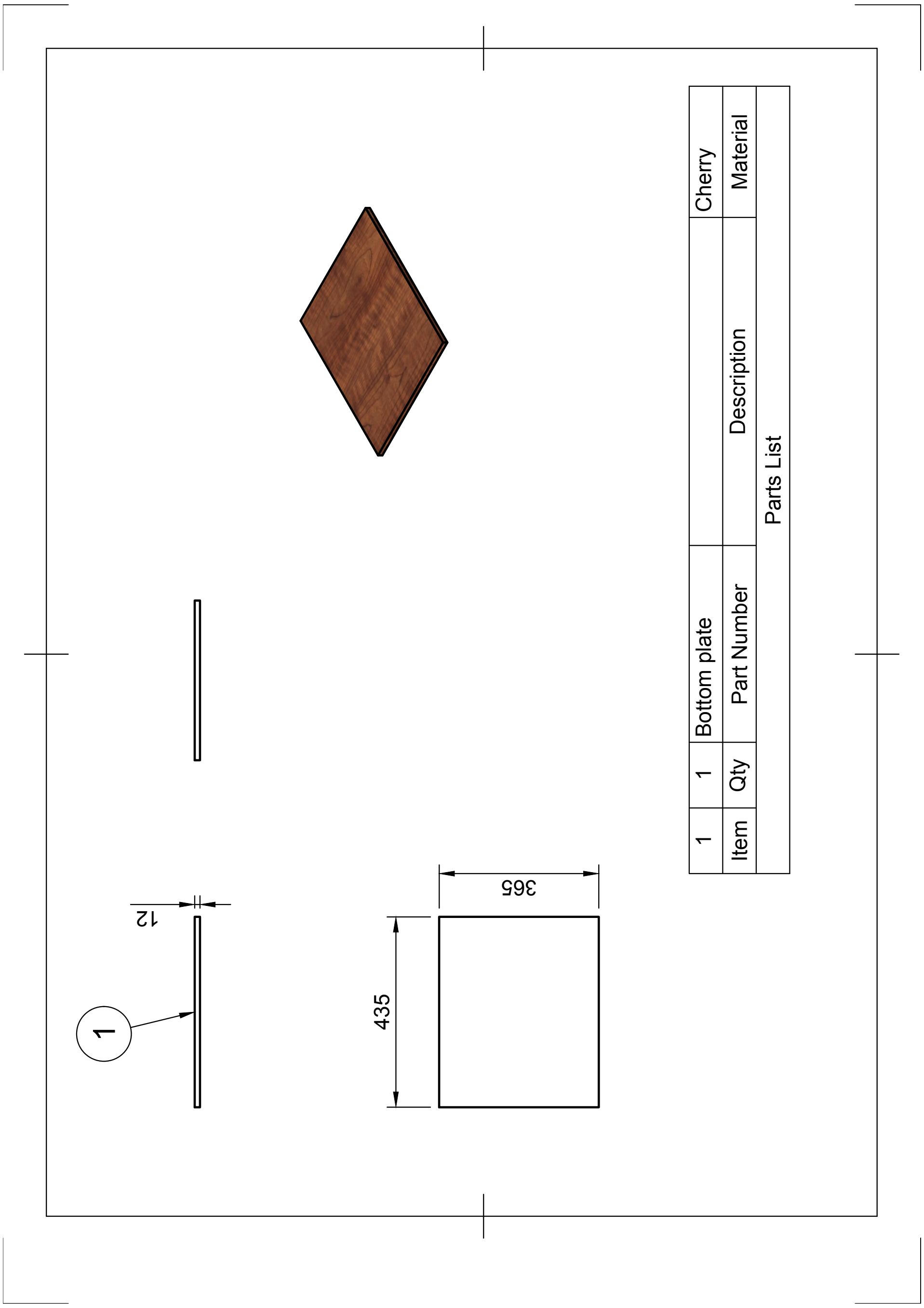


Figure A.2: Drawing of the bottom plate of the fixture.

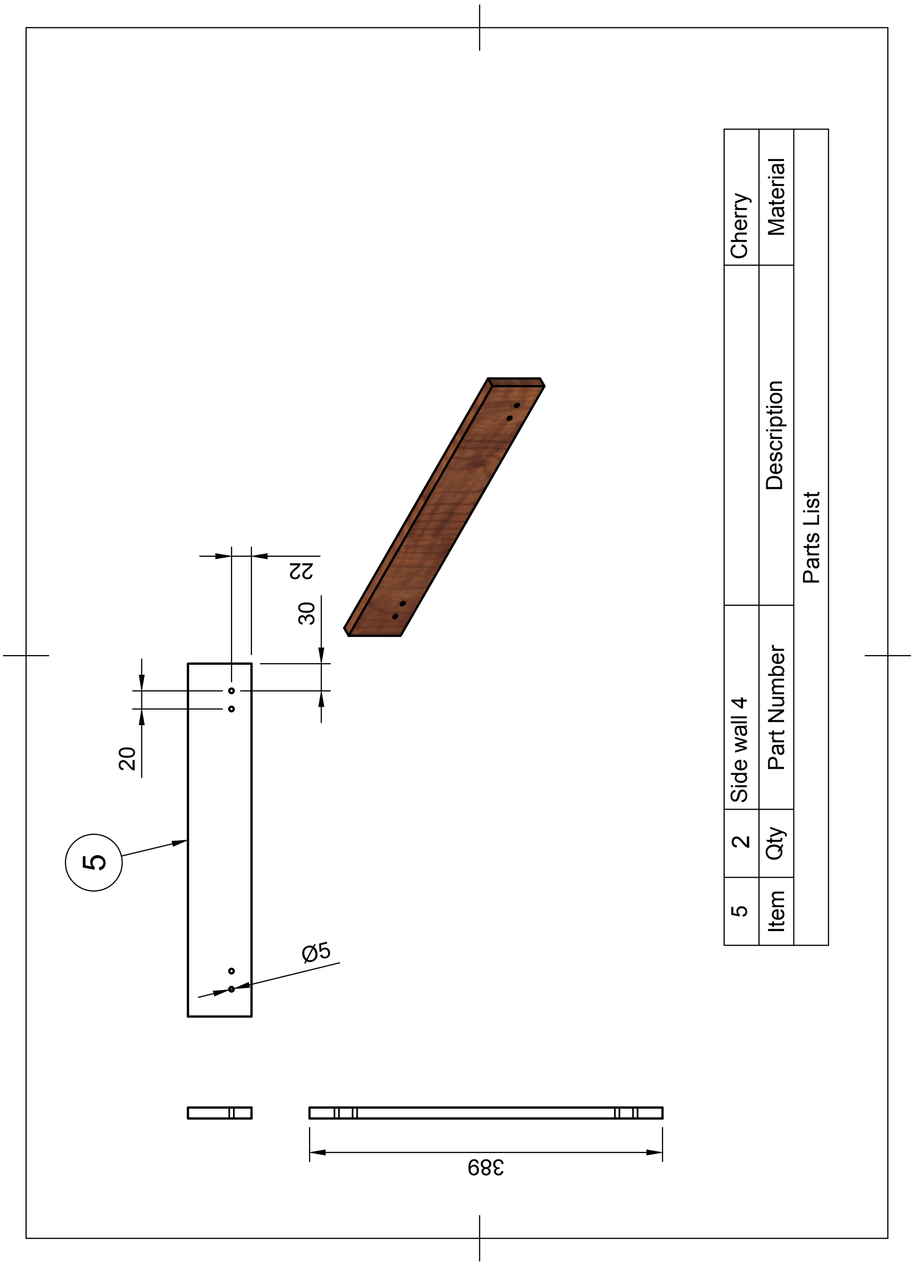


Figure A.3: Drawing of the Side walls 3 and 4 of the fixture.

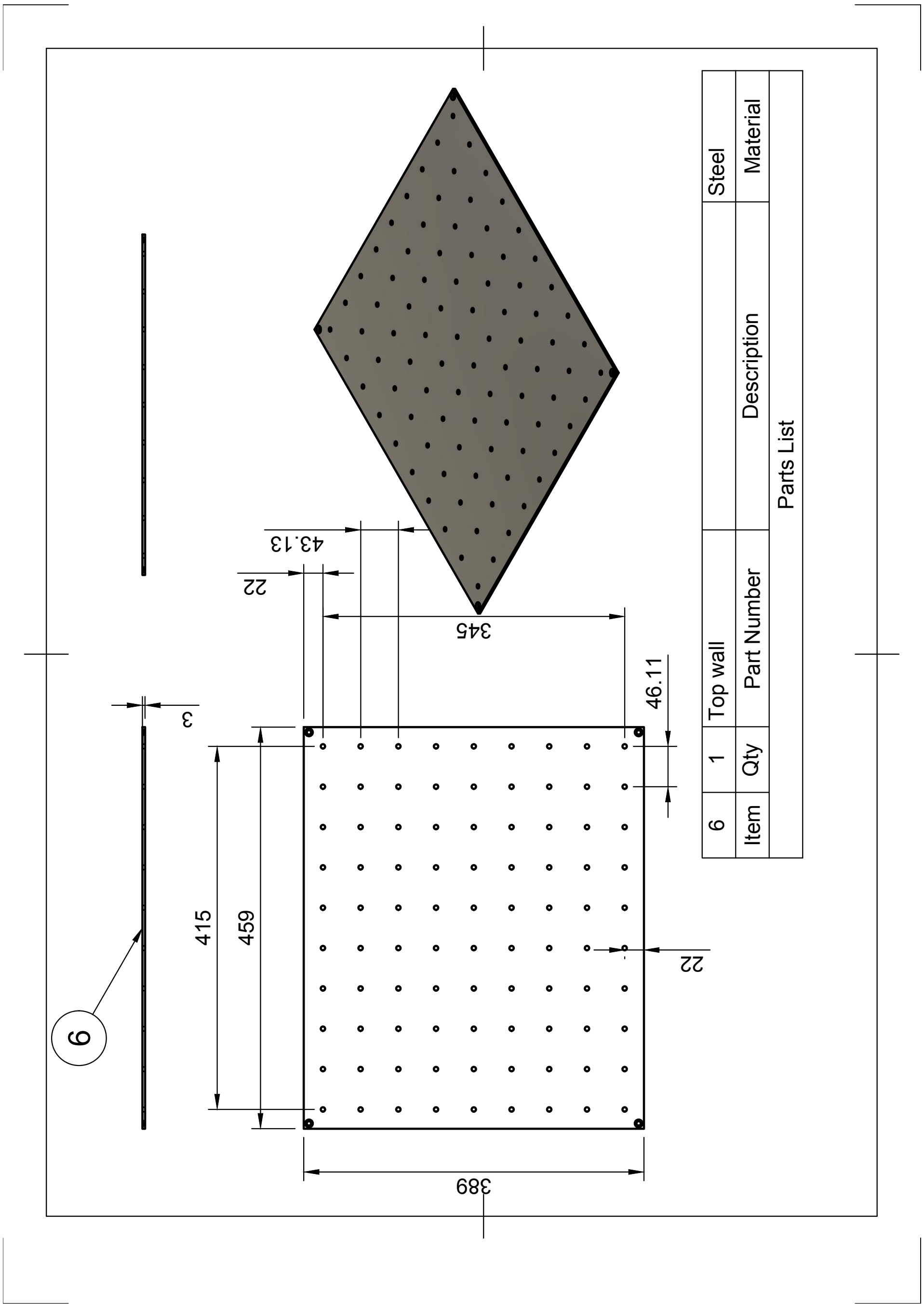


Figure A.4: Drawing of the top plate of the fixture.

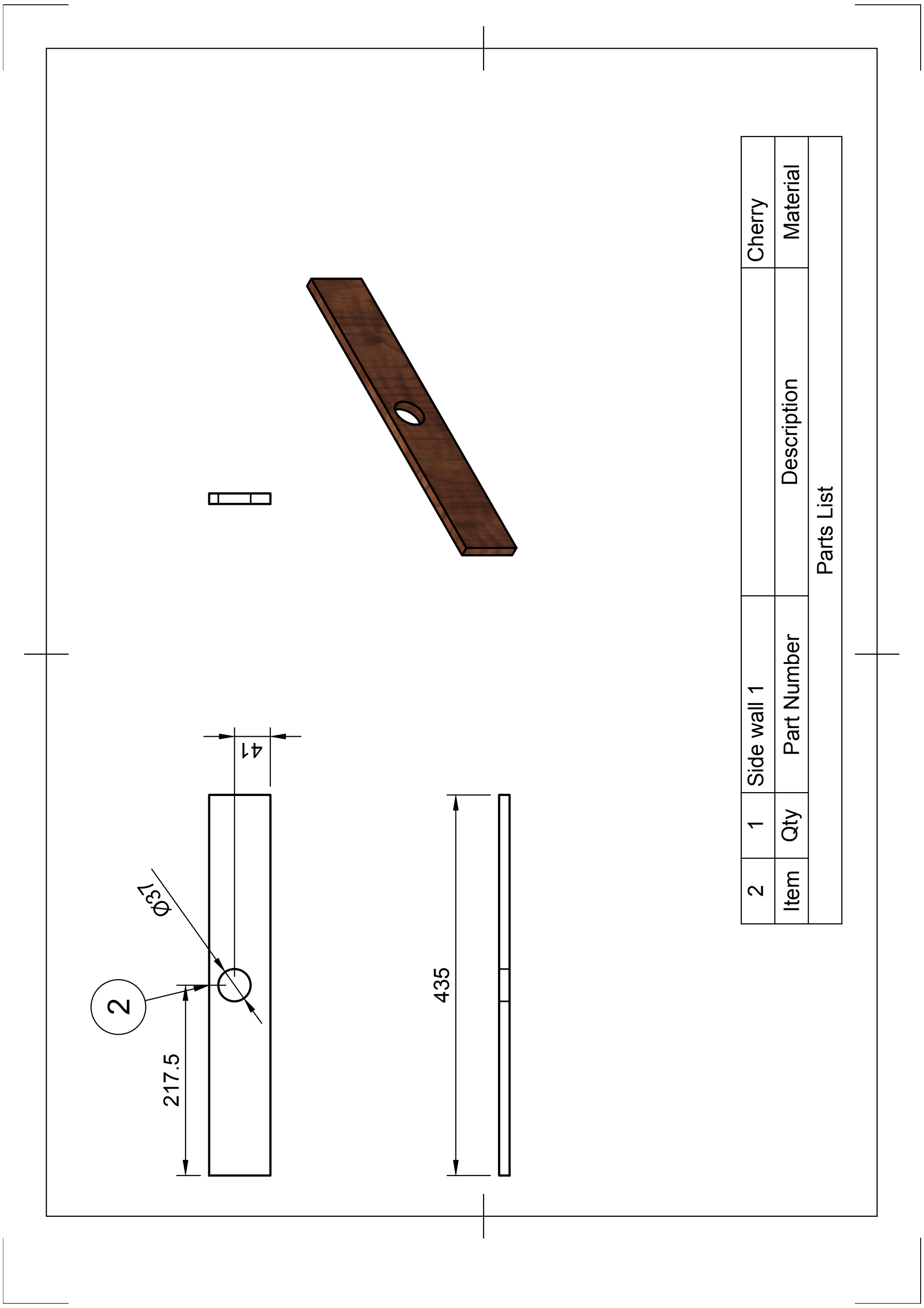


Figure A.5: Drawing of the Side wall 1 of the fixture.

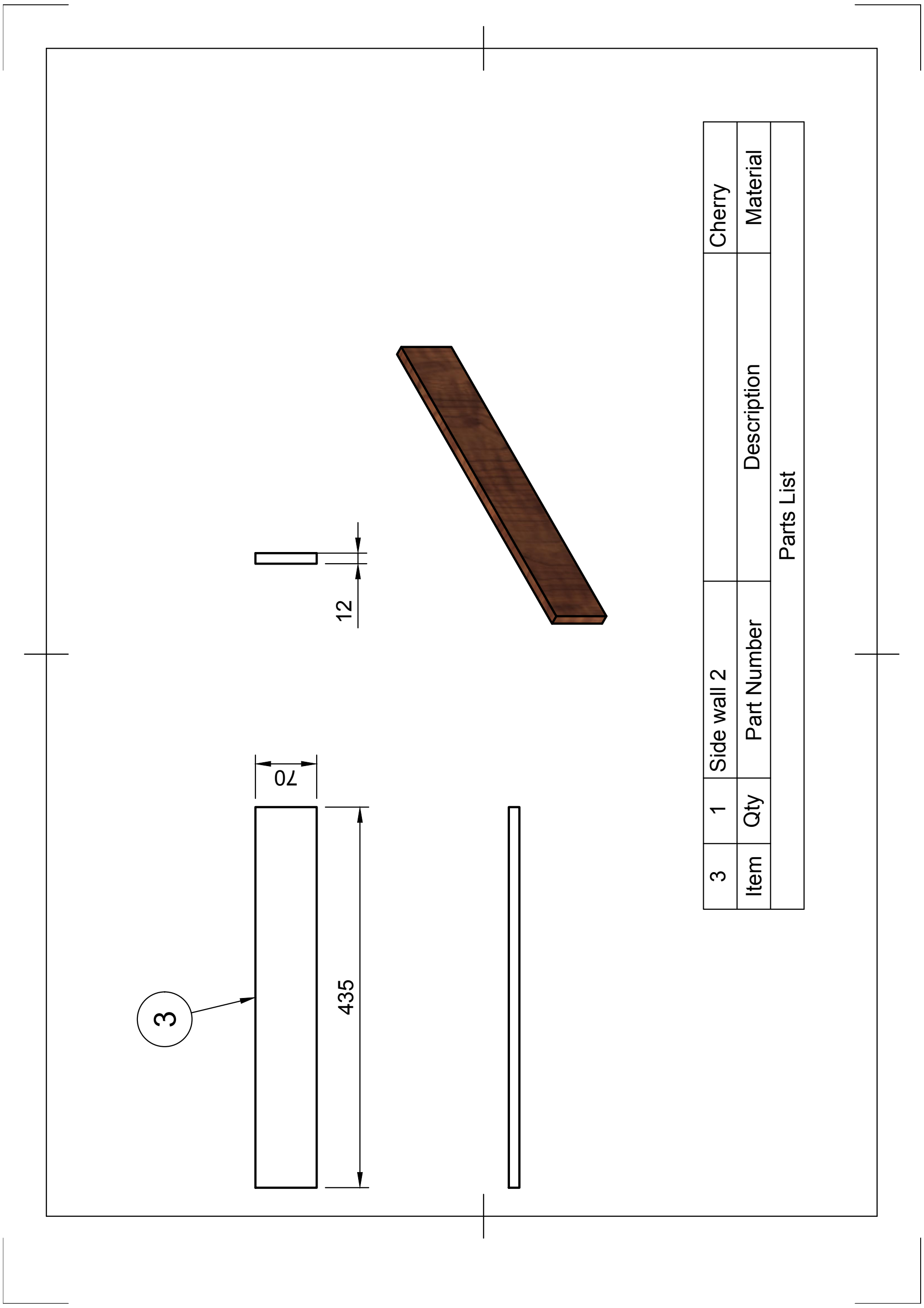


Figure A.6: Drawing of the Side wall 2 of the fixture.

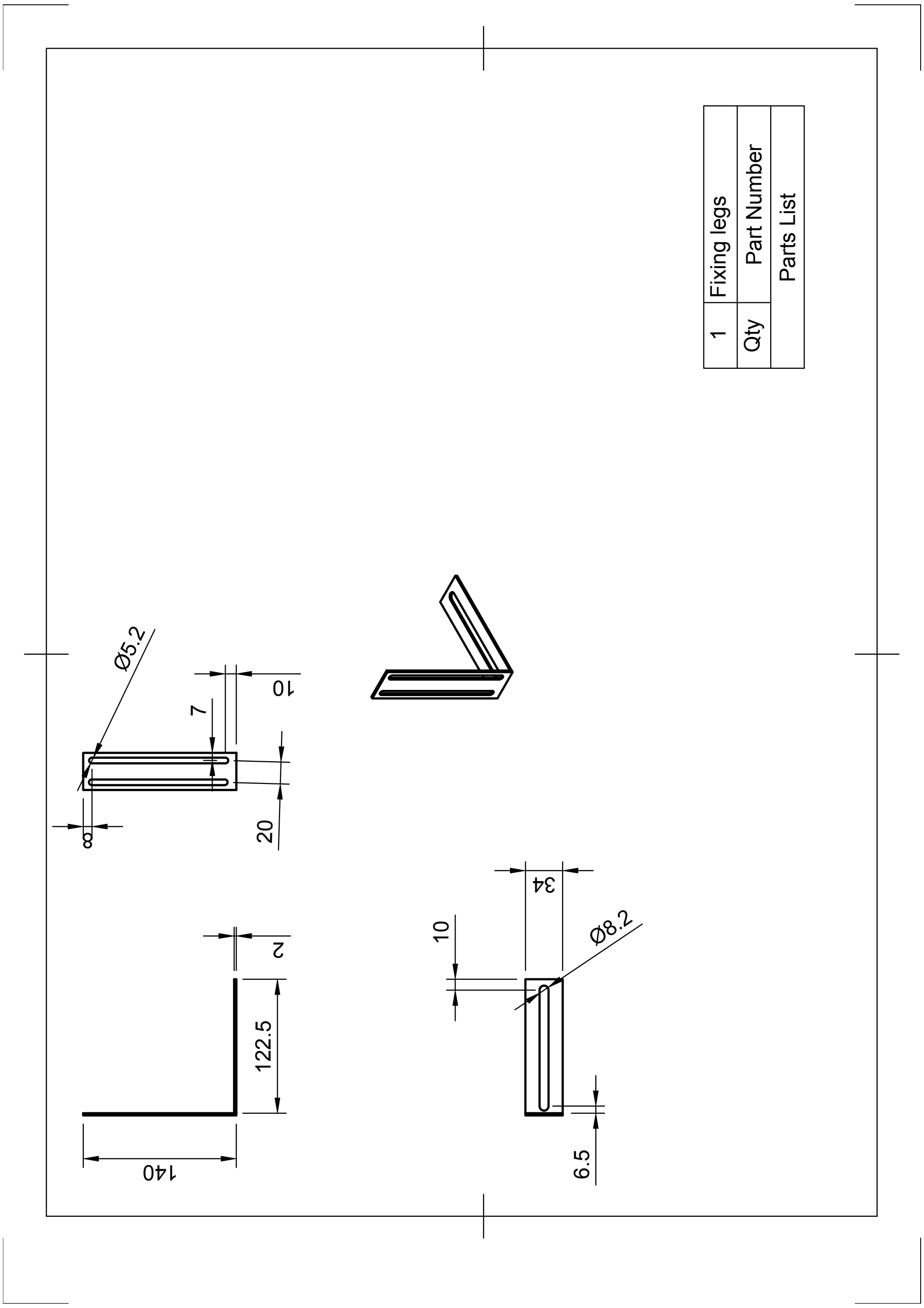


Figure A.7: Installation legs.

Appendix B

Pneumatic Diagrams

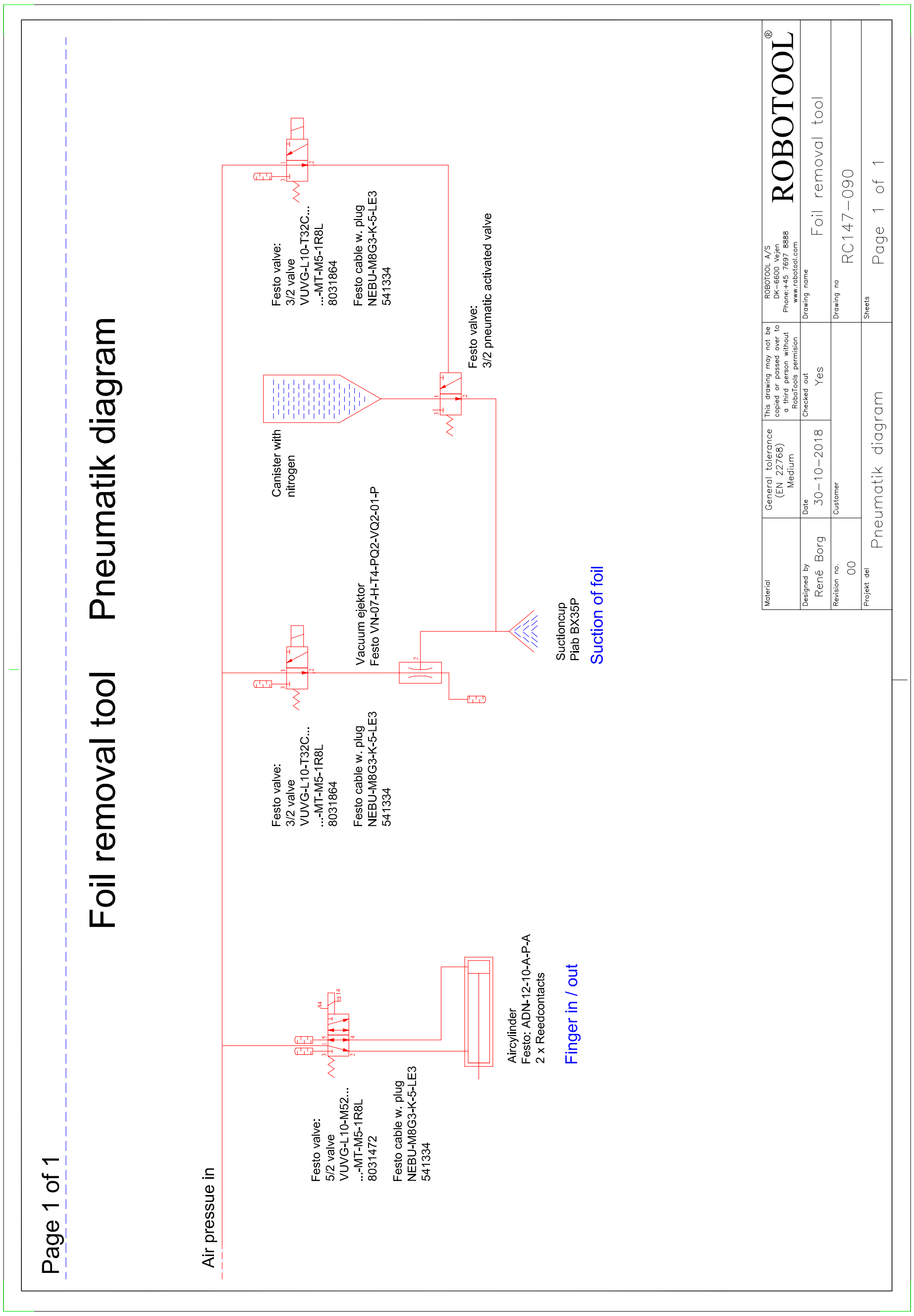


Figure B.1: Original pneumatic diagram of the end-effector

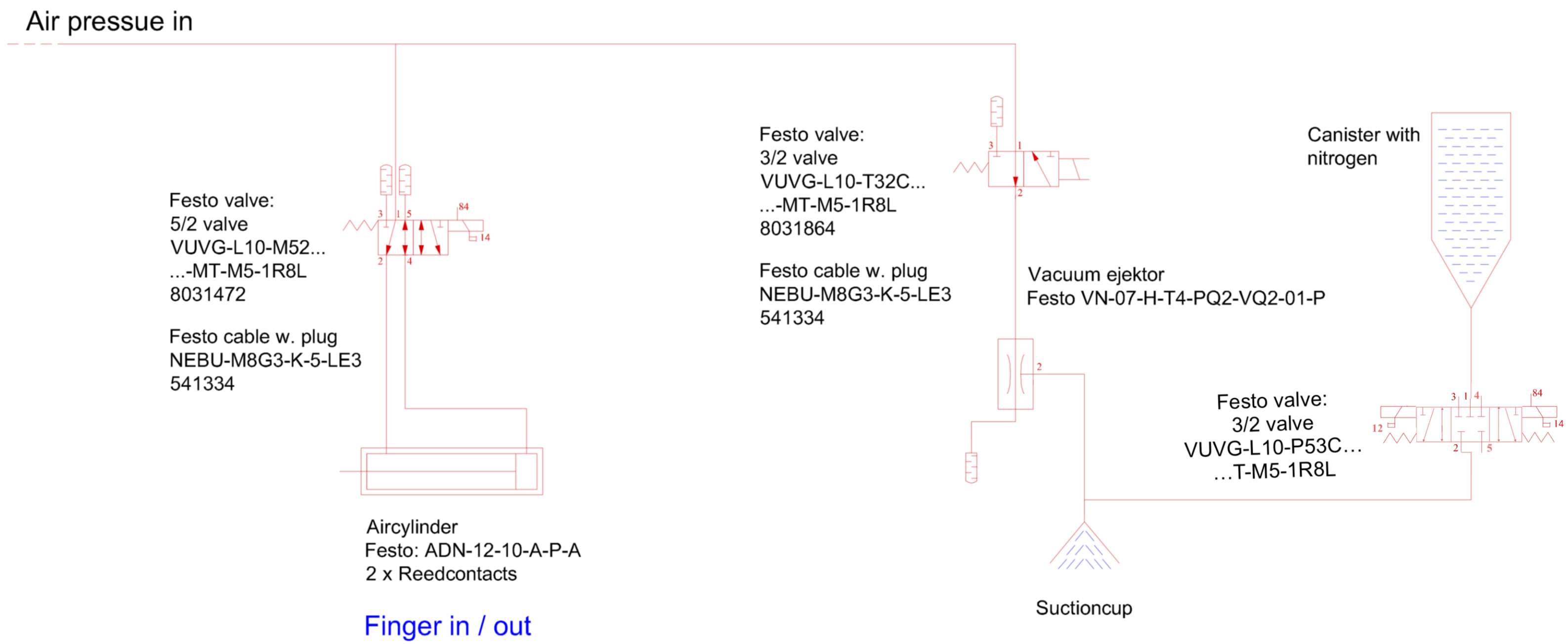


Figure B.2: Modified pneumatic diagram of the end-effector

Appendix C

Schematics

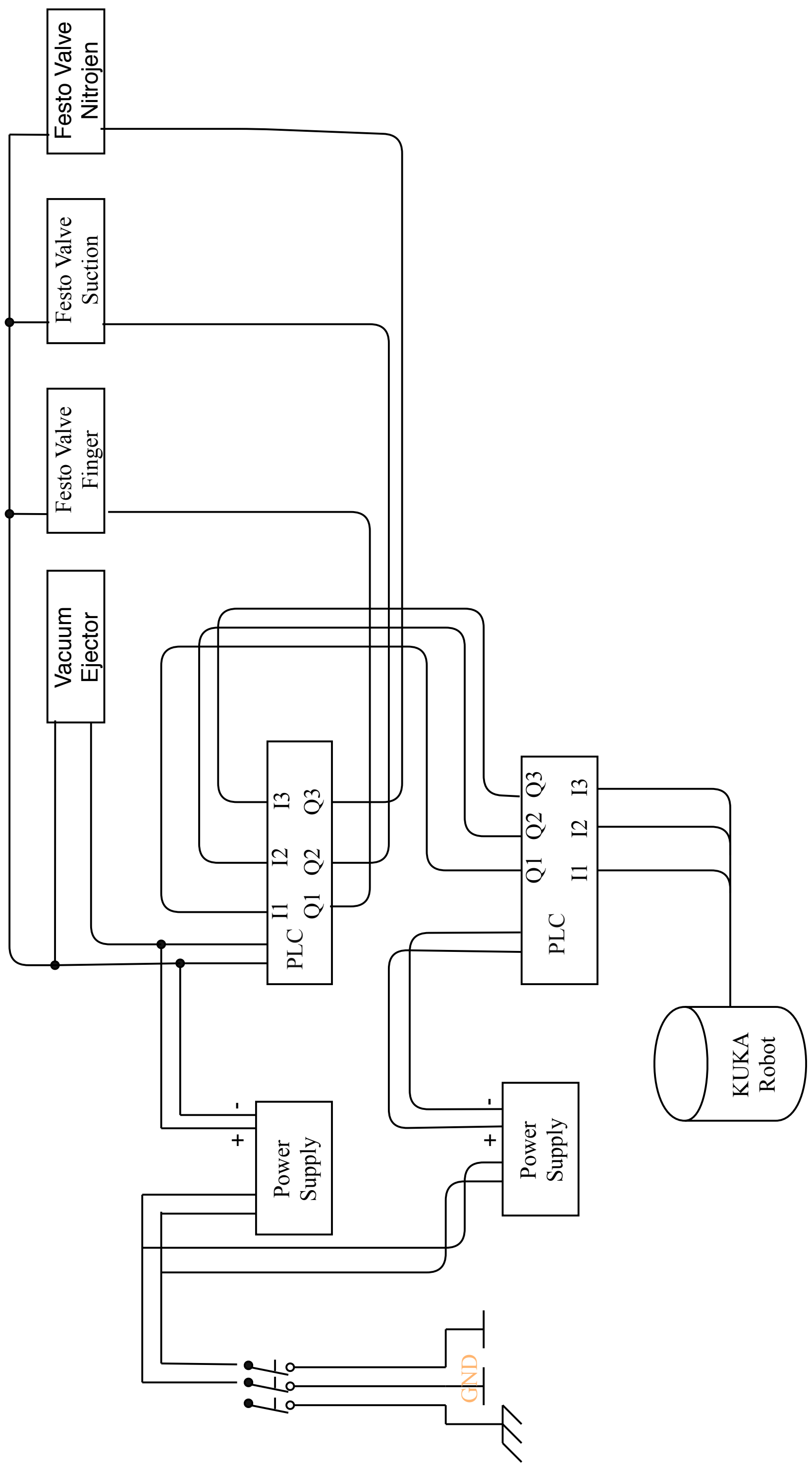


Figure C.1: Schematic of electrical connection