DESIGN OF A SOFT GRIPPER FOR PICK AND PLACE APPLICATION

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechatronics Engineering

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April 2021

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DESIGN OF A SOFT GRIPPER FOR PICK AND PLACE APPLICATION"** was prepared by **TAN CHUAN ZHI** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechatronics Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

A soft robotic pick and place system is a system used to pick things up from one location and place them in the other location by the mean of a soft gripper. The fluidic elastomer material is one of the most commonly used material in the fabrication of soft gripper. Apart from the type of material, the fluidic elastomer soft gripper's different geometry design will give different performance. The fluidic elastomer with corrugated pockets design is used in this project to fabricate the soft gripper. The specific fluidic elastomer used in this project for soft gripper fabrication is Ecoflex 00-30 and Ecoflex 00-50. The soft gripper produced capable of performing pick and place operation with different shape of the object and fragile object. Among different kind of manipulator design, the cartesian type was chosen to provide motion and path planning for the soft gripper. The mechanical structure of the cartesian manipulator and its control firmware was well researched, designed and constructed in this project. This soft gripper pick and place system capable of performing pick and place operation with 3 degrees of freedom. To ensure an accurate and reliable system, configurations and experimentations are performed to measure the performance of the system. Further tuning and calibration were carried out to improve the system. The system has an XY positioning accuracy of 96.15% and an error of only 4.46% speed deviation during point to point travel.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

N	Newton
V	Volt
kPa	Kilo pascal
ms	Millisecond
cm	Centimeter
m	meter

ABS	Acrylonitrile Butadiene Styrene
AC	Alternating current
CAD	Computer-aided design
CNC	Computer numerical control
CMCO	Conditional Movement Control Order
DC	Direct current
DEA	Dielectric elastomer actuators
DOF	Degree of freedom
EAP	Electroactive polymers
FYP	Final year project
IDE	Integrated Development Environment
IPMC	Ionic polymer-metal composite
LCD	Liquid-crystal display
MEMS	Microelectromechanical systems
SCARA	Selective compliance assembly robot arm
SMA	Shape memory alloy
SME	Small and medium-sized enterprises
STL	Stereolithography
PCB	Printed circuit board
PLA	Polylactic acid

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

A pick and place robot or machine has been greatly implemented in the industry nowadays, especially in the semiconductor and automation industries. It reduces most of the labour-intensive job and increases productivity by having the advantages of relatively high travel speed than human and never gets tired. A pick and place robot consists of a manipulator and gripper. The manipulator is the robot's moving mechanism that moves and position tools or gripper within a certain work envelope. There are many types of manipulator available in the market, such as cartesian, delta, polar, articulated, etc. While for the gripper, we can have a mechanical gripper, vacuum gripper, magnetic gripper, adhesive gripper, soft gripper, etc.

The decision on which type of manipulator and gripper to be used greatly depends on the application. For handling fragile and delicate object, the soft gripper is preferable as it can reduce the risk of damaging the object. It also has the advantage of flexibility because it can grip a variety of objects without the need for replacement of the gripper. On many occasion, a pick and place machine cannot be implemented due to some barriers or limitations. For example, the need for knowledge in mathematical model and control system of the tip position positioning. The typical problem face by the articulated robot is the singularity caused by the inverse kinematic problem. This limitation becomes a problem for small and medium-sized enterprises (SME), especially those with limited resource and expertise. Thus, to ease the implementation of a pick and place system, one good option is to go for the cartesian manipulator (also known as rectilinear robot or gantry robot) as it is relatively easy in terms of positioning control.

Therefore, this project is developing a soft gripper with a cartesian manipulator for pick and place application. This report will focus on the development of the soft gripper and the development of the cartesian manipulator.

1.2 Importance of the Study

The undertaking project's importance is to lower down the barrier for implementing the automation device such as a pick and place system with a soft gripper by introducing and developing a relatively uncomplicated cartesian manipulator easy self-fabricated and low-cost soft gripper. It is important in the sense that this study can provide a guideline for the implementation of simple automation technology to increase productivity. Besides, the volume of work envelop of the cartesian manipulator can be customized easily, making it able to be used in various environments and even different applications. At the same time, a soft gripper enables one to transfer the object that is fragile, brittle or even soft without worry about damaging the object, which the conventional rigid gripper cannot achieve.

1.3 Problem Statement

The industry has widely used conventional rigid grippers for quite a long time. It has the limitation that only able to be used for a few numbers of the object due to the shape of the gripper surface is designed according to the grasping object's shape. Besides, if a rigid gripper is to be used on the soft or brittle object, there is necessary to monitor the applied grabbing force on the object with the help of a force-sensitive resistor sensor or any other equivalent sensor. This makes the control of the system complicated. Thus, the other alternative is proposed: using a soft gripper that possesses the characteristic of flexibility and ease of fabrication and low cost.

For SME who have budget constraint and limited resources of expertise, they tend to refuse to implement the pick and place system even the production is needed. They rather stick to the conventional method in which the job is distributed to the manual labour. This can be due to several reasons: the longer time for return on investment as a robotic manipulator is usually higher in cost. Therefore, the development of a cartesian manipulator is proposed with the intention to provide easy control and a low-cost manipulator.

1.4 Aim and Objectives

The main aim of pursuing this development project is to construct a soft gripper for pick and place application. A functional soft gripper pick and place system that able to grab various objects within a certain range of size is expected to be produced at the end of the project. In order to achieve this, three objectives had been listed as follow:

(i) To develop a soft gripper that is capable of grasping the objects of different shape.

(ii) To develop a cartesian manipulator with a working volume of 60 x 60 x 80 cm.

(iii) To integrate cartesian manipulator and soft gripper to perform pick and place application.

1.5 Scope and Limitation of the Project

The development of soft gripper and cartesian manipulator is based on the resources and manufacturing technology available. Thus, the material used to develop the soft gripper is limited to Ecoflex silicon rubber. The precision of the cartesian manipulator is limited by the fabrication method which is mainly 3D printing of parts. The parts produced from 3D printing is not as low tolerance as fabricated from CNC machine. The lack of precision tool during the assembly process also limited the performance of the cartesian assembly. Lastly, the condition of components received from the supplier also affects the precision of cartesian assembly as well.

CHAPTER 2

LITERATURE REVIEW

2.1 Type of Soft Actuators

The advancement in soft robotics and materials science have enabled the rapid growth in soft actuators. The soft actuators developed by the past research can be classified into types of gripper material and actuation method. This section presented the different type of soft gripper that has wide research on it.

2.1.1 Fluidic Elastomer

One of the materials that have been widely used in the fabrication of soft actuators is the fluidic elastomer. The fluidic elastomer usually used is silicon rubber. The basic structure of fluidic elastomer consists of two soft elastomer layers, and they are separated by a flexible and yet relatively inextensible constraint (Marchese, Katzschmann and Rus, 2015). The constraint material is typically made of paper, plastic, cloth, stiffer rubber, etc. The pressurized air drives the actuation of this actuator. The air supply will enter the fluidic channels embedded in the elastomer layer, then it induces stress on the elastic material and produces localize strain. With the presence of inextensible film, the difference in strain produced can cause the bending actuation as shown in Figure 2.1.

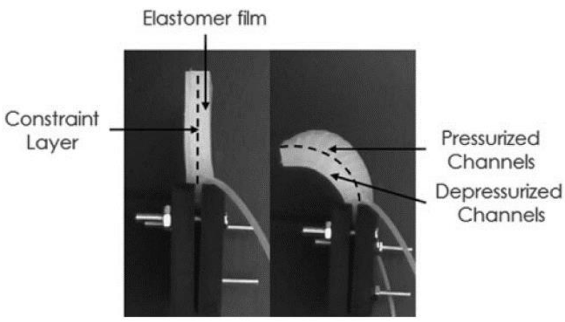


Figure 2.1: The actuation of fluidic elastomer actuator with a constraint layer. (Marchese, Katzschmann and Rus, 2015)

Besides, the fluidic elastomer actuator can also be designed without the inextensible constraint layer. The corrugated pockets can be designed into the geometry of the flexible finger that can provide bending motion(Patil, et al., 2020). This kind of gripper design will have a regular bumpy structure pattern on its surface, as shown in Figure 2.2. With the supply of pressurized air, the finger supposedly tends to elongate in the axial direction; however, due to the flat face side is stiffer than the corrugated side, the finger bend to the flat face side instead. According to the study of Patil, et al. (2020), they also develop an analytical model to obtain an optimum geometry of corrugated surface for flexible finger and establish the basic equation governing the flexing deformation of fingers.

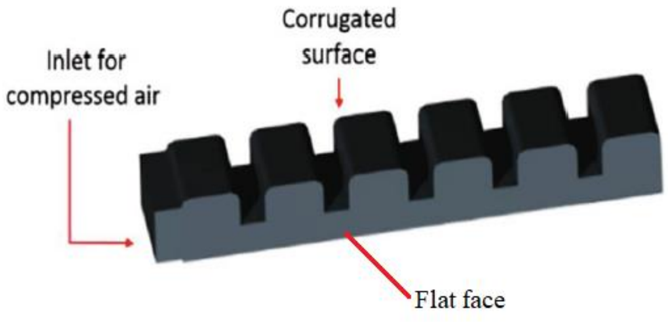


Figure 2.2: The of fluidic elastomer finger with corrugated surface (Patil, et al., 2020).

In the study of Ariyanto, et al. (2019), they develop a similar elastomer actuator with a material named RTV 52 silicon rubber. The actuator can receive positive and negative pressure (vacuum pressure), the positive pressure causing inflation while the negative pressure is causing deflation (Figure 2.3). They had illustrated that this simple actuator can bend in a different direction depending on the air pressure supplied. The gripper's deflation is particularly useful when using it to grasp a container from the inside, such as a cylindrical cup.

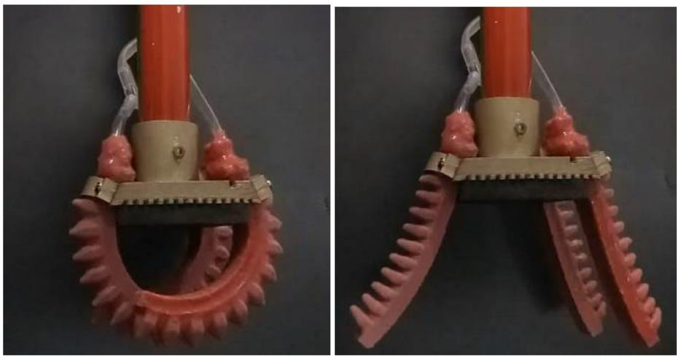


Figure 2.3: The inflation and deflation of the soft gripper (Ariyanto, et al., 2019)

Apart from the aforementioned design, instead of only having a single chamber receiving the pressurized air, Yamanaka, et al. (2020) designed a soft gripper finger with two separated air chamber (Figure 2.4). Each chamber is equipped with an air pressure supply tube separately. By having two chambers, the direction of bending can be chosen by apply pressure to one of the chambers. The actuator will bend toward the direction of the unsupplied chamber. Similarly, this bending motion is realized by the difference in elongation between the thin outer wall and the thick inner wall. They also introduce the rib design feature to suppress the gripper finger's radial expansion and allow more precise dimensional control.

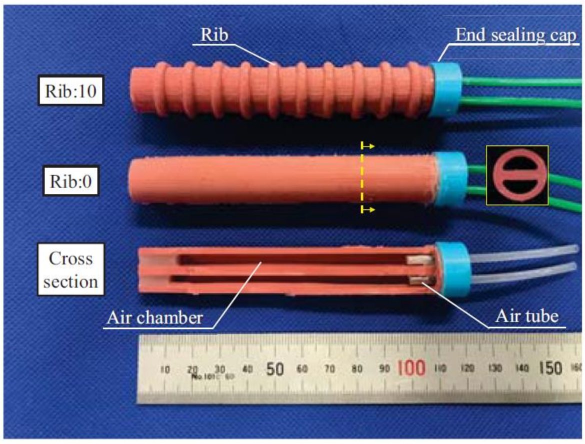


Figure 2.4: The soft gripper finger with two air chamber (Yamanaka, et al., 2020).

Galloway, et al (2013) developed fibre-reinforced soft actuators from a fluidic elastomer with a strain limiting surrounding layer such as fibreglass embedded into silicon rubber. Similar to the rib design discussed above, this also can reduce elastomer strain on the external layer and constrain radial swelling during pressurization of the actuator, thus promotes higher bending curvatures. With the addition of the reinforcement layer, the actuator also believes to withstand higher pressure. Since the force is proportional to the air pressure and to the surface area where the pressure is exerted, this gripper can generate higher forces than one without the reinforcement (Shintake, et al., 2018). Figure 2.5 shows a fibre-reinforced soft gripper bend at large bending curvatures with different input pressure.

Figure 2.5: Range of motion of the fibre-reinforced soft gripper at different applied pressure (Galloway, et al., 2013).

2.1.2 Electroactive Polymers

Apart from fluidic elastomer, the material such as electroactive polymers (EAP) is also commonly used to produce soft gripper. One of the types of EAP called dielectric elastomer, this material produce actuation with applied voltage. The structure of dielectric elastomer composed of a thin elastomer membrane that is sandwiched between two compliant electrodes. The voltage will cause an electrostatic force between electrodes and then produce actuation (Gunter, et al.). Few researchers developed a dielectric elastomer actuator with self-organized minimum-energy structures to show that the dielectric elastomer can grasp an object (Kofod, Paajanen and Bauer, 2006). However, this actuator is usually smaller in size and generate relatively lower stress. Thus, it is more often to be used in the MEMS application. Although this actuator required a low amount of energy, the supply voltage needed to produce actuation is very large.

2.1.3 Shape Memory Alloy

Shape memory material such as shape memory alloy (SMA) can be used to make soft gripper. Nickel-titanium alloy in the form of wire coil is a very typical material used by the researcher to develop SMA actuator. When this coil is heated up via Joule heating by the DC current, it contracts, and this contraction is used to open the gripper (Zimmer, et al., 2019). The principle behind why this shape memory alloy can change its shape is due to the change in their crystallographic microstructure between the martensite phase and austenite phase (She, et al., 2016). Then, this causes the change in Young's modulus and thus the geometry of structure as well. The SMA in the coil or springform is designed and used to release the parallel plate gripper, as shown in the study. Hellebrekers, et al. (2018) and Zimmer, et al. (2019).

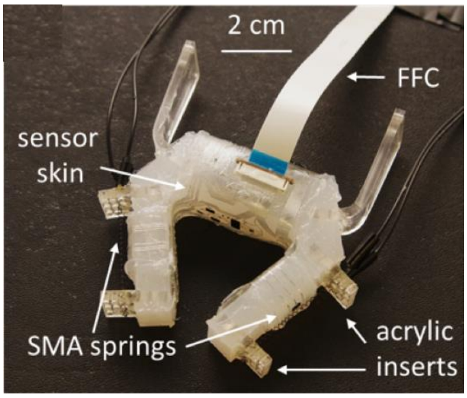


Figure 2.6: SMA spring parallel plate soft gripper (white) (Hellebrekers, et al., 2018).

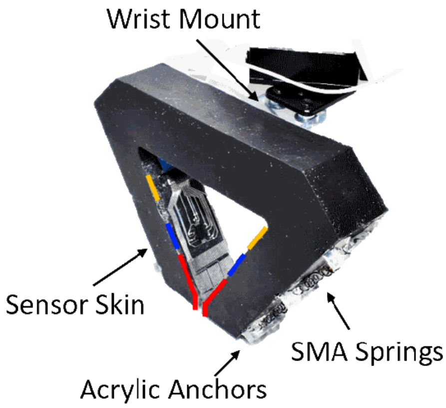


Figure 2.7: SMA spring parallel plate soft gripper (black) (Zimmer, et al., 2019).

One of the drawbacks of this gripper design is the gripping force is almost constant and cannot be manipulated by the input supply. Since this is a trigger-to-open gripper, its gripping force is relatively low, and it depends on the rest state of the gripper. As reported by She, et al. (2016) and Hellebrekers, et al. (2018), the gripping force developed was 3 N and 0.6 N, respectively. The response time of the gripper is relatively slow as the SMA require time for heating up. Furthermore, the SMA's cooling is carried out by natural convection, which required time as well, and it is usually slower than the heat up time. Thus, to accelerate the cooling, using multi-wire with the parallel connectiono increase the surface to volume ratio is proposed (Simone, Rizzello and Seelecke, 2017). In this article, they also reported that the gripper developed has 1.4 N of the gripping force. The strain produced by the SMA gripper also relatively low compare to fluidic elastomer, the soft gripper, as in Figure 2.6, reported having a gripper separation distance of 10.16mm at the closed state and 34.04mm at opened state.

2.2 Actuation Method

The soft gripper can operate at different mode of actuation such as pneumatically, electrically and even chemically, depending on the design and material of the soft gripper. One of the most commonly used technique is pneumatic network when controlling the fluidic elastomer actuator. In the pneumatic system, the electrical energy is converted to mechanics, in the form of the pressurized gas by a pneumatic piston pump or compressor (D'Almeida, et al., 2019). A basic pneumatic network consists of a pump or compressor, directional control valves, relay, microcontroller, tubing, sensor, power supply, etc. A development team named SoftRobotics Toolkit (n.d.) has developed an open-source fluidic control board to operate, control, and test fluidic soft actuators, as shown in Figure 2.8.

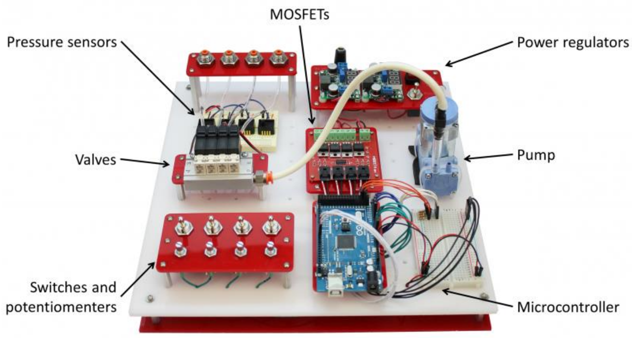


Figure 2.8: Fluidic control board (Soft Robotics Toolkit n.d.).

The advantages of using pneumatic for controlling soft gripper include fast-acting, clean, ease of control, market availability, low viscosity, etc (Mosadegh, et al., 2014). In the study of Mosadegh et al. (2014), they also improve the design of fluidic elastomer gripper to achieve faster response speed from an un-actuated state to a quasi-circular state with 50ms reported.

Next, a soft gripper can also be actuated by the use of an external electric motor. This is done by placing the cables inside the elastomer gripper, then pulling the cable by the motor will cause the gripper to bend and close (Figure 2.9). Thus, it is also sometimes called a tendon-driven soft gripper. The gripper will then provide the soft grasping by passively adapting to the shape of the object's surface that needed to be grabbed.

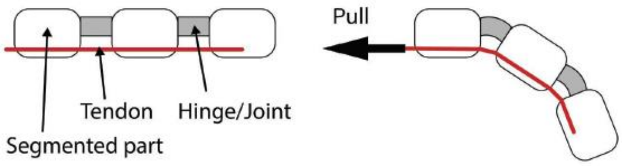


Figure 2.9: An illustration of a single tendon-driven soft gripper finger (Shintake, et al., 2018).

Since the driving device (motor) is located outside of the soft gripper, there is a wide range of motor selection, and it is not affected much by the size and geometry of the soft gripper. Thus, it is possible to design a soft gripper that can provide high force by choosing a suitable high torque motor. the gripper's force also depends on the nature of the material used. Tavakoli, et al (2017) had built a soft prosthetic hand driven by two DC motors and the integration of a sensor for the development of autonomous grasping posture (Figure 2.10). The material used is silicon rubber.

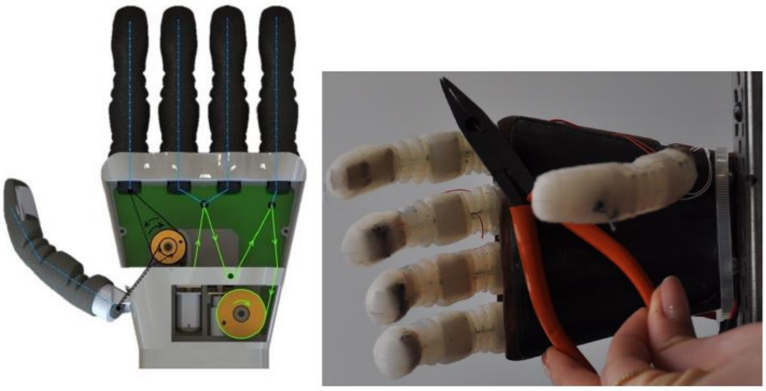


Figure 2.10: The conceptual design and actual prototype of two DC motors driven soft prosthetic hand developed by the researchers (Tavakoli, et al., 2017).

There are also many kinds of the electrical actuated soft gripper. For example, as discussed in the previous section, the electroactive polymers (EAP) soft gripper is controlled by the voltage source, while shape memory alloy (SMA) is controlled indirectly by the heating caused by the current flow. This heating is known as joule heating or ohmic heating, caused by the electric current passing through a conductor. The power of heating can be related to the current and resistance as shown: $P = I^2R$. Two typical EAP that can respond to an electrical stimulus is dielectric elastomer actuators (DEA) and ionic polymer-metal composite (IPMC). The soft gripper using electroadhesion method to grab the object is also power by the electrical. This gripper uses electrical energy to manipulate thenumber of electric charges on both surfaces between the device and the object. The phenomena achieve this adhesion called coulomb force or electrostatic force where the attraction between negative and positive electric charges happen. However, generating a high electric field for gripping objects requires very high voltage, typically rating at kilovolts. Figure 2.11 shows an example of an electrical actuated soft gripper.

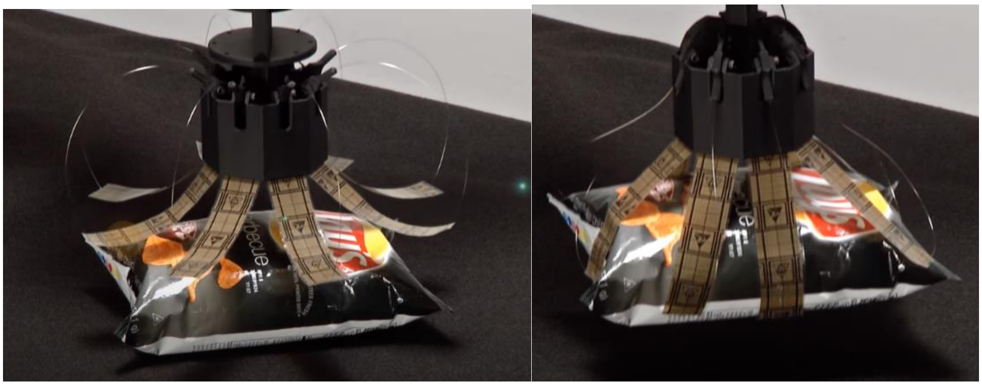


Figure 2.11: Before and after grasping of an electroadhesion soft gripper (Grabit Inc, 2014).

2.3 Summary On The Gripper

The type of soft gripper available is not limited to the discussion above. Apart from the aforementioned soft gripper, we also have granular jamming soft gripper, 3D printed soft gripper, flex-shaped soft gripper and many more. The actuation method of the soft gripper is greatly dependent on the material and the construction of the gripper. It can be actuated by compressed air, heat, electrical, motor, chemical, etc. Table 2.1 summarises the type of soft gripper that has been discussed.

Table 2.1: Summary of discussed soft gripper.

Type of Soft gripper	Gripping force	Control	Change in strain	Energy required	Example of material	Fabrication
Fluidic elastomer	High	Easy	Large	Low	Elastosil M4601 Ecoflex 00-30	5-8 simple steps
Electroactive polymer	Low	Easy	Small	Small (for DEA) High (for IPMC)	Dielectric Elastomer Actuators (DEA) Ionic Polymer-Metal Composite (IPMC)	6-9 steps (involve complex steps)

Shape memory alloy	Low	Relatively difficult	Small	High	Nickel-titanium alloy	6-9 steps (involve complex steps)

There also discussed 4 different design of fluidic elastomer with a constraint layer, corrugated pockets, double chamber design, and fibre-reinforced design. Different designs have their own advantages and disadvantages as well. The table below showed the summary of these four fluidic elastomers soft gripper design.

Table 2.2: Summary of different design of fluidic elastomer soft gripper.

Design of fluidic elastomer soft gripper	Gripping force	Bending direction	Fabrication
With constraint layer	Moderate	One	1 more step compared to corrugated pockets design
With corrugated pockets	Moderate	One (usually) Two (with positive and negative pressure)	5-6 steps
Double chamber	Moderate	Two	5-6 steps
Fibre-reinforced	High	One	7-8 steps

2.4 Type of Manipulator

There are many types of manipulator been used in the automation industry, some example of manipulators include cartesian type, articulated type, delta robot (parallel robot), SCARA, cylindrical manipulator, polar robot and many more.

One of the most commonly used manipulators is the Cartesian manipulator. The cartesian manipulator is a three degree of freedom. Three of its principal axes of control are linear. Therefore, it is also known as a linear robot/ rectilinear robot. The popular application for cartesian robots is milling machine, plotter, 3D printer, etc. Figure 2.12 s that the schematic of three joint of a cartesian manipulator is linear type and is used for only translational motion. Motion planning and control problems have always been the main challenges for many types of manipulators, especially those with a higher degree of freedom. However, the characteristic of a cartesian manipulator reduces the complexities while solving the motion planning problem, leadingo more reliable and robust solutions for real-world deployment (McTaggart, et al., 2017). The design of cartesian manipulator (Figure 2.13) from McTaggart, et al. (2017) and his team had won the Amazon Robotics Challenge 2017. Amazon Robotics Challenge 2017 is an automated warehouse pick and place challenge. According to them, the difficult task in the challenge is the positioning of the end effector. Thus, the implementation of the cartesian manipulator over the robotic arm can reduce the challenges. Their cartesian manipulator design also reduces the chance of collision and avoid singularities in the inverse kinematics as it only happens for the robotic arm.

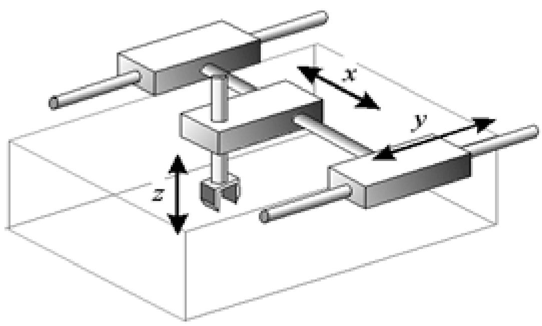


Figure 2.12: Simple schematic of a cartesian manipulator.

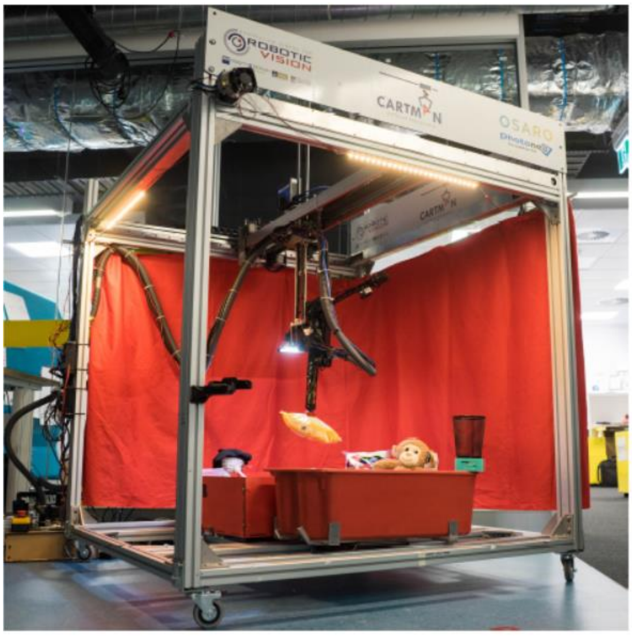


Figure 2.13: Cartesian manipulator designed by McTaggart, et al. (2017).

The articulated robot is a manipulator with rotary joints and usually has a higher degree of freedom of around 3 to 10. They can usually seem in the industry for highly automated application. The structure of an articulated robot is illustrated in Figure 2.14. The main body of the robot was connected to the base through the first revolute joint. While one more revolute joint connects perpendicularly to the robot body and couple the shoulder to body. A parallel revolt joint is used to attach the shoulder to the robot arm at the end of the robot shoulder. While at the end of the robot arm, other joints are then used to attach the wrist and the end effector. The 6 direction of rotation of robot axes is shown in Figure 2.15. Overall, the design of the robotic arm is closely mimic the human arm. The articulated manipulator has high flexibility in the production operations, and this makes it suitable for many applications, for example, pick and place process, material handling, palletizing, arc welding, packaging and many more. One of the advantages of using an articulated robot is its versatility and large workspace volume to its mechanical footprint ratio. However, the disadvantages of using articulated robots include high capital cost and the expertise capable of operating the industry (Granta, 2016). There are still many parameters that needed to be considered when choosing the articulated robot as a manipulator to carry out the task. Those parameters were summarized in Table 2.3.

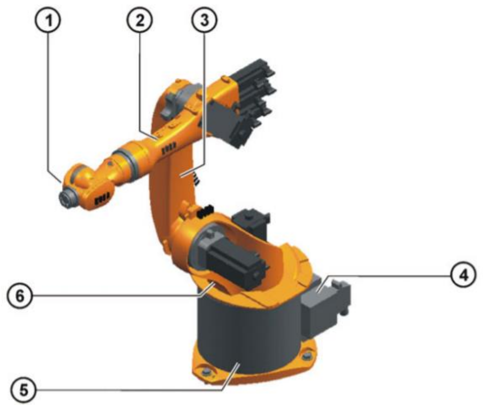


Figure 2.14: An example of a robotic arm model KR 20-3 from KUKA.

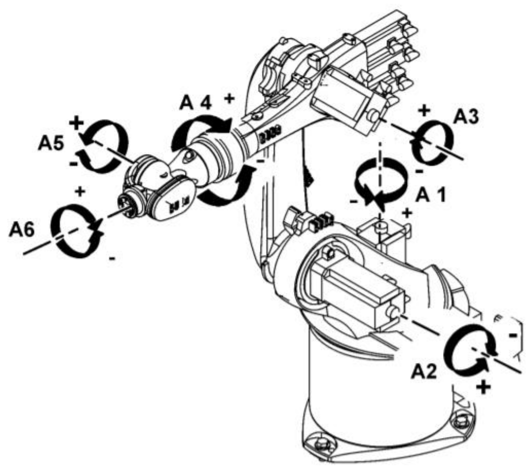


Figure 2.15: Direction of rotation of robot axes.

Table 2.3: Summary of characteristics of an articulated robot (Pandilov and Dukovski, 2014).

Feature	Articulated robot
Workspace	Large
Solving forward kinematics	Easy
Solving inverse kinematic	Difficult
Position error	Accumulates

Force error	Averages
Maximum force	Limited by minimum actuator force
Stiffness	Low
Dynamics characteristics	Poor, especially with increasing the size
Modelling and solving dynamics	Relatively simple
Inertia	Large
Areas of application	A great number in different areas, especially in industry
Payload/weight ratio	Low
Speed and acceleration	Low
Accuracy	Low
Uniformity of components	Low
Calibration	Relatively simple
Workspace/robot size ratio	High

Next, the delta robot is also another kind of manipulator often being used in the semiconductor industry and food manufacturing industry. In terms of structural topology, the delta robot is classified as a parallel manipulator. Its kinematic structure takes the open loop-chain form. In contrast, the opposite of a parallel robot is the series robot in the form of an open-loop kinematic structure. The structure of the delta robot is shown in Figure 2.16. It is a head-mounted manipulator with the motors or other actuators embedded in the base structure to drive the linked arms below (Kaewkorn, et al., 2020). This design reduces most of the weight on the moving arms and can provide very high velocity and acceleration capability to the robot (Wilson, 2015). However, one drawback of this manipulator is its low payload capacity. Since they are often only used in high-speed pick and place application of electronic components in the PCB assembly line and food packaging processes, they do not require a large force to carry out the task. Other characteristics of the delta robot are summarized in Table 2.4.

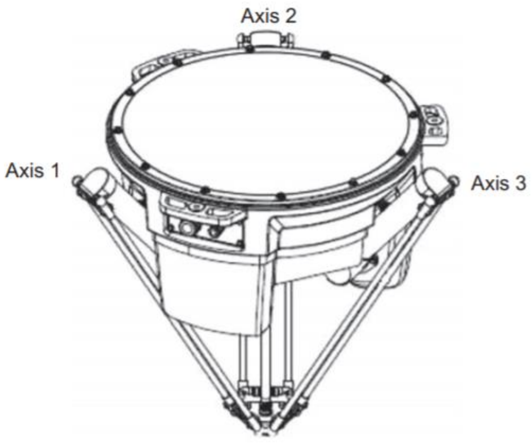


Figure 2.16: Schematic of 3 degrees of freedom delta robot (Wilson, 2015).

Table 2.4: Summary of characteristics of delta robot (Pandilov and Dukovski, 2014).

Feature	Rating
Workspace	Small and complex
Solving forward kinematics	Very difficult
Solving inverse kinematic	Easy
Position error	Averages
Force error	Accumulates
Maximum force	Summation of all actuator forces
Stiffness	High
Dynamics characteristics	Very high
Modelling and solving dynamics	Very complex
Inertia	Small
Areas of application	Currently limited, especially in industry
Payload/weight ratio	High
Speed and acceleration	High
Accuracy	High
Uniformity of components	High
Calibration	Complicated
Workspace/robot size ratio	Low

Another robot used with a similar application as a delta robot called SCARA robot (Selective Compliance Assembly Robot Arm). They were used in the food, pharmaceutical, electronic and manufacturing industry to sort, packaging, transporting silicon wafer, product inspection, fastening bolt, drilling, welding, chamfering, tapping and so on. Most of the SCARA manipulator has 4 degrees of freedom. Figure 2.17 shows the diagram of a SCARA robot. Its 4 axes are consist of a rotational base (Joint 1), a linear vertical motion (Joint 3), and two rotational motions in the same vertical plane (Joint 2 and Joint 4). A group of researcher work on a sorting system based on CoDeSys claimed that the advantages of the SCARA manipulator include high flexibility, good rigidity of lead hammer and high horizontal flexibility (Feng, Sun and Tian, 2019). Besides, other researchers who work on the simulation and modelling of the SCARA robot also pointed out some advantages: short cycle time, high speed, reliable, flexible operation,and accurate path control (Zhang and Zhang, 2019). However, the SCARA manipulator is a highly nonlinear dynamic system which makes it difficult to identify the parameter's value needed during trajectory tracking. Data such as mass, inertia, moment, etc are essential to establish an accurate dynamic model for tooltip positioning. To cope with these challenges, few researchers utilize the Solidwork software and Matlab Simulink SimMechaincs to model the SCARA manipulator to get a mathematical representation and develop a proportional–integral–derivative controller to control the manipulator respectively (Ibrahim and Zargoun, 2014).

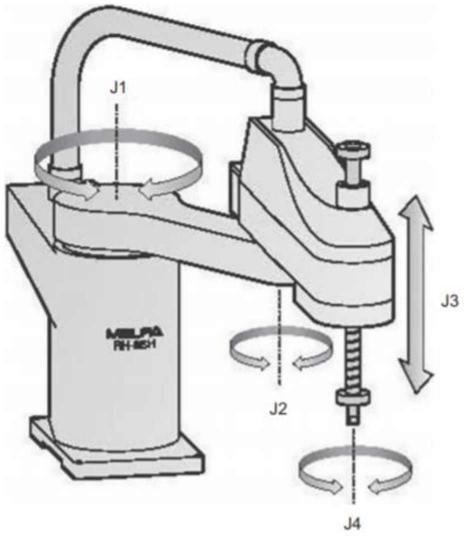


Figure 2.17: Diagram of a 4-dof SCARA robot.

Last but not least, there is also another less common manipulator than the aforementioned manipulators, such as the cylindrical robot and polar robot. The 3 degrees of freedom cylindrical robot consist of rotational motion, vertical motion and reach motion, as shown in Figure 2.18. Generally, the rotational motion is powered by a motor couple with pinion and gear while a pneumatic actuator powers linear motion. The cylindrical manipulator uses a cylindrical coordinate system which is a 3D coordinate system that defines a target point positions by the distance (both magnitude and direction) from a chosen reference axis or reference plane. While the origin is where the intersection of the reference plane and the axis and its three coordinates is given zero. This type of manipulator is useful for objects that need to have rotational symmetry around their longitudinal axis. In term of the control system, the cylindrical configuration manipulator needed a more sophisticated design than a cartesian one. This manipulator's typical applications include pick and place, spot welding, palletizing, grinding, coating, injection moulding, and many more.

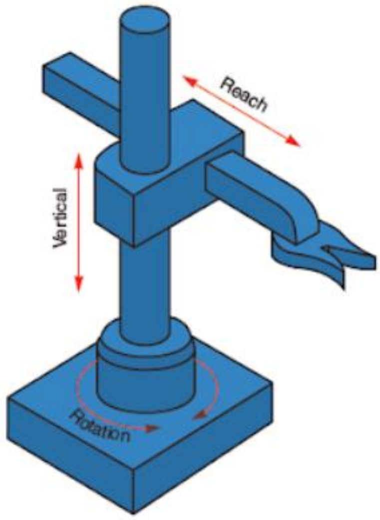


Figure 2.18: The general configuration of a cylindrical robot.

The polar robot is quite similar to the cylindrical robot, it is also 3 degrees of freedom manipulator. It consists of two rotary joint and one linear joint. Its arm, which is the linear joint part, is connected to a base and twisting joint. Unlike the cylindrical robot, It uses the polar coordinate system, which from a spherical-shape like work envelope, thus sometimes polar robot also known as a spherical robot (Figure 2.19). In order to specify a point on the polar coordinate, it needs three parameters, radius(R), the angle from XZ plane (θ), and angle from Z-axis (φ), as shown in Figure 2.20. The polar robot application was widely used in the car manufacturing industry for spot welding purposes. Besides, it is also used for assembly operations, painting, fettling, tool handling and many more.

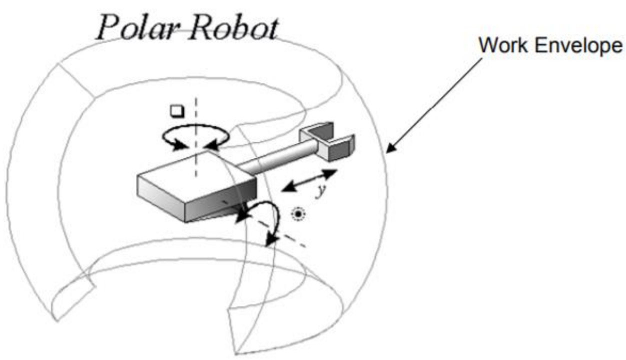


Figure 2.19: Polar robot and its work envelope illustration.

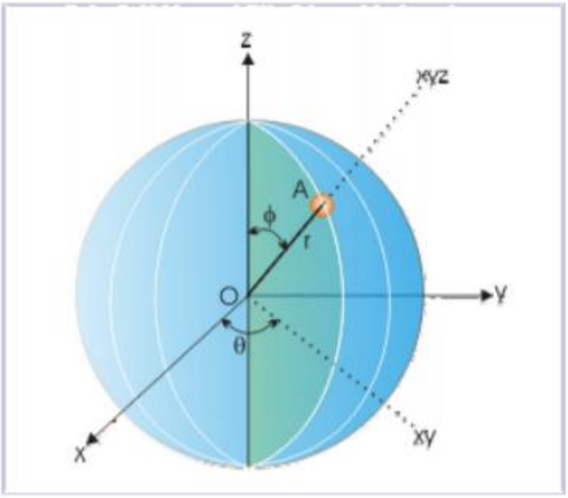


Figure 2.20: Diagram of a polar coordinate system.

2.5 Summary On The Manipulator

The reviewed manipulator types are not an exhaustive list. There are still many more manipulator available in the industry. The selection of manipulator type is very dependent on the application, type of industry, the throughput of the production, material to be grasped and many more aspects. The table below summarized some of the discussed manipulator types with some characteristics.

Table 2.5: Summary of the characteristic of discussed manipulator type.

Type of manipulator	Degree of freedom	Control system	Speed	Payload	Reference
Cartesian	Normally 3 only	Relatively simple	Slow to moderate	Low to moderate	McTaggart, et al. (2017)
Articulated	4 to 6 or more, Typically 6	Complex	Moderate to Fast	Wide range from low to very high (up to 100kg)	Granta (2016) Pandilov and Dukovski (2014)
Delta	3	Complex	Very fast	Low (typically up to 2kg)	Kaewkorn, et al. (2020) Wilson (2015)

					Pandilov and Dukovski (2014)
SCARA	4	Complex	Fast	Moderate	Zhang and Zhang (2019) Ibrahim and Zargoun (2014)

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter discusses the resources needed to carry out the development project, how the project was carried out, the design approached, the detailed design, and the work plan. As a result from the literature review, the soft gripper with the corrugated pocket with material Ecoflex silicon rubber and a cartesian manipulator was chosen to be implemented.

3.2 Material, Component Selection and Required Software

3.2.1 20 x 20 Aluminium Profile

The 20mm x 20mm aluminium profile is used as the main component for constructing the cartesian manipulator. It is easily obtained from the market for a various length. It has a 'T' slot where other components or parts can be easily mounted onto it by T sliding nut and bolt and other fasteners.

Figure 3.1: Diagram of 20 x 20mm aluminium profile and fasteners used.

3.2.2 Microcontroller and Motherboard

The Arduino Mega board and RAMPS 1.4 Shield are used as the main controller board to operate the cartesian manipulator. The Arduino Mega board used to store the main program code and firmware. While RAMPS 1.4 Shield is the PCB for the stepper motor drivers, it eases the wiring connection between the main microcontroller board and the stepper motor driver.

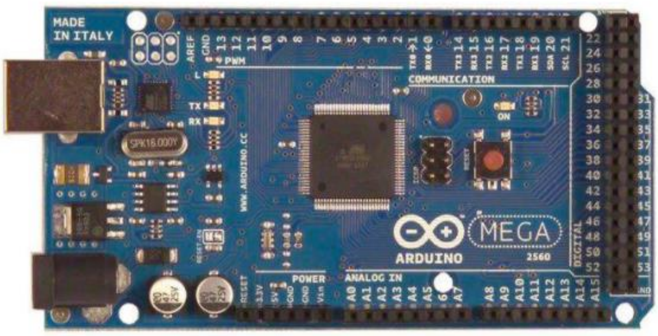


Figure 3.2: The Arduino Mega board.

Figure 3.3: The RAMPS 1.4 Shield.

3.2.3 Stepper Motor and Stepper Motor Driver

All cartesian manipulator actuators are selected to be using NEMA 17 HS4401 stepper motor while the motor driver is A4988. The selected motor has the specification of 1.7A rated current, 40 N·cm holding torque, 1.8° per step and 200 steps per revolution, its microstep can up to 3200 steps per revolution. The A4988 driver can provide sixteenth-step resolution, which is also the configuration used in the design. Sixteenth-step resolution provides a smoother motion for the stepper motor. This motor driver also provides easy control with just 2 pins which are the step input and direction input from the microcontroller.

Figure 3.4: NEMA 17 HS4401 stepper motor.

Minimum Logic Voltage:	3V
Maximum Logic Voltage:	5.5 V
Continuous current per phase:	1 A
Maximum current per phase:	2 A
Minimum Operating Voltage:	8 V
Maximum Operating Voltage:	35 V

Figure 3.5: A4988 stepper driver and its specification.

3.2.4 Directional Control Valve and Relay

The directional control valve used to control the airflow is a 2/2 way 12V DC solenoid direct actuated valve with spring return. 2 pieces of the pneumatic valve are needed to redirect the air into the soft gripper and redirect the air to the atmosphere from the gripper. The relay is used to control the power supply or the signal to the directional control valve. A 2 channel 5V active low relay module is used. The relay receives input from the microcontroller.

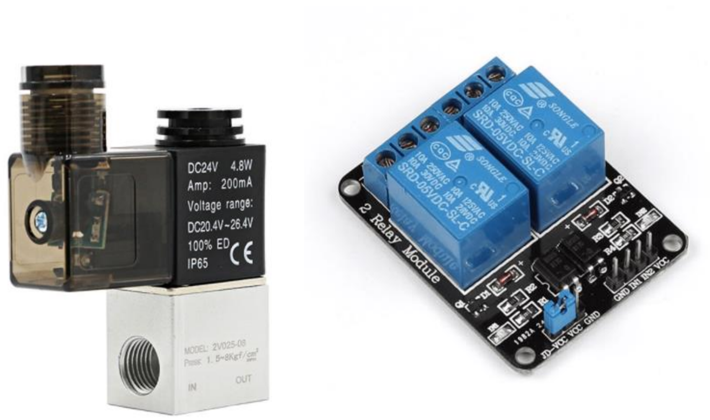


Figure 3.6: A 2/2 way 12V DC solenoid direct actuated valve and 2 channel 5V active low relay module used.

3.2.5 Ecoflex Rubber

The Ecoflex series silicon rubbers from Smooth-On, Inc is used to fabricate the soft gripper. The Ecoflex 00-30 silicon rubber has the characteristic of strong, soft, and able to stretch many times from its original size without tearing and will return to its original shape without distortion. Ecoflex 00-30 consists of two parts which are part A and part B. They are in liquid form before mixing. By mixing part A and part B with a 1:1 ratio and leave it at room temperature for curing for around 4 hours, we will obtain a cured silicon rubber. We can form the desired shape by pouring them into the designed mould. Another series which is Ecoflex 00-50, have a higher tensile strength and tear strength.

Figure 3.7: Part A and Part B of Ecoflex 00-30 silicon rubber.

3.2.6 3D Printing Material and 3D printer

The mould is necessary to give shape for the uncured silicon rubber to solidify into the desired shape. The soft gripper is designed by CAD software Solidworks, and then the mould is generated from the model. The mould will be 3D printed with material polylactic acid (PLA). The mould should have a good surface finish to minimize the adhesion between the mould and the silicon rubber. The brackets, holders, and other mountings of the cartesian manipulator are fabricated, or 3D printed using Acrylonitrile Butadiene Styrene (ABS) and PLA. The 3D printer used in this project is model Ender 3 from Creality 3D

Technology Co., Ltd. It is an FDM 3D printer with a printing size of 200mm x 200mm x 250mm.

3.2.7 Software – CAD Solidworks, Arduino IDE, Pronterface

The Solidworks from Dassault Systèmes is used as the main CAD software to design soft gripper and cartesian manipulator, to model assembly of the mechanical structure, to generate mould, to simulate the motion of XYZ axes, to customize the mounting, bracket and holder, and to make sure the mechanical feasibility. The version of Solidworks used is the year 2019. Besides, The Arduino Integrated Development Environment (IDE) is used to write the program, configure and boot the Marlin firmware. The Pronterface from Printrun is used as the main software to control the cartesian manipulator. This includes the motion in the X, Y and Z axis, monitor the state of the limit switch and control the actuation of the soft gripper.

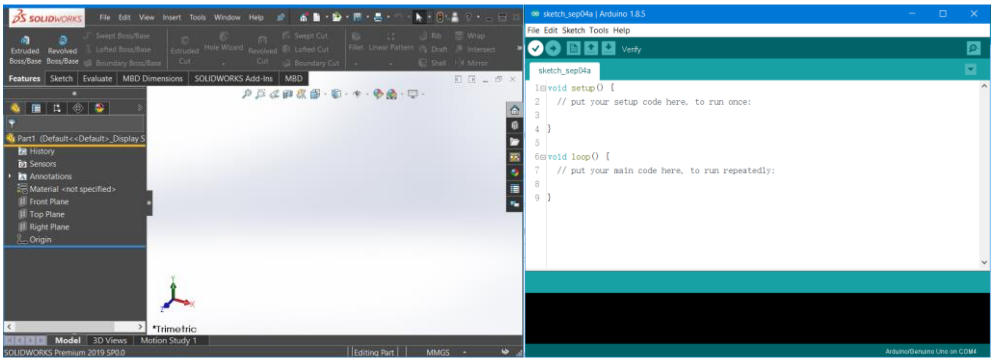


Figure 3.8: Solidworks interface and Arduino IDE interface.

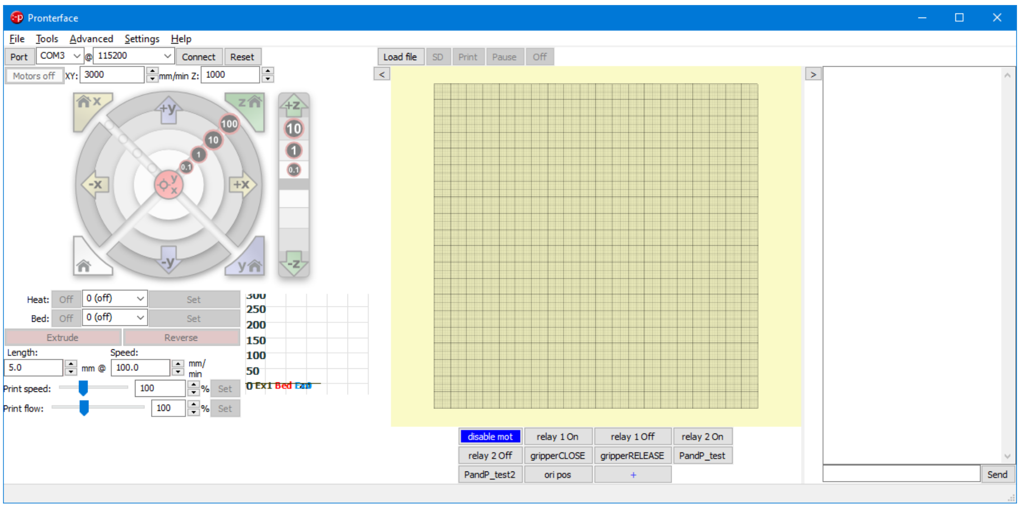


Figure 3.9: The interface of Pronterface.

3.2.8 Power Transmission Components

The power transmission components required to build the project include the lead screws, timing belts and pulley. The specification of the lead screw is 8mm diameter, 2mm pitch, 8mm lead, 1000mm length. The GT2 timing belt with 20 teeth, 6mm width, and bore size of 5mm and 8mm are used. The timing belt that is compatible to the pulley is used, it is a 2mm pitch and 6mm wide timing belt. These components are shown in the figure below.

Figure 3.10: The power transmission component such as lead screw, pulley and timing belt.

3.3 Mechanical Design of Cartesian Manipulator

3.3.1 Main Frame

The mechanical structure of the cartesian manipulator is separated into two subassemblies for ease of design and fabrication. The first subassembly is the mainframe. It is the main structure and the largest in dimension. The mainframe comprises 12 pieces of aluminium profiles, 4 pieces of linear shaft guide, and 4 sets of lead screw drives with the stepper motors. The linear guides are used to constraint the XY platform to ensure its linearity in Z-axis, while the lead screw drive provides the motion to the platform for moving up and down. Figure 3.11 shows the modelling of the cartesian manipulator main frame. All components are joined by the fasteners and 3D printed mounting. The detailed of the drawing and modelling file can be obtained in the appendix A.

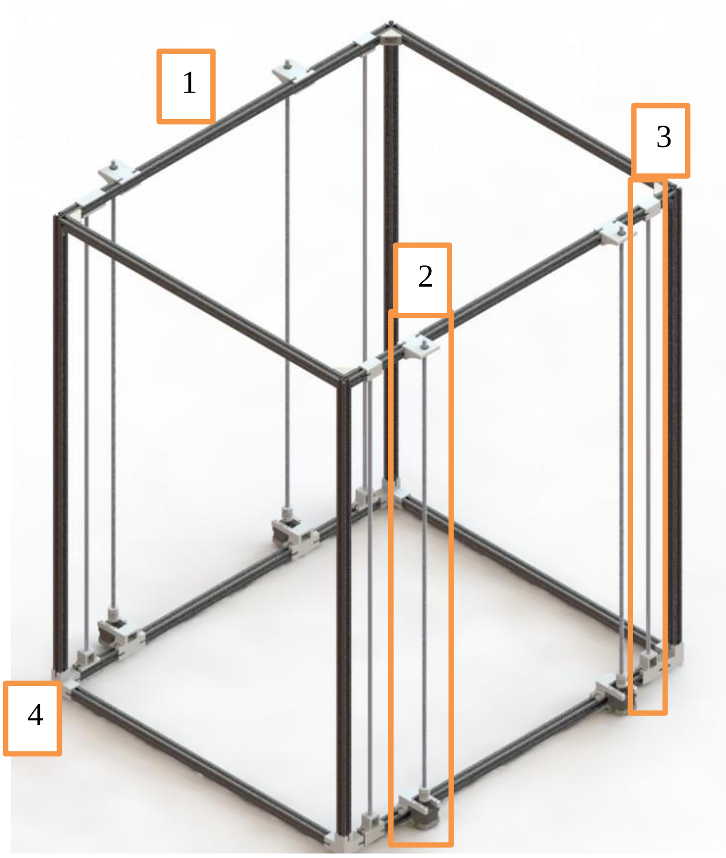


Figure 3.11: The main frame of the design cartesian manipulator.

1) Aluminium profile

2) Lead screw drive

3) Linear guide

4) Customized bracket

3.3.2 XY Platform

The XY platform is the subassembly designed to integrate any components that are responsible for XY-axis motion. Figure 3.12 shows the modelling of the XY platform. The XY platform's main structure is consisting of 4 pieces of aluminium profiles that are joined together to form a square frame by 4 pieces of brackets. The brackets also designed to hold the linear guides. The linear guides are mean for the XY-axis sliding blocks to install on it. The sliding blocks will carry 2 pieces of linear shafts perpendicular to each other, these 2 pieces of linear shafts will pass through an upper soft gripper holder. Two pieces of stepper motors are installed on the aluminium profile by customized mounting. Two pieces of trapezoidal nut with mounting are designed to install on the left side and right side of the aluminium profile. They are responsible for receiving motion from the lead screw.

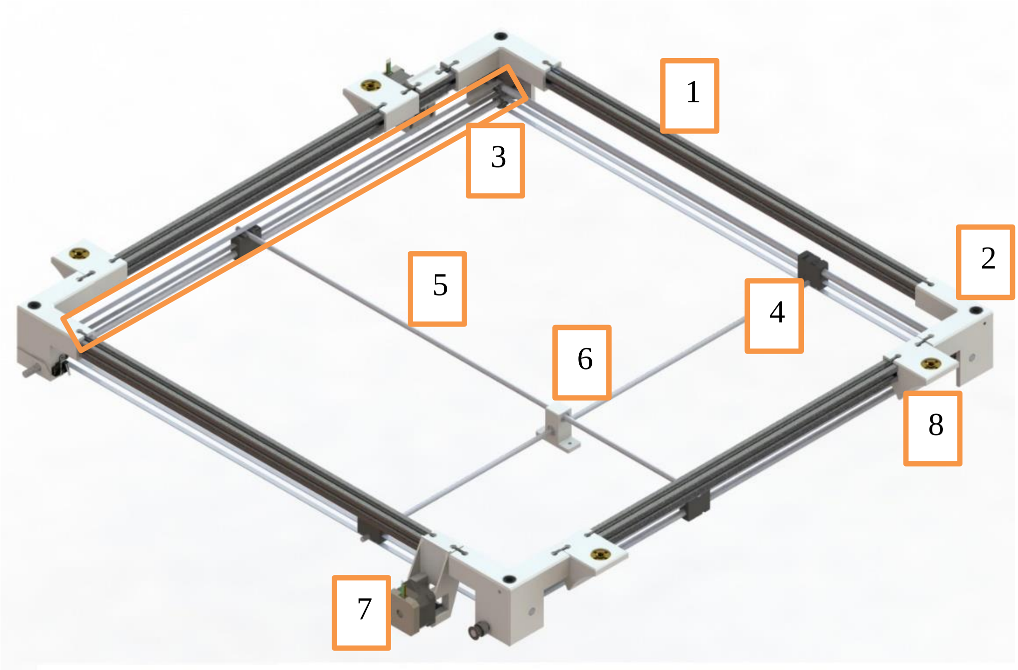


Figure 3.12: The XY platform of the cartesian manipulator.

1) Aluminium profile

2) Customized bracket

3) Linear guide and timing belt

4) Sliding block

5) Linear shaft

6) Upper soft gripper holder

7) Stepper motor with mounting

8) Trapezoidal nut with mounting

3.3.3 Holders, Brackets and Mounting

All of the holders, brackets and mounting are designed and 3D printed. They serve as the joint to hold all the standard component together include aluminium profile, linear guide, motor, etc. Design iteration has been carried out after the printed product tested with the fit and tolerance with other joining components. Figure 3.13 shows some of the design brackets and mounting.

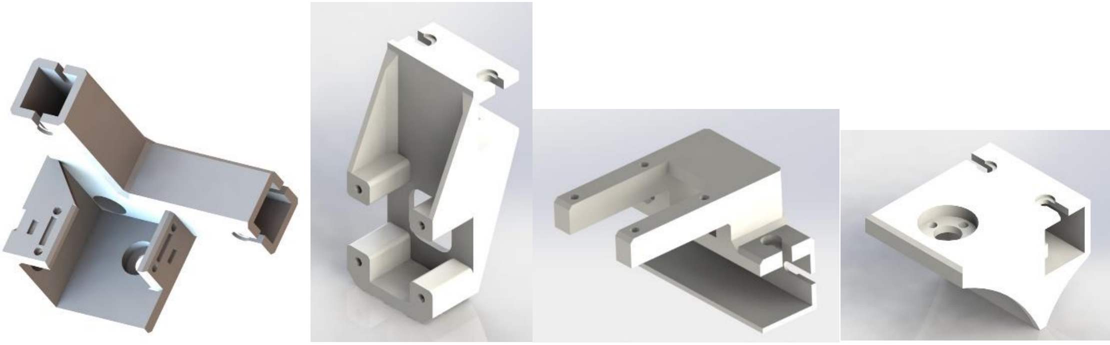


Figure 3.13: The designed bracket, holder and mounting.

3.3.4 Evolution of Cartesian Manipulator Design

The changes in the design of the cartesian manipulator are necessary to solve the problem faced during the prototype construction. Table 3.1 summarizes the design changes and the problem of each design. The major changes only made for the z-axis drive mechanism.

Table 3.1: The features of each manipulator design and their drawbacks.

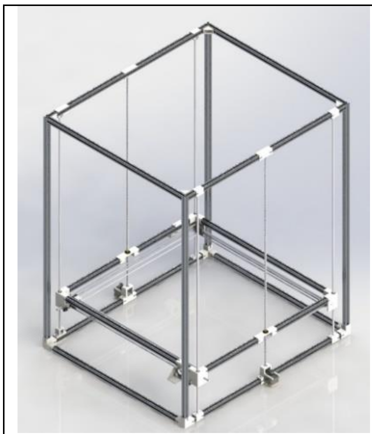
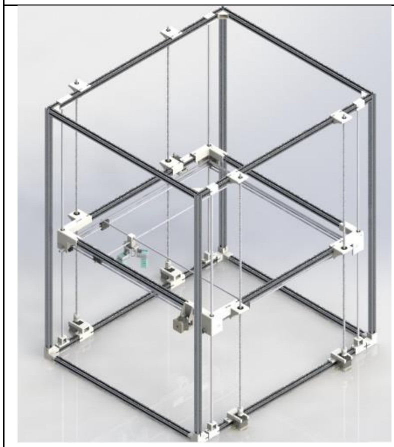
 Figure 3.14: Design 1	Feature: The left and right side aluminium profile of the XY platform is separated into 2 pieces with a mounting on the middle, the lead screw will drive the platform through that mounting. Problem: The separated aluminium profile becomes a concave shape making the XY platform to lost its flatness and affect moving up and down motion.
 Figure 3.15: Design 2	Feature: The mounting is made longer to solve the concave issue. Problem: The concave shape of the XY platform was reduced but to eliminated.

 Figure 3.16: Design 3	Feature: The separated aluminium profile was changed to a whole length profile. The mounting is redesigned to fit the lead screw at the side. Problem: The whole length profile solved the concave issue but the uneven weight distribution due to the location of the stepper motor causes the slanting of the XY platform.
 Figure 3.17: Design 4	Feature: This is the final design. Two Z-axis lead screw drive was increased to four Z-axis lead screw drive to support and drive each corner during rising and lowering of the platform. Advantage: It provides more friction. The platform will not slide down when the stepper motor is not powered. Problem: The synchronization of the four stepper motor needed to design carefully.

3.4 Soft Gripper Design

3.4.1 Soft Gripper Modelling

The soft gripper is made up of 3 pieces of a similar soft finger. The design of the soft finger is adopted from online open-source: Soft Robotic Toolkit. CAD software Solidworks design the soft finger. The mould is then generated from the designed soft gripper by the ‘combine’ feature in Solidworks. Figure 3.18 show the final design soft finger. The soft finger dimension is 5mm in length, 20mm in width and 19mm in height. This soft finger consists of 6 air chambers. The cross-sectional area of each air chamber is 3 x 14mm. The external separation between each chamber is 1mm.

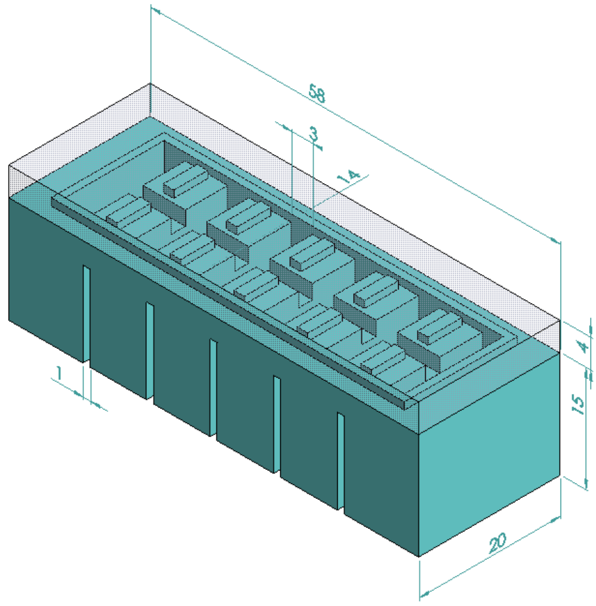


Figure 3.18: The individual soft finger modelling.

There are 3 moulds needed to fabricate soft finger, namely lower inner mould, lower outer mould and base mould. The lower mould is designed into 2 pieces for ease of removal after silicon curing. The base mould is to create a 4mm layer cure silicon. The two cured part is then joined together with 1mm uncured silicon. The fabrication step is discussed in the next subchapter.

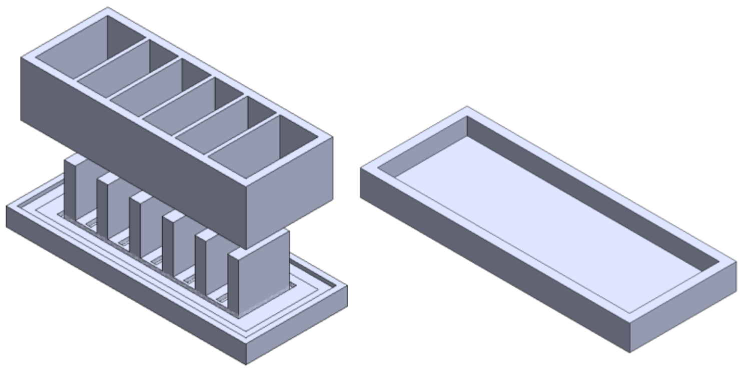


Figure 3.19: The lower inner mould, lower outer mould and base mould.

3.4.2 Soft Gripper Fabrication

The final material used for soft gripper fabrication is Ecoflex 00-50. The series of fabrication steps are shown in the figures below (Figure 3.20 to 3.24). Firstly, the 3D printed moulds were prepared before silicon mixing. Then 23g of type A Ecoflex was pouring into a container and followed by 23g of Ecoflex type B.

Stirling process was carried out to make sure they are properly mixed. Next, the mixed silicon was carefully poured into the prepared moulds. A strip of paper was placed on the base mould's top to act as a strain limiting layer. A toothpick punctured the visible air bubble. They were then left at least 4 hours for curing. The lower mould was removed, the Ecoflex was mix again with a small amount, it was then used to adhere the two pieces together.

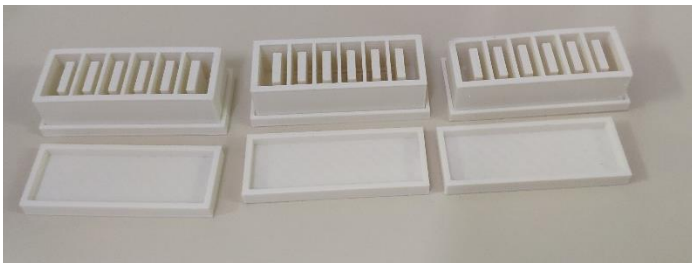


Figure 3.20: Preparation of 3D printed moulds.

Figure 3.21: Pour the same amount of A type and B type Ecoflex and mix them.

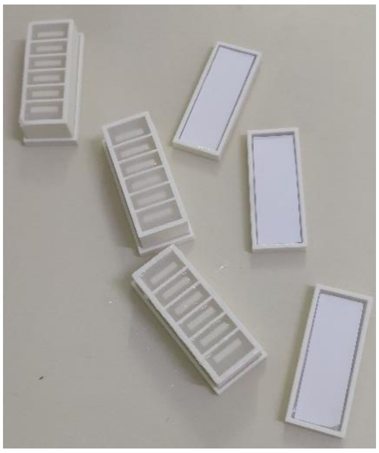


Figure 3.22: Pour the mixed silicon into the moulds.

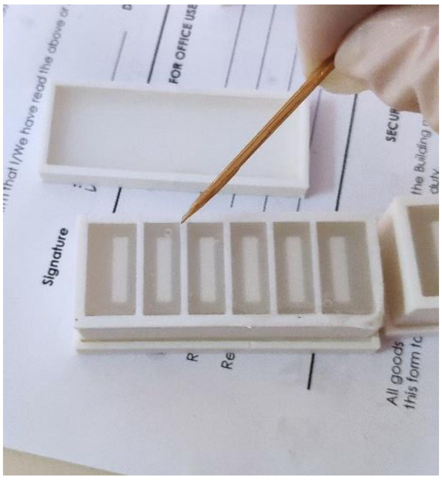


Figure 3.23: Puncture the air bubbles.

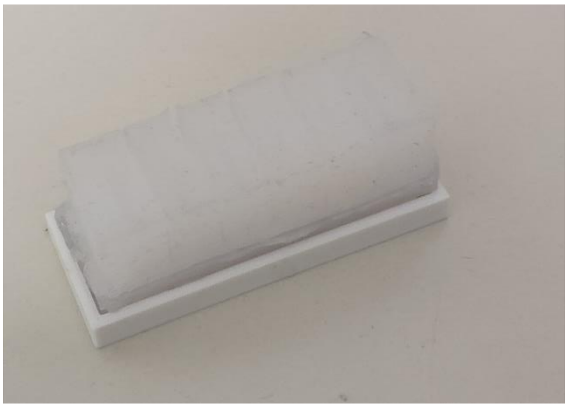


Figure 3.24: Joining two parts together.

After hours of curing, we obtained a complete soft finger. A hole was punctured, and a 3mm tube was inserted into the soft finger. The compressed air supply was used to actuate the soft finger for leakage checking (Figure 3.25).

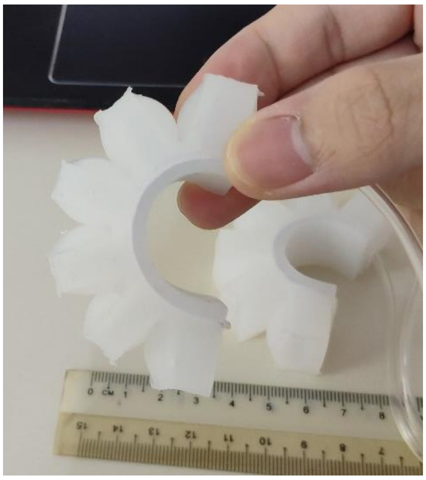


Figure 3.25: Actuated soft finger with compressed air supply.

A soft gripper holder is then designed according to the dimension of the produced soft finger. Figure 3.26 show the soft gripper holder model. It is fabricated by a 3D printer with material PLA. All of the components were integrated together to form a complete soft gripper (Figure 3.27).

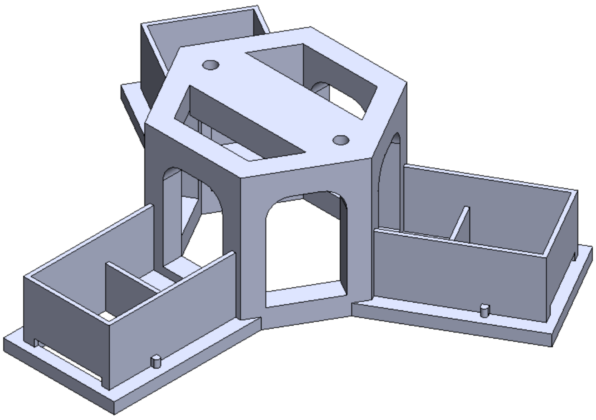


Figure 3.26: Soft gripper holder modelling.

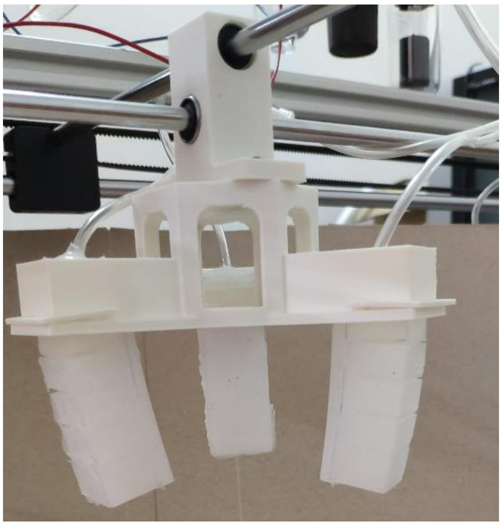
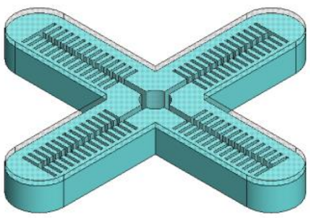
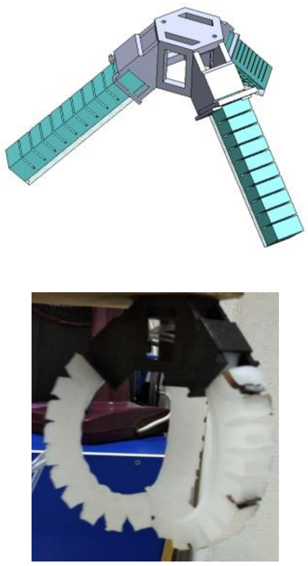
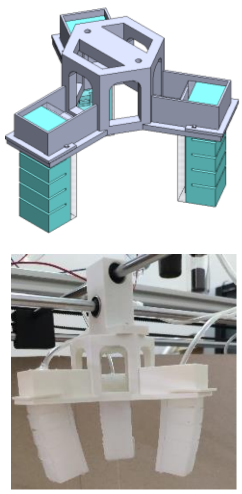


Figure 3.27: A complete soft gripper integration.

3.4.3 Evolution of Soft Gripper Design

The changes in the soft gripper design were carried in order to optimize the grasping performance. Table 3.2 summarizes the design changes of each model. The changes were made on the soft finger and its holder.

Table 3.2: Summary of the design changes on the soft gripper.

 Figure 3.28: Design 1	This is four fingers as a whole gripper. This design is not commonly seen in the industrial soft gripper. This gripper is difficult to mount and lower positioning accuracy due to higher soft structure coverage.
 Figure 3.29: Design 2	The first prototype soft gripper is longer in length (103mm) with an angle of 45° inserted into the holder. The long length soft finger makes it too flexible during unactuated moving. The soft gripper is expected to maintain reasonable rigidity. By the 45° configuration, the soft gripper is bending down before being powered due to the gravity effect.
 Figure 3.30: Design 3	The length of soft fingers is reduced. The insertion angle was also changed to 90° vertically downward. After the motion test and actuation test with the prototype, we can observe that rigidity was improved from the previous design. This was chosen to be the final design.

The spacing of each finger can be controlled or adjusted by redesign the soft gripper holder. However, it is limited by the length of the soft finger and the objects to be grasped. For general pick and place application, the spacing was designed so that the gripper can fit any object with around 70mm diameter cylindrical volume, as shown in Figure 3.31.

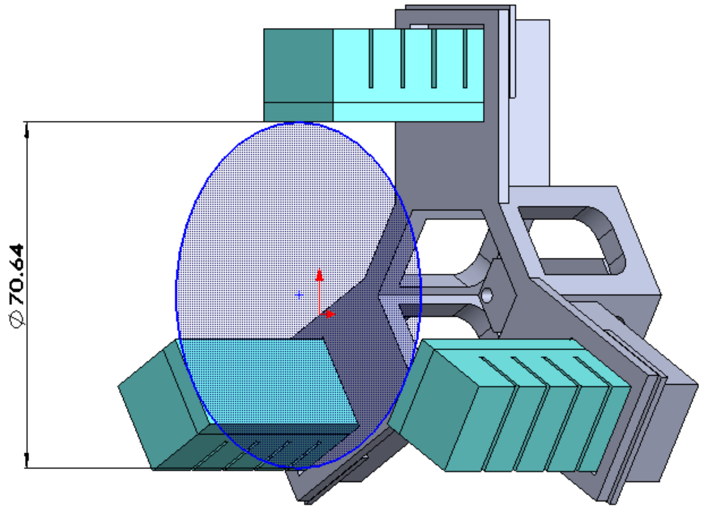


Figure 3.31: Soft gripper integration model with indicated spacing.

3.5 Electrical and Electronics Design

The electrical and electronics design include the connection between Arduino Mega, Ramps 1.4, stepper motor drivers, stepper motors, pneumatic solenoid valves, limit switches, etc. The connection is shown in Figure 3.32. The Ramps 1.4 is a modular shield that directly stacks on top of Arduino Mega. The other components will directly connect to ramps 1.4 by cables.

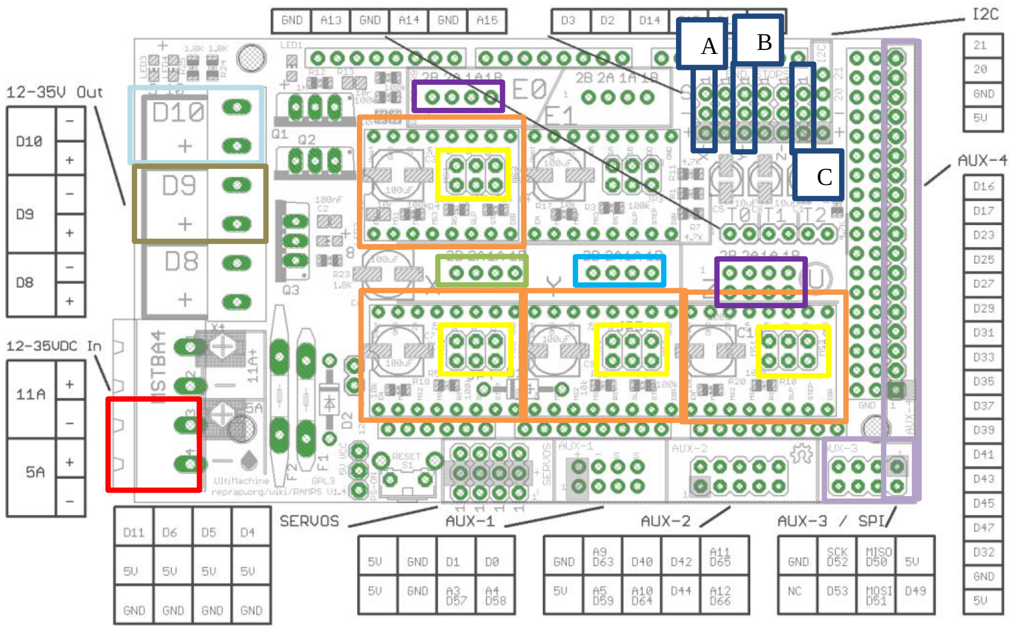


Figure 3.32: Connection of Ramps 1.4 with other components.

Connect to stepper motor driver A4988

Connect to 12V power supply

Connect to X-axis stepper motor

Connect to Y-axis stepper motor

Connect to either 2 Z-axis stepper motors

Connect to either 2 Z-axis stepper motors

(D9) Connect to first pneumatic valve

(D10) Connect to second pneumatic valve

A Connect X-axis minimum limit switch (home position)

B Connect Y-axis minimum limit switch

C Connect Z-axis maximum limit switch

Connect to LCD screen

Short the terminal with jumper

Firstly, the jumpers were inserted to control the precision of the motor movement to 1/16 micro-stepping. The 4 pieces of the A4988 stepper motor driver also inserted into the pin as labelled in Figure 3.32. Each X-axis and Y-axis motor are connected to the respective pin as indicated in colour box labelling. While there are 4 pieces of Z-axis stepper motor used, and two stepper motors can be connected to either one of the two terminals as shown. An extension is needed to branch the terminal into two terminal. For the LCD screen connection, the wire is also like a shield design where it only directly stack on top of the lower pin of ramp 1.4. The X-axis and Y-axis minimum home position limit switches are connected to the terminal A and B respectively. While for Z-axis is using the maximum home position, it is connected to the terminal C. 12V power supply is connected to a power terminal. The circuit for pneumatic valves was changed from relay setup to direct connection with ramps 1.4. The first pneumatic 2/2 way valve is connected D10 terminal, and the second valve is connected to the D9 terminal.

3.6 Pneumatic System Design

A simple pneumatic system was designed to control the compressed air in and out from the soft gripper. The designed pneumatic circuit is shown in Figure 3.33. There are two 2/2 way valve used. One is used to control the airflow into the soft gripper while the other is used to let the air flow to the atmosphere. D10 and D9 are the signals send from the microcontroller. They are activated one at a time. When D10 is activated, D9 must be deactivated and vice versa. When the D10 is activated (D9 deactivated), the valve switch position to operating mode, allowing the air from the compressor to enter the soft gripper. When D9 activated (D10 deactivated), the first valve back to its original state, stopping supply from the compressor and at the same time, the second valve switched to operating mode, allowing the air to escape to the atmosphere.

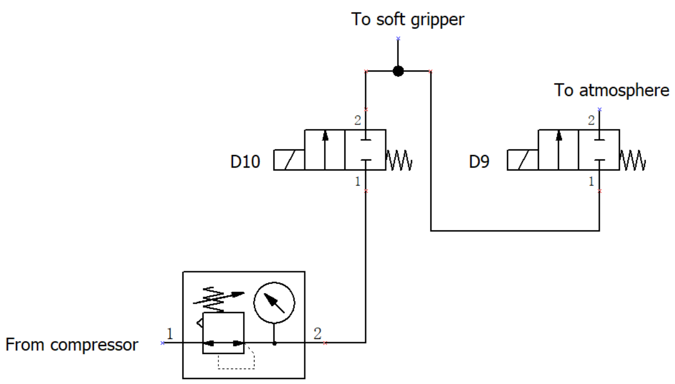


Figure 3.33: The designed pneumatic circuit for soft gripper actuation.

3.7 Firmware Design

The firmware used in this project is Marlin firmware, an open-source firmware. Marlin firmware is primarily developed for fused deposition modelling type (FED) 3D printers. This firmware runs G code and M code commands and instruction sets. It can send movement coordinates to stepper motors through the stepper drivers and manages all input sensors and output devices. Furthermore, Marlin firmware is also extended to be used in a different configuration 3D printer such as Delta, SCARA printers and Hangprinter. Apart from the 3D printer, its application also included CNC milling machine, laser beam machine, pick and place machine, laser cutters and many more. Therefore, it is suitable and chosen to control the pick and place cartesian manipulator in this project.

3.7.1 Marlin Firmware Configuration

The firmware is well developed and only the configuration on the parameters needed to be modified before implement it into the cartesian manipulator. The version of the firmware is 2.0.4.4. The Arduino IDE is used to modify and configure the firmware. Table 3.3 shown all the configuration made on the Marlin firmware as well as the explanation.

Table 3.3: The summary of configuration made on the firmware.

Parameter	**Configuration code**	**Remark**
Communication speed	#define BAUDRATE 115200	The communication channel used when connected to Pronterface
number of extruders	#define EXTRUDERS 0	The is no extruder used
Temperature sensor used	#define TEMP_SENSOR_0 0	There is no temperature sensor used
Z-axis minimum homing	//#define USE_ZMIN_PLUG	The Z-axis minimum home position is disabled

Z-axis maximum homing	#define USE_ZMAX_PLUG	The Z-axis maximum home position is enabled
Board used	#define MOTHERBOARD BOARD_RAMPS_14_EFB	The motherboard used is Ramp 1.4
Stepper driver used	#define X_DRIVER_TYPE A4988	Stepper motor driver used A4988
Axis steps per unit	#define DEFAULT_AXIS_STEPS_PER_UNIT { 83.2863, 83.2863, 400, 400 }	The number of steps required for travelling 1mm
Feedrate for end effector/ gripper	#define DEFAULT_MAX_FEEDRATE { 6000, 6000, 10, 10 }	(X-axis,Y-axis,Z-axis,Extruder) unit is mm/m for XY-axis while mm/s for Z-axis, extruder is used as another Z-axis, this is default speed
Feed rate (self specified)	#define MAX_FEEDRATE_EDIT_VALUES { 9000, 9000, 10, 10 }	Maximum XY-axis speed can go to 9000mm/m equivalent to 15cm/s
Stepper motor acceleration	#define DEFAULT_MAX_ACCELERATION { 5000, 5000, 50, 10000 }	Unit mm/s^2
Each axis jerk value	#define DEFAULT_XJERK 20.0 #define DEFAULT_YJERK 20.0 #define DEFAULT_ZJERK 0.4	To get a smoother stepper motor motion
Homing direction	#define X_HOME_DIR -1 #define Y_HOME_DIR -1 #define Z_HOME_DIR 1	Set the homing to maximum Z-axis direction. XY-axis remains default
Feedrate during homing	#define HOMING_FEEDRATE_XY (100*60) #define HOMING_FEEDRATE_Z (20*60)	Homing speed for XY-axis is 100mm/s and 20mm/s for Z-axis
Printing size = gripper travel volume	#define X_BED_SIZE 590 #define Y_BED_SIZE 590 #define X_MIN_POS 0 #define Y_MIN_POS 0 #define Z_MIN_POS -845 #define X_MAX_POS X_BED_SIZE #define Y_MAX_POS Y_BED_SIZE #define Z_MAX_POS 0	The gripper moving area up to maximum coordinate of <590, 590, -845>

LCD screen user input encoder	#define REVERSE_ENCODER_DIRECTION	Mapping the clockwise input of encoder to downward and increase signal in LCD screen
Number of Z-axis stepper driver	#define NUM_Z_STEPPER_DRIVERS 2	2 Z stepper driver, each driver for 2 Z stepper motor, total 4 motors
Auxiliary pin	#define PINS_DEBUGGING	Uncomment this in order to use the auxiliary pin for other purposes such as controlling relay

The axis steps per unit is the parameter for the number of stepper motor's steps required for travelling 1mm. It is calculated based on the specification of mechanical components used. For the XY-axis, the pulley mechanism is used, the pulley has a 12.23mm circumference. For the Z-axis, the lead screw mechanism is used, it has a 2mm pitch, and 8mm lead.

For XY-axis:

$$\text{Steps\_per\_mm} = \frac{\text{motor\_steps\_per\_rev} \times \text{driver\_microstep}}{\text{circumference of pulley} \times \pi}$$

$$\text{Steps\_per\_mm} = \frac{200 \times 16}{12.23\pi} = 83.2863$$

For Z-axis:

$$\text{Steps\_per\_mm} = \frac{\text{motor\_steps\_per} \times \text{driver\_microstep}}{\text{lead}}$$

$$\text{Steps\_per\_mm} = \frac{200 \times 16}{8} = 400$$

The homing direction for XY-axis has remained as default, while Z-axis needed to be flipped as its home direction is at maximum coordinate. Figure 3.34 below shown the home position and its maximum coordinate for each axis.

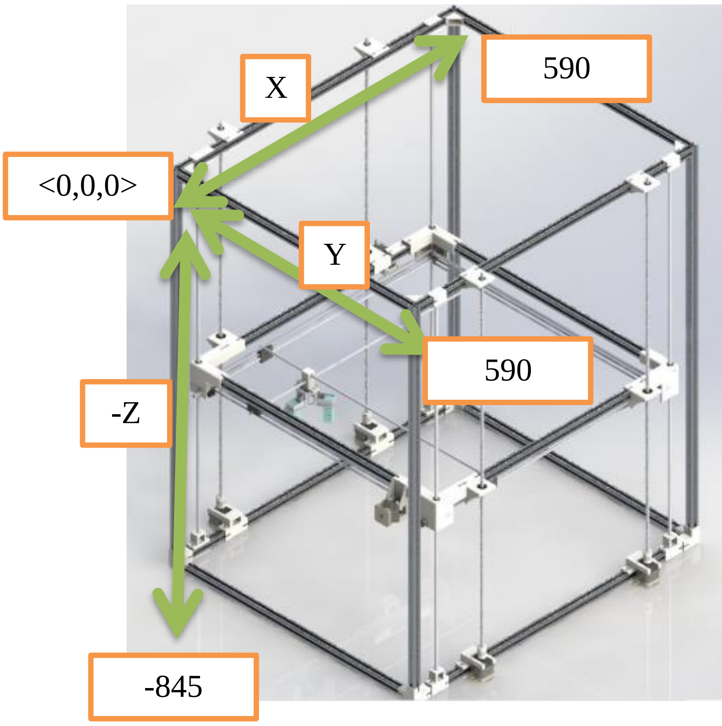


Figure 3.34: Home position for XYZ-axes.

3.7.2 G Code and M Code

The motion of the cartesian manipulator is controlled by sets of G and M code sending from the Pronterface software. The G code used in controlling the cartesian manipulator and soft gripper is listed in Table 3.4. The explanation of each command also listed in the table as well. The gripper's actuation is mainly controlled by the signal from terminal D9 and D10. When the state of D10 is set high, and D9 is set low, the gripper will be closed and vice versa. Homing is necessary after the machine is powered off. Homing can be used for a respective axis by indicating the X, Y or Z after the G28 code. For the movement of the soft gripper, the G1 code will be used. The parameters include the federate or speed and location needed to be filled. The federate is in the unit millimetre per minute. Delay code is used when a series of command is sent and the time interval between each code is needed.

Table 3.4: G code and M code needed for controlling cartesian manipulator and soft gripper.

Command	G code	Remark
Release gripper	M42 I M1 P10 S0 M42 I M1 P9 S255	Remove air from the soft gripper
Close gripper	M42 I M1 P10 S255 M42 I M1 P9 S0	Pump air into the soft gripper
Homing gripper	G28	Home the gripper to <0,0,0>
Homing individual axis	G28 X	Home x-axis only
Move gripper XY	G1 F6000 X200 Y200	Go to absolute coordinate <200,200> with speed 6000mm/m or 100mm/s
Move gripper Z	G1 F600 Z-100	Move the height of the platform to absolute coordinate -100 with the speed of 10mm/s
Move gripper XYZ	G1 F6000 X200 Y200 Z-100	Go to absolute coordinate <200,200,-100> with speed 6000mm/mm or 100mm/s Max speed for Z is 10mm/s
Delay	G4 S2	Delay 2 seconds
Delay	G4 P500	Delay 500 milliseconds
Get current position	M114	Get current XYZ coordinates infomation

3.8 Project Planning and Work Plan

The overall flow of the project is summarized in Figure 3.35. In the development of this project, there are four main tasks which are soft gripper design, cartesian manipulator design, circuit design and firmware implementation. Before the design task, the research and literature review was first carried out in order to obtain sufficient knowledge and resources for the development of the project later. A performance test was carried out before and after the integration of the result from the four tasks. When the problem found, improvement and solution were proposed to overcome it. After the design was finalized they were combined together and perform pick and place operation.

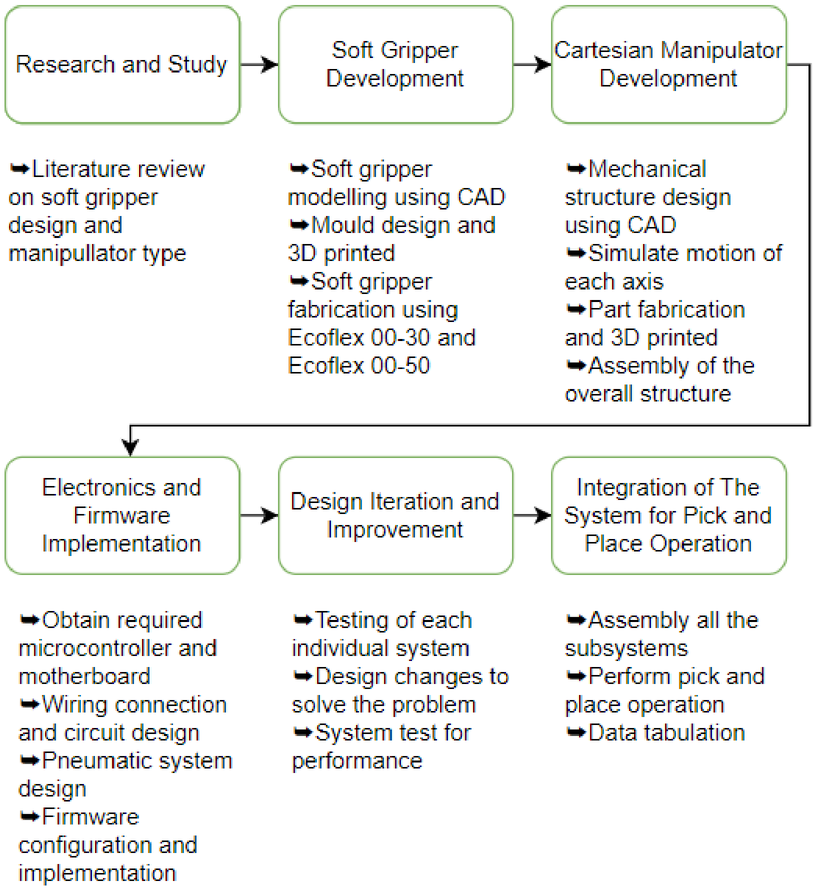


Figure 3.35: The overall flow of the project.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Soft Gripper Assembly

The soft gripper assembly consists of three soft fingers with the corrugated pocket design, soft gripper holders and pneumatic air piping. The individual soft finger is fabricated by material Ecoflex 00-50. The soft gripper holders are fabricated by 3D printing with material PLA. The tube connected to the soft finger is the nasal cannula with 3mm diameter. It is then further extended to a 6mm polyurethane pneumatic tube. The developed soft gripper assembly is shown in Figure 4.1.

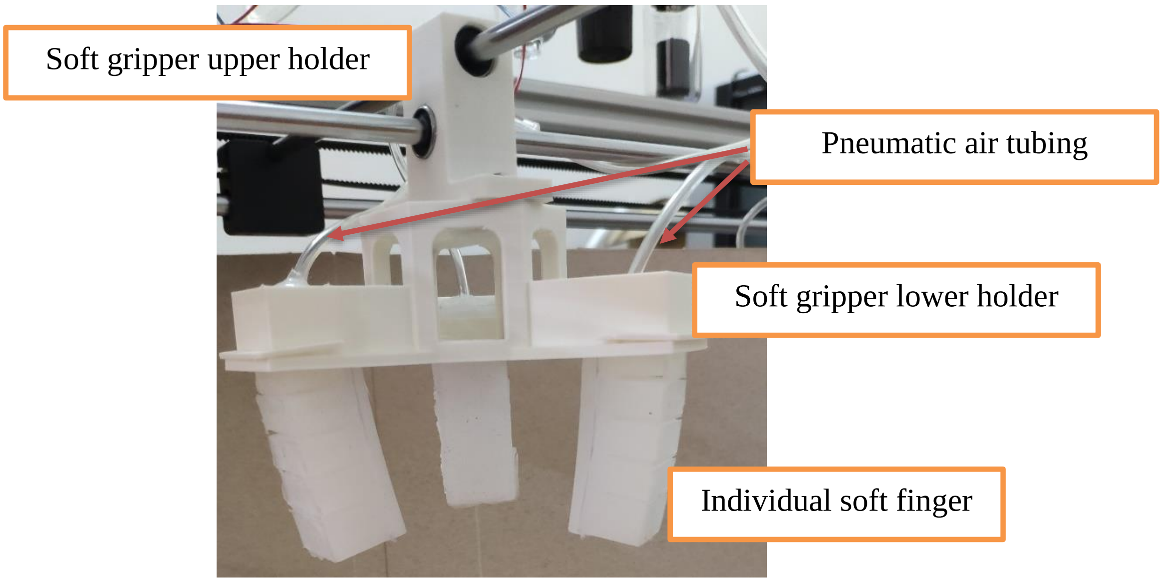


Figure 4.1: The fabricated soft gripper assembly

The soft gripper was supplied with compressed air in order to monitor its actuation state. The pressure regulator was slowly tuned to regulate the optimum pressure for the soft gripper. Figure 4.2 shows the actuated soft gripper, and Figure 4.3 shows the actuated soft gripper with grasping an object.

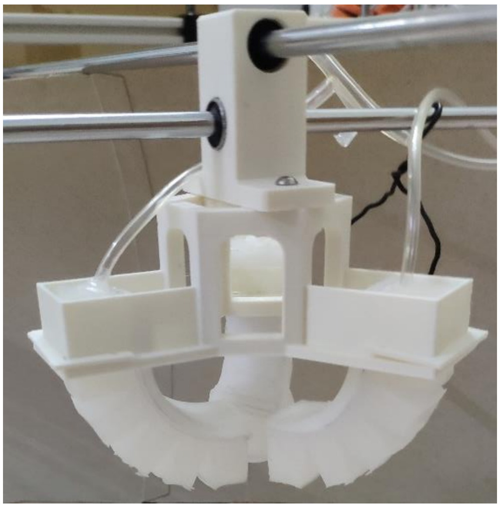


Figure 4.2: The actuated state of the soft gripper.

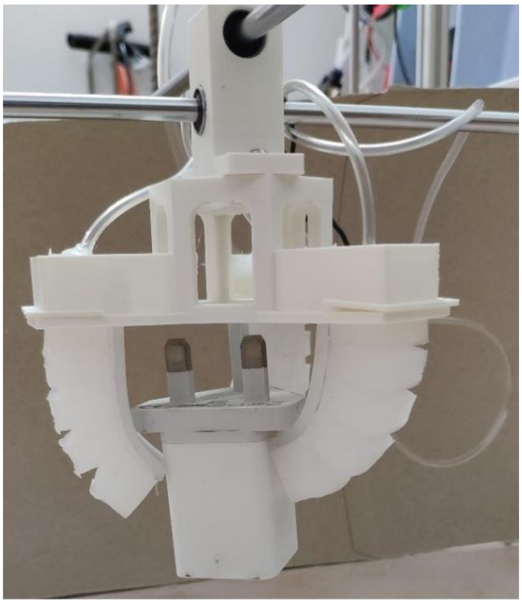


Figure 4.3: The actuated state of the soft gripper with grasping a phone adapter.

4.2 Mechanical Construction and Hardware Assembly

Figure 4.4 shows the complete mechanical assembly of the cartesian manipulator. The constructed cartesian manipulator has a footprint of around 860 x 830 x 1130 mm (XYZ direction). While the soft gripper travel volume measured is 590 x 590 x 845 mm. It is slightly smaller than the stated objective in term of the XY dimension. However, it did not affect the overall pick and place performance of the system.

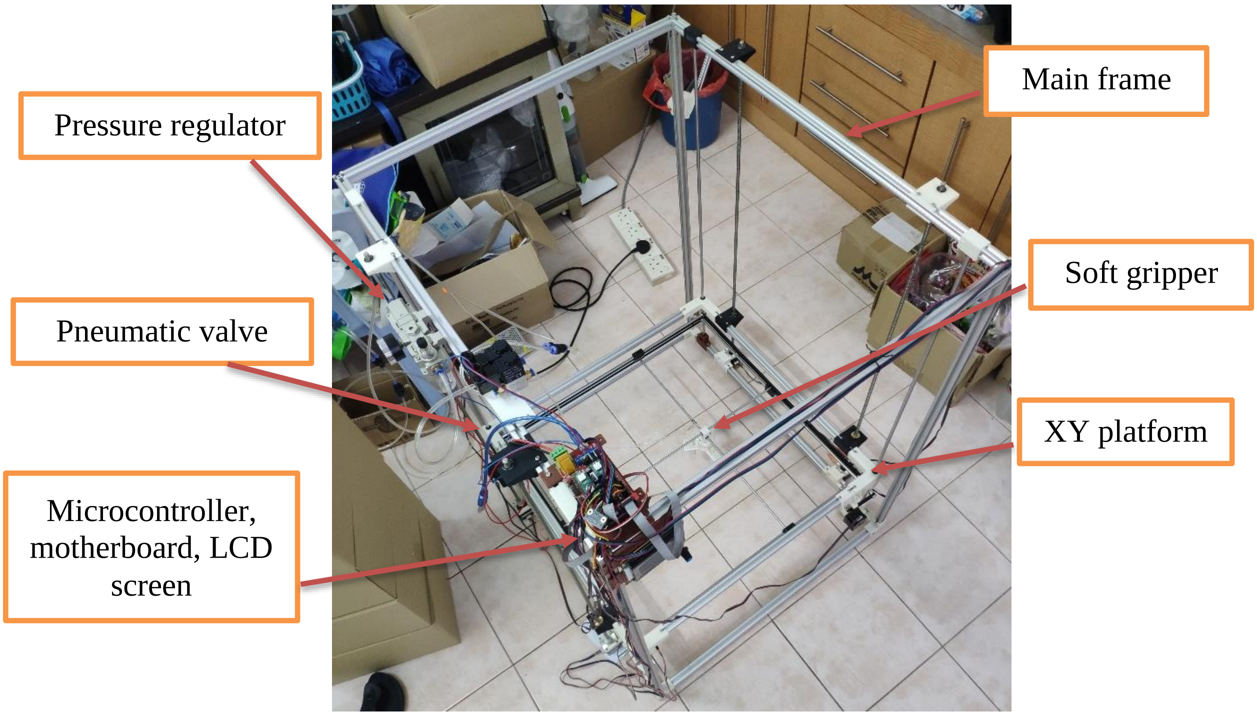


Figure 4.4: The complete mechanical assembly of the developed cartesian manipulator with labelling.

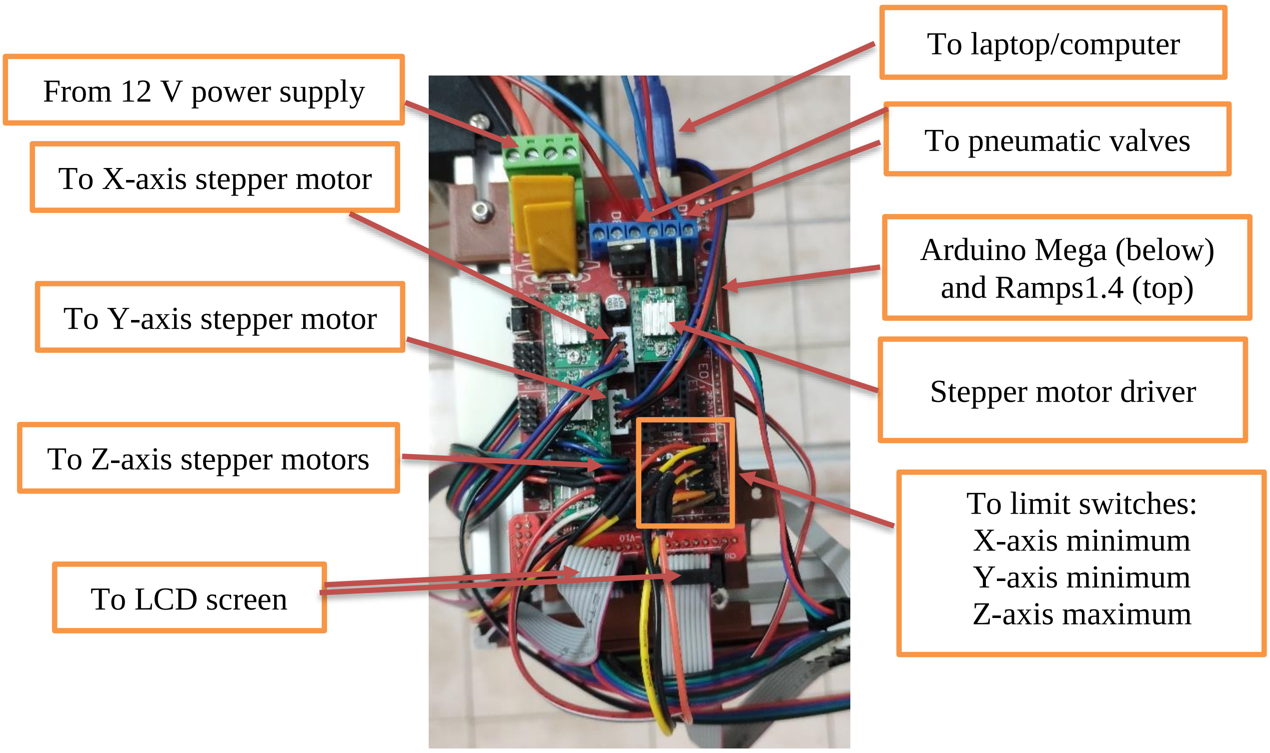


Figure 4.5: The constructed electronics components with labelling.

The constructed electronics circuit is shown in Figure 4.5. The main boards used are Arduino Mega and Ramp 1.4. The Ramps 1.4 motherboard is directly stacked on the top of Arduino Mega. It has the perfect fit pin layout for the Arduino Mega board. 4 pieces of green colour stepper motor drivers (A4988) are stacked onto Ramps 1.4 board. While all the wires are connected to other components and devices, respectively, as labelled in Figure 4.5.

The constructed pneumatic system is shown in Figure 4.6. The components used included a compressor, tubing, pressure regulator, 2 pieces of the pneumatic valves, and jumper wires for signalling.

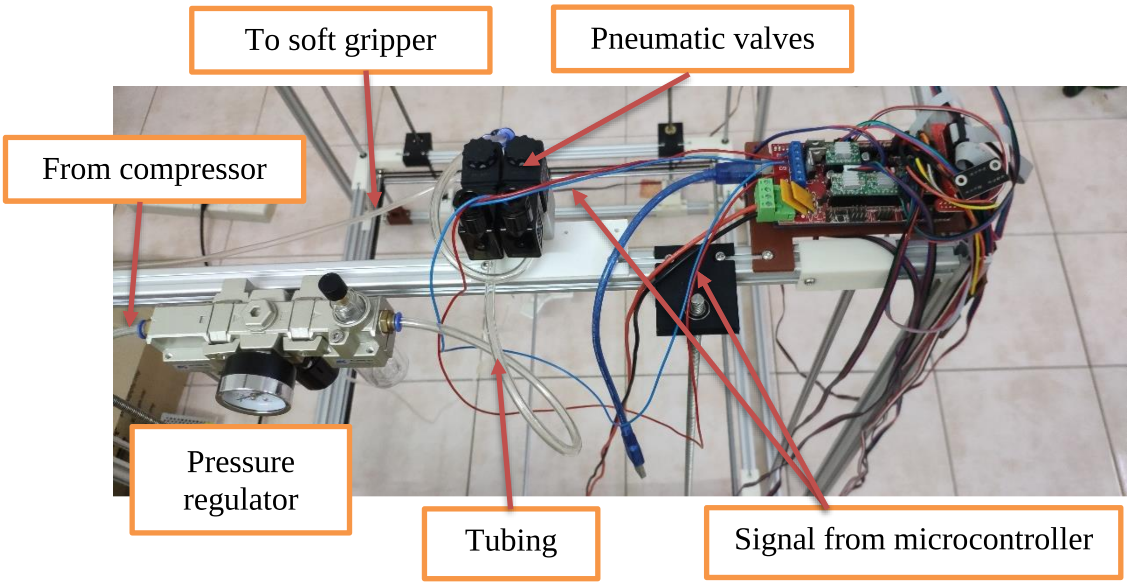


Figure 4.6: The constructed pneumatic circuit with labelling.

4.3 Pick and Place Performance

4.3.1 Motion of XYZ Axes and Speed Performance

To measure each individual axis's speed performance, the cartesian manipulator is programmed to move in only a single axis with a targeted speed to a certain position by a certain distance. A stopwatch measures the travel time, and this value will be used to calculate the measured speed. The percentage difference is then obtained to show the variation between the speed it supposes to be and the actual speed it travels. Table 4.1 to Table 4.3 shown the data obtained for the X, Y and Z-axis.

Table 4.1: Single x-axis travel speed performance

X-axis travel distance, mm	Target speed, mm/s	Measured travel time, s	Measured speed (travel distance/ measured time), mm/s	Percentage different, %
200	50	4.13	48.43	3.14
200	60	3.56	56.18	6.37
400	70	5.88	68.03	2.81
400	80	5.2	76.92	3.85
500	90	5.65	88.5	1.67
500	100	5.13	97.47	2.53
Average percentage different, %				3.4

Table 4.2: Single y-axis travel speed performance

Y-axis travel distance, mm	Target speed, mm/s	Measured travel time, s	Measured speed (travel distance/ measured time), mm/s	Percentage different, %
200	50	4.05	49.38	1.24
200	60	3.43	58.31	2.82
400	70	5.94	67.34	3.80
400	80	5.33	75.05	6.19
500	90	5.45	91.74	1.93
500	100	5.29	94.52	5.48
Average percentage different, %				3.58

Table 4.3: Single z-axis travel speed performance

Z-axis travel distance, mm	Target speed, mm/s	Measured travel time, s	Measured speed (travel distance/ measured time), mm/s	Percentage different, %
100	5	20.86	4.79	4.20
100	6	17.19	5.82	3.00
200	7	28.92	6.92	1.14
200	8	25.55	7.83	2.13
300	9	33.84	8.87	1.44
300	10	30.43	9.86	1.40
Average percentage different, %				2.22

From the result obtained, we can observe that the X and Y-axis have a similar speed performance while Z-axis has better speed performance compared to the X and Y-axis. One of the factors that cause the X and Y-axis to have higher percentage difference is the parameter steps per mm configured in Marlin Firmware as shown below:

```
#define DEFAULT_AXIS_STEPS_PER_UNIT   { 83.2863, 83.2863, 400, 400 }
```

Due to the firmware's limitation, it only able to send the steps with floating-point up to 2 decimal places. Therefore, the third and fourth decimal value ignorance contributes to the difference in the target speed and actual speed. While Z-axis has a relatively low percentage difference as its steps per mm is an integer which is 400 steps/mm. However, a small deviation in the data obtained might be due to human error during the data tabulation. There exist a certain latency for starting and ending of the stopwatch by the observer.

Apart from individual axis travel, the performance test was also carried out to point travel within the cartesian volume. Each of the axes is moving together at the same time. The maximum speed programmed is 100 mm/s, 100 mm/s and 10 mm/s for X,Y and Z-axis respectively. However, the speed for the longest time taken axis will affect the other two axes. The theoretical travel time is calculated for the axis that has the longest time taken to reach the final position. Table 4.4 tabulated 5 sets of data for theoretical travel time and actual measured travel time.

Table 4.4: Point to point travel performance with the speed of (100,100,10) mm/s

Coordinate travel initial position	Coordinate travel final position	Theoretical travel time,s	Measured travel time, s	Percentage different, %
<100,100,-200>	<180,250,-230>	3	3.11	3.67
<100,100,-200>	<360,400,-150>	5	5.18	3.6
<100,100,-200>	<245,150,-270>	7	7.32	4.57
<100,100,-200>	<500,200,-90>	11	11.47	4.27
<100,100,-200>	<40,20,-300>	10	10.62	6.2
Average percentage different, %				4.46

The average percentage difference is higher than those in single axis travel. The combination of all axes travel is expected to produce a higher error as shown in the result obtained. Nevertheless, the latency for time recording still exists in this data acquisition.

4.3.2 Positioning Accuracy

To measure the accuracy in positioning, the setup is shown in Figure 4.7. The end effector was changed to a pen to point the paper's position for the initial and final position, respectively. The actual distance was calculated while the actual distance was measured between two points.

Figure 4.7: The setup to measure XY positioning accuracy.

Table 4.5: Accuracy test for distance between two XY coordinates

XY initial position	XY final position	Calculated distance, mm	Measured Distance, mm	Percentage different, %
<100,100>	<200,200>	141.42	147	3.95
<200,200>	<300,250>	111.80	116	3.76
<300,250>	<550,150>	269.26	279	3.62
<550,150>	<550,550>	400.00	416	4.00
<550,550>	<500,350>	206.16	213	3.32
<500,350>	<390, 550>	228.25	237	3.83
<390, 550>	<100,420>	317.80	332	4.47
Average percentage different, %				3.85

Seven sets of data were tabulated. The average accuracy for positioning is 3.85%. The deviation mainly contributed by the mechanical imperfection and the steps per mm value sending from the microcontroller. The mechanical imperfection includes the straightness of the lead screw used and the limitation of the measurement tool. Similarly, the electronics only sent steps per mm up to two decimal places.

4.3.3 Pick and Place Performance for Different Objects

The pick-and-place operation was carried out to determine the developed system's capability to grasp and place the different objects. Two objects were placed in the designated position. The soft gripper will pick an item at a time and place it in a container. The time taken for the whole process was recorded in Table 4.6. The time taken depends on the position of the objects and container and the height of the objects. The video of the operation can be obtained in the appendix B.

Table 4.6: Pick and place performance for the different object with axis speed of (100,100,10) mm/s

Object 1 <initial position> <final position>	Object 2 <initial position> <final position>	Time taken to complete pick and place operation, s
Egg <100,100,-810> <330,40,-795>	Ping Pong <200,300,-835> <380,40,-795>	58
Phone adapter <100,100,-820> <400,400,-820>	Sanitiser spray <100,300,-790> <300,400,-790>	79
Lithium-ion battery <300,100,-800> <400,400,-800>	Pepper container <100,300,-763> <300,400,-763>	61

Three sets of different objects were chosen which include egg, ping pong, phone adapter, sanitizer spray, lithium-ion battery and pepper container. For the first set of object, the egg is placed on position 1 and the ping pong place on position 2, they were then be picked and placed on the egg tray with position 3 and 4, respectively. Figure 4.8 shows the before and after pick and place operation of egg and ping pong. Similarly, for the second and third set of objects, the final position was changed inside a container box. The pick and place for the third set of objects are shown in Figure 4.9.

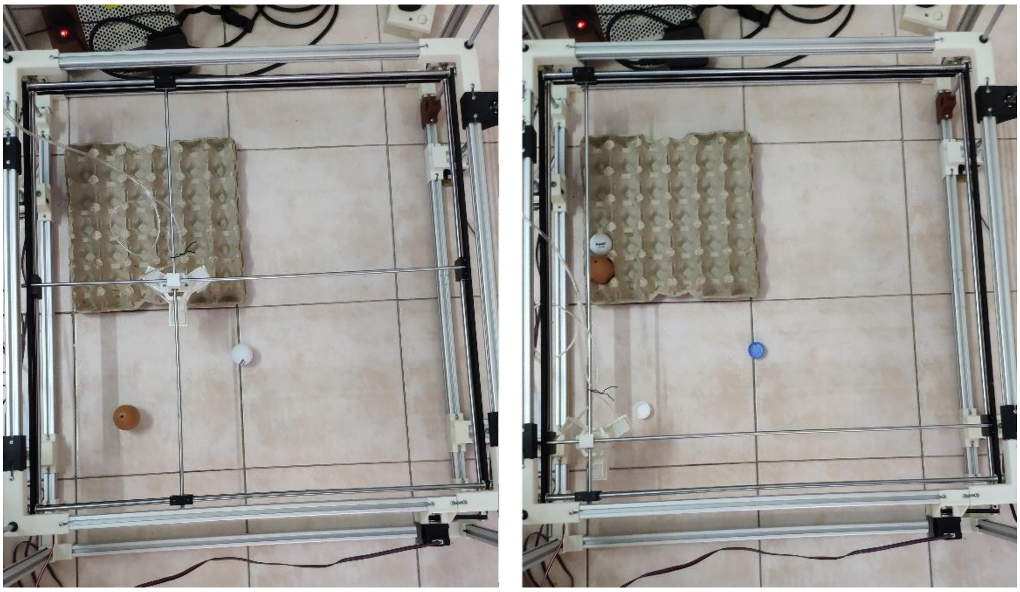


Figure 4.8: The before and after pick and place operation for egg and ping pong

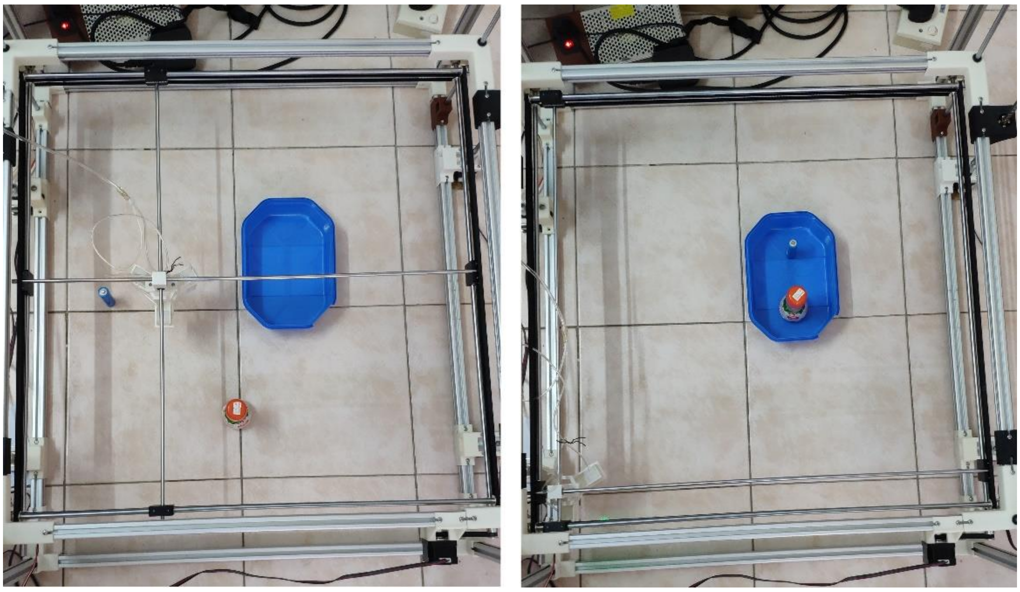


Figure 4.9: The before and after pick and place operation for lithium-ion battery and pepper container.

The pick and place operation successfully shows that the developed soft gripper with a 3-DOF cartesian manipulator can grasp the regular and irregular shape of the object and place them in a designated position.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this project, a soft gripper pick and place system with three degrees of freedom cartesian manipulator was successfully developed and constructed. The developed cartesian manipulator has a working volume of 590 x 590 x 845 mm. The system was able to perform a pick and place operation by soft gripper on a different object. The soft gripper was fabricated by fluidic elastomer Ecoflex 00-50 with the corrugated pockets design. The design was changed few times after the product is fabricated and tested to obtain the optimum geometry design. The mechanical structure of the cartesian manipulator was constructed. Design iteration was carried out to resolve the axis motion issue. The electronics circuit and pneumatic system were designed and constructed to control the cartesian manipulator's motion and actuate the soft gripper respectively. An open-source firmware was adopted and configured to fit the mechanical structure and the electronics components used. Some performance test was done to evaluate the system and to optimize them. However, the system's performance is not perfect due to the limitation in electronics and the fabrication of the mechanical component.

5.2 Recommendations for future work

The current developed soft gripper pick and place system can be improved into fully automated machine vision system. A machine vision system can be used to recognize the object and detect its location. Then sending the coordinate information to the microcontroller to perform pick and place operation. Besides, there is room for improvement on the cartesian assembly, first one is the fabrication of the parts by using a CNC machine. Second, the alignment tool such as jig or other precision tools can align when each component is joined together to make sure the linearity, straightness, flatness, etc on the assembly. For positioning accuracy, a position feedback system can be added to ensure the end effector travels to a precise location. The feedback system can use encoder motors or camera system to feedback the current position to the microcontroller. Any deviation is the targeted location and current location, the microcontroller should send a signal to the motors to move again to reduce the differences.

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APPENDICES

APPENDIX A: CAD Files For Cartesian Assembly And Soft Gripper

Cartesian Manipulator

https://drive.google.com/drive/folders/1b9WTrDt1UNO0WA0MHyjZDZX9iaWR7lV0?usp=sharing

Soft Gripper

https://drive.google.com/drive/folders/1TshRf1pOBbX4cri6w23egKaDYqFUBIQv?usp=sharing

Pronterface

https://drive.google.com/drive/folders/1BPMaQu-ZeSsUMm-XJ0JDUKXh62b0c53j?usp=sharing

Marlin Firmware

https://drive.google.com/drive/folders/1SdZbiOe5_iGFzaMONHVeJahAbnNJIMWv?usp=sharing

Email to tanchuanzhi1008@1utar.my if the file is not accessible.

APPENDIX B: Video For Pick And Place Operation

Pick and place of smartphone adapter and sanitizer spray

https://drive.google.com/file/d/1xGsC1OIs5K6NizKLzVz3jha_Axf1-yZM/view?usp=sharing

Pick and place of dummy battery

https://drive.google.com/file/d/1xBZ4Hp8SlDQ5UiXD7WfhHMWVJtAz_vx0/view?usp=sharing

Email to tanchuanzhi1008@1utar.my if the file is not accessible.