تصميم مقبض لإصبع لمساعدة كبار السن على التحكم في حركة اليد

Design human finger motion control mechanical gripper

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- هندسة ميكانيكية من جامعة ألاباما – الولايات المتحدة الأمركية .
- حاصل على الماجستير من جامعة لندن ساوث بانك – المملكلة المتحدة .
- يعمل في وزارة الكهرباء والماء .
- عضو جمعية المهندسين الكويتية .

ملخص البحث :

يعد تطور الروبوتات أمراً بالغ الأهمية لمستقبل الصناعة ، فمن الصعب تخيل منظمة تصنيع حديثة دون استثمارات في الأتمتة ووالتحكم بعمليات الإنتاج للحصول على أنظمة تصنيع مرنة.

إن الموصلات النهائية للروبوتات هي العنصر الأكثر أهمية لفهي المسؤولة عن أداء العديد من المهام ن ومن خلال البحث الذي حصل من خلاله المؤلف على درجة الماجستير فقد تم تصميم الذراع الروبوتية لتكون قادرة على التعامل مع مايحيط بها . وتمت برمجة وحدة التحكم في الذراع لتعليمها كيفية أداء هذه المهمة من خلال حفظ تسلسل محدد لمجموعة من الحركات وتكرار نفس الحركات في كل مرة.

فإن الهدف الأساسي لمشروع تصميم وبرمجة ذراع روبوتية مرنة تساعد ذوي الإعاقة وكبار السن في تحقيق مستوى أعلى من الاعتمادية، وبالتالي تحسين صحتهم النفسية.

Abstract

The evolution of robotics is critical to the industry's future. It is difficult to imagine a modern manufacturing organisation without investments in automation and manipulation of production processes. Using industrial robots and manipulators to automate the production process of gaining tending flexible manufacturing systems. The end effector of the robot is the most important component because it is in charge of performing numerous tasks. The robotic arm is designed to be able to manipulate its surroundings, such as controlling assembly line workpieces. And the controller of the arm is programmed to teach it how to perform this task by memorising a specific sequence of a group of movements and repeating the same motions every time. As a result, the primary goal of this project is to design and control a flexible robot end effector for specific industrial tasks. This project aims to design and programme a flexible robot arm that will assist disabled and elderly people in satisfying a higher dependency level, thereby improving their psychological health. Several studies were conducted in order to optimise the gripper system's performance, and it was decided to consider 3D printing the 3D modelled gripper system using ABS material, which was predicted to achieve the highest performance when compared to either PLA or Polyester materials. Each constructing part of the gripper system was given a detailed geometrical description. The stepper circuit was primarily made up of a stepper motor and an Arduino. It was decided that the stepper would be controlled by three main orders: short (S), long (L), and stop (S). The Arduino had been programmed with the code for the control circuit. The servo circuit was mostly made up of a servo motor connected to an Arduino. It was decided that the servo motor would be controlled by two main orders: open (O) and close (C) (C). To investigate the manufactured gripper system, several testing scenarios were chosen. It was discovered that increasing the weight of the cup increased the friction force significantly. It is worth noting that when the cup weight is increased to 350 grammes (3.5 N), slippage occurs after 2 minutes, indicating a critical gripper system operation that should not be exceeded.

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Chapter One: Introduction

1.1. Overview

Recently, the manufacturing industry development has been categorised into three main categories. These categories are Small production, Medium Production and Massive Production. It is not possible for small production which utilises fully robots to keep in step with the social growing requirements for Low-Volume, High-Mix manufacturing. For the manufacturing that all the workers are human, there was a significant increase in the cost of the labour. When considering this issue, it is required to construct a system that has more flexibility for the purpose of enhancing the reconfigurability as well as the dexterity of the current system of manufacturing via taking into consideration the coordination and the combination of the above two respects, considering their enhancing the overall effectiveness. It has been proved that, if it is possible to provide robots with sufficient flexibility, it is possible to provide a boost in the quality of the products and thus there will be a reduction in the cost. There are some issues that appeared with the utilisation of robots in manufacturing industries. As there is a difficult for the robot to effectively deal with the parts of the assembly that have complex shapes. They often depend on external sensors to aid with the work of the assembly. However, human workers have high skills in completing tasks that have high complexity using their hands. Therefore, it is required for the manipulators of the robot to have the ability to perform these tasks like the human workers. Therefore, great attention had been paid to the end effector of the robot such as the gripper (Chen, et al., 2015). It is impossible to view the human hand as a compound system for gripping in integrates both handling tools as well as sensors. The human hand has the ability to provide flexibility for the process of grasping, adaptability and stability in addition to other capabilities for manipulations with the aid of the feedback of the sensor as well as foreknowledge under the control of the brain. It is required from all robotics to interact with different sensors involving hearing sensors, visual sensors, tactile sensors and so on. It is also required from the robotics to interface with the complex and variable physical environment in addition to facilitating the implementation and development of closed-loop control policies. Significant efforts have been paid for the purpose of imitating the advantage aptitudes of the hands of the human through the utilisation of several sensors in order to grasp different types of objects with the tough sense as well as visual perception. Via the integration of several sensors, the gripper will be able to analyse the information between the object and the gripper besides having the ability to grasp the object. Moreover, based on the data of the fusion sensory, it is possible to perform online decision making. Therefore, it is possible for the gripper to be viewed as a data source. The integration of the sensors has the ability to provide powerful functionality such as interactivity, visual acuity, touch as well as stability. The integration of control and drive technology besides the integration of the sensors will provide a more intelligence gripper (Zhang, et al., 2020).

It is possible to define the gripper as a part that has very significant importance in the industrial robots which have the ability to interact with the environment and objects which have been grasped for the tasks of manipulations (Raval & Patel , 2016). Recently, the robots have been utilised for elderly or disabled people. It has been stated by the World Health Organization that it is possible to achieve several functions such as grabbing, picking up, carrying and moving objects through the utilisation of robots. It has been stated by (Balaguer, et al., 2005) according to survey that has been carried out in order to investigate the opinion of the carrying about robot aids that about 50% of the participants feel that it is possible to have a positive influence on the care level by utilising robot arm (Dune, et al., 2007).

1.2. Project scope

The evolution of robotics is critical to the industry's future. It is difficult to picture a modern manufacturing organisation without investing in production process and manipulation automation. Automation of the gaining tending flexible manufacturing systems production process employing industrial robots and manipulators. The end effector of the robot is the most crucial component because it is in charge of completing many activities. The robotic arm is designed to allow it to manipulate its surroundings; for example, the robot can control the workpieces on the assembly line. And the controller of this arm is programmed to teach it how to execute this task by storing a specific sequence of a group of movements in memory and repeating the same motions every time. As a result, the primary goal of this project is to develop and control a flexible robot end effector for the purpose of executing certain tasks in the industrial sphere.

1.3. Project aim

This project aims to develop and control a flexible robot arm that is estimated to help disabled persons and elders in satisfying a higher dependency level that resulted in enhancing their psychological health.

1.4. Project objectives

To satisfy the latter mentioned aim, a group of objectives were decided to be achieved. These objectives are presented as follows;

1. To carry out a literature review regarding the gripper types and their functionalities in addition to the grasping mechanism itself.
2. To apply a material selection process based on a performance index that would be calculated regarding to the favorable and unfavorable properties.
3. To 3D model the gripper mechanism required to be manufactured.
4. To 3D print the constructing parts of the gripper mechanism.
5. To program the controlling unit that would be used in controlling the gripper.
6. To test the fabricated gripper mechanism.
7. To analyse results and discuss them.
8. To outline the conclusions and setting recommendations.

Chapter Two: Literature Review

2.1. Grippers type

The joint in the chain of kinematics between the hand and the robot arm is referred to as the robot wrist. Based on the application, it is possible that the wrist may have one dof or more than one dof. The assemblies of the wrist and arm of the robot are utilised for positioning the end-effector which has the main responsibility to complete the work. The gripper is the simplest form of the end effector. It is possible to classify the grippers according to some criteria which are represented as follow;

- **According to the utilised actuation type.**

This gripper classification depends on the source of actuator utilised by the gripper. Pressurized air is used in pneumatic gripper as the movement source of the figures through the implementation of pneumatic actuators such as pneumatic cylinders or cylinders motors. The simplest type of gripper is the pneumatic gripper. On another hand, the gripper uses the hydraulic actuation is more powerful than the pneumatic gripper, however, there will be an increase in the weight of the system. It is also possible to utilise an electronic gripper as it provides some features such as a clean and efficient system and its control is easy (Raval & Patel , 2016).

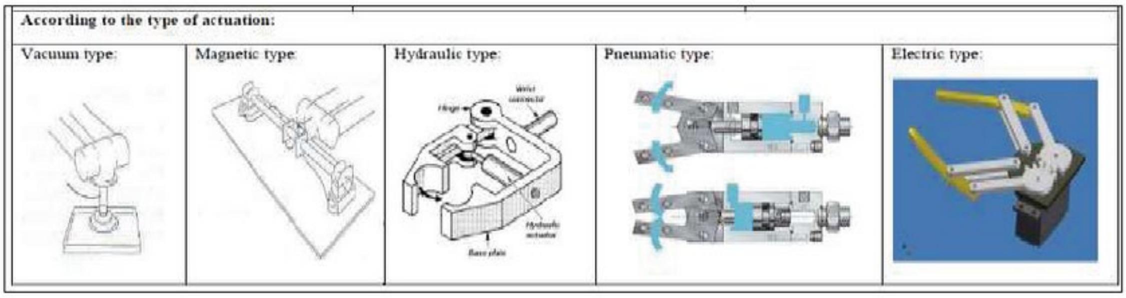


Figure 2-1. Classification according to the type of actuation (Raval & Patel , 2016).

- **According to the mechanism type**

There is a wide possibilities range for the category of linkage for the purpose of actuating the closing and the opening of the gripper. It is estimated by the linkage of the design for how to convert the gripper input force into the force of gripping implemented by the figures. It is also determined by the configuration of the linkage how there will be an opening for the figures of the gripper and how the gripper will actuate quickly. One of the linkage mechanisms is the configuration of the gear and rack. In this type, a position will be attached to the rack gear which will provide the linear motion. Two partial pinion gears will be driven by the rack movement in terms of closing and opening the figures. Another type is the cam mechanism. This type covers the arrangement of follower and cam through the utilization of spring. The closing and the opening of the figures are provided by the cam. Another type is the screw mechanism. In this type, a motor is used to turn a screw usually accompanied by a mechanism in order to reduce the speed. A threaded block is transmitted in one direction when there is a rotation for the screw in one direction. Tin order to perform the opening and closing operations, the figures are attached to the threaded block (Raval & Patel , 2016).

2.2. Grasping process

(Zhang, et al., 2020) was carried out in order to optimise and design a gripper for the process of picking based on the model of grasping. Detailed information about the components of the hardware has been provided in this study in addition to detailed data about the end effector control strategy. The mechanism of the control of servomotor has also been investigated and analysed. A mathematical model for the gripper has also been analysed based on harvesting movements. This study used a servo motor for the purpose of controlling the closing as well as the opening of the gripper through the utilisation of PWM signals in order to adapt to the picking complex situation. Picking and grasping some objects without causing any damage is considered one of the most significant challenges for the gripper. In order to decrease the mechanical damage, (Wang, et al., 2015) designed a platform for flexible gripping for the robot through the utilisation of impedance control for grasping force tracking. It is possible to measure the force as well as the position during the process of grasping in order to be able to control them. The error could be then corrected by a force feedback impedance controller. The flexible method of grasping provided in this study has the ability the reduction the mechanical damage caused by the gripper during the grasping and picking process. In the process of grasping, the mechanical relies on both the sensitivity of the product to damage in addition to the gripper’s aggressiveness. It is possible to control the grippers' aggressiveness through the utilisation of flexible materials and sensory feedback. The sensitivity of the products to damage could be estimated from the physical properties of the materials of the products. Therefore, for controlling the grasping, the grasping product physical model is required to be taken into consideration.

2.3. Gripper manufacture

(Wang, et al., 2016) Demonstrated a 3D printed soft robot gripper with a modular design that was particularly created for use in lunch box packaging, which was one of the things on display. The gripper is made up of three elastic digits that are linked to the foundation through an elastic ring, which is attached to a stable foundation by an elastic ring. It was decided to build a snap-lock mechanism that would eliminate the need for screws in the operation of attaching and removing the gripper to make it as easy as feasible. The soft finger structure was created using a fluidic elastomer actuator technique, which is becoming more popular. This was made feasible by 3D printing the majority of the parts. Researchers were able to investigate three finger designs, as well as soft gripper designs, for grabbing and lifting deformable items for future exploration via the use of finite element (FE) analysis and experiments. In conclusion, researchers observed that different finger designs lead to different curvatures throughout the finger's length as well as different stress distributions when the finger is compressed. Thanks to the gripper that has been designed, it is capable of grasping and lifting objects of varied shapes and softness.

(Amend, et al., 2016) The researchers have uncovered a lot of exciting new technologies as soft robotics continues to increase in popularity. These technologies need additional exploration. Even before advanced techniques can have a substantial influence on real-world applications, they must first make it to the commercial market. First and foremost, they must be effectively introduced to the market. Thus, researchers will be able to determine whether or not researchers have accurately predicted or foreseen the magnitude of the effect that they are now experiencing in the field of soft robotics. Because of their attempts to commercialize jamming-based robotic gripper innovation in a device named VERSABALL, Empire Robotics has been one of the first firms to strive toward this aim until 2013. Their failure to establish a viable business model around this technology in a timely manner will result in the closure of their doors by the spring of 2016. There are some important lessons acquired from the technical side of commercialization that may be shared with others who are going through a similar process. They want to reach their goal of giving this information by setting up a framework for innovation activities that can be used to encourage more research and make research results more useful.

(Galloway, et al., 2016) Investigated that the underwater gripper, which uses soft robotics techniques to softly handle and sample fragile creatures on the deep reef is shown here. Current methods of manipulating deep sea robots have been pushed by the petroleum industry, and as a consequence, have had negative effects on marine life. It is possible to use soft material robotics because of the intrinsic resonant frequency of soft and delicate surroundings and organisms. Soft robot end effector design concepts, benchtop measurement of their grasping capabilities. Benthic fauna has never been sampled before using soft robots in deep water environments. Other deep marine habitats, such as coral reefs, are centers for distinct biological varieties and genetic adaptations, including mesophilic and deep-water reefs. Scientists have only recently been able to explore and study coral reefs down to 128 meters below the ocean's surface because of advancements in technical diving, remotely operated vehicles (rovs), and submersibles. Due to easier access, mesophilic reef biology has grown rapidly during the last several decades. 19 percent of shallow coral reefs throughout the globe have already gone, and another 35 percent are likely to vanish over the next four decades, according to estimates from the scientific community. However, there is a possible sanctuary for coral reefs at depths greater than 30 m from human and natural influences. In comparison to other very varied environments, deep reefs remain relatively understudied.

(Wang, et al., 2015) Investigated that the special appeal of soft fluidic actuators, which are composed of elastomeric matrices with embedded soft substrates, is that they are inexpensive and can be readily modified to meet the needs of specific applications. Such actuators, on the other hand, have a restricted contemporary use due to the fact that their design has traditionally been dependent on intuitive reasoning. The theoretical and experimental validation of quasi-static analytical and finite-element technique models for bending in free space and force production A collection of methodical design principles is provided in this work to assist the robotics community in the creation of soft actuators by gaining knowledge of how they alter their responses as a function of input pressure for a variety of geometrical factors. The suggested analytical model is also implemented in a regulator, where it is shown that it is capable of converting pressure information into bending angle in real time. A thorough knowledge of soft multilateral actuators will enable future design ideas to be swiftly iterated and their effectiveness anticipated, allowing for the exploration of new and inventive technologies that create more complicated movements.

(Homberg, et al., 2015) Proposed a soft hand that is able to grasp and detect objects with high robustness. With a very compliant hand, it is possible to have inherent resilience to grasping uncertainty; however, because the security and convenience of the hand and item are unknown, it is impossible to tell if a grasp was successful in picking up the correct thing. Soft fingers were modified and joined to make a three-finger gripper that can be simply connected to current robots, such as the Baxter robot's wrist, to grasp objects more easily. Adding resistive bend sensors to each finger allowed us to get an accurate configuration estimate that was adequate for discriminating between varieties of items. The item gripped by the gripper may be recognized using one data point from each of the gripper's fingers. For both encircling grasps and pinch grasps, a clustering approach is described that finds the relationship between each clutched item and its surroundings. This hand is a first step toward powerful proprioceptive soft grasping that is not dependent on the sense of touch.

2.4. Soft gripper

The development of soft grippers provides facing the challenge of the rigid grippers which have lack adaptability, flexibility and or compliance. This type of grippers could be driven by different methods such as shape memory alloy (SMA), cable, hydraulic, pneumatic and motors. The soft gripper is driven by a pneumatic design special ventilation chamber through the utilisation of deformable material. Therefore, the selection of elastic material is the key point of the design of the gripper besides the selection of the air cavity design. There are two major types of the pneumatic actuators structure which are multi-chamber type and fibre-reinforced type. The motion f the grasping is produced by negative pressure or positive pressure for the gripper deformation. A soft robotic gripper with a pneumatic network is shown in figure 2a which has been designed by the Harvard University Whiteside research group through the utilisation of elastic silicone rubber which has been manufactured through the utilisation of 3D printing technology. It has been proven that this gripper has the performance of small loading capacity, mutual accommodation with the environment, flexible movement and large deformation. Another study developed a soft robotic gripper with four figures which is possible to adjust the length based on the shape and the size of the object that is required to be trapped. By the fibre restraint idea, the design of the fibre-reinforced actuator has been performed, which is composed of rigid material in addition to super-elastic material. Depending on a fibre-reinforced actuator, (Chen, et al., 2019) developed a soft robotic grippe which is fibre-reinforced with three figures as shown in figure2. A typical example of a soft gripper that utilises the negative pressure is shown in figure 2 d.

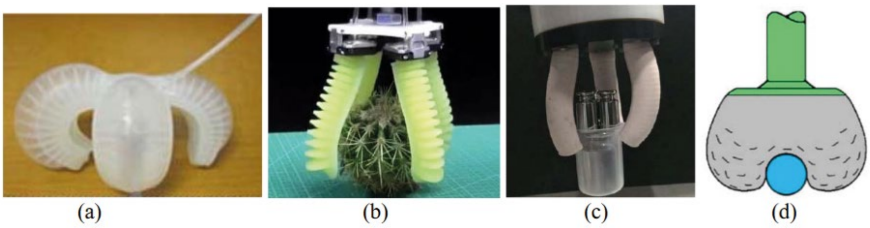


Figure 2-2. Soft grippers with various actuation (Long, et al., 2020)

2.5. Grippers for Disabled people

(Peer, et al., 2008) presented a telemanipulation multi-fingered system whereby a robotic gripper with three figures is operated and controlled by a human. Through the utilisation of the exoskeleton, force feedback is provided. The application of the appropriate position and force is required for the various kinematic structures of the gripper of the robot and the human hand. This study presented a point-to-point position approach for mapping after investigating typical algorithms for human mapping to a robotic hand. There was a division for Barrett hand inverse kinematics and human hand forward kinematics and also this study proposed a position mapping approach depending on a projection of the fingertip position of the human on the trajectory of the gripper. The position mapping provided good performance in the first evaluation of the experiment of the real hardware as different grasp kinds including power grasps and precision could be performed. The maximum torque significantly influenced the force feedback quality.

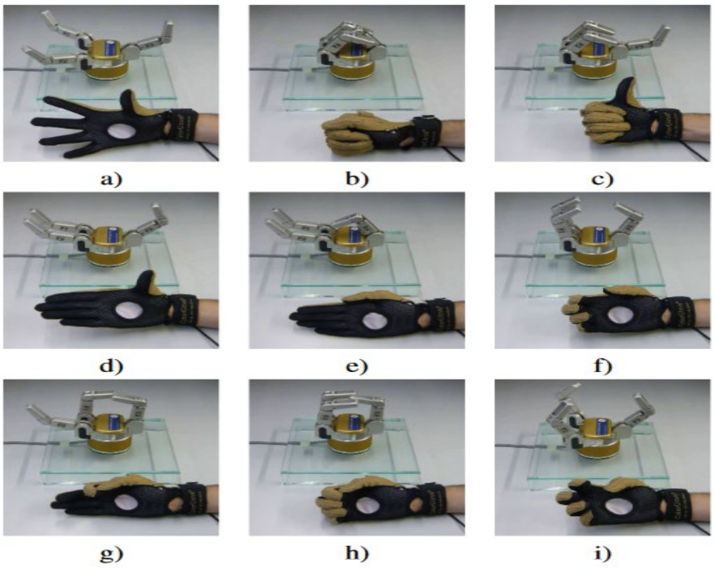


Figure 2-3. Barrett Hand poses corresponding to human hand (Peer, et al., 2008).

According to the grasping principle, it is possible to divide the gripper into fur main types involving, universal grippers, magnetic, vacuum and mechanical fingers. In the vacuum gripper type, it is usually a suction cup which picks up the object through the principle of the difference in the pressure between the outside and the inside of the cup. This type of gripper could be utilised to grasp and pick objects with smooth and flat surfaces, in addition, to carrying out a huge number of handling operations. Therefore, this type of gripper is utilised commonly in transport robots for a wide range of applications, especially in the packaging field. In the magnetic gripper type, the objects could be handled via electromagnetic attraction produced by electromagnet energization. This type of gripper has the ability to enhance the loading and unloading efficiency of objects. However residual electromagnetic issues could be caused. Therefore, it is not allowed to use this type of gripper for object grasping which does not allow remanence. In the type of mechanical figure, the figures are utilised for the purpose of grasping the objects and they either utilise the friction force to clamp them or enclose them. The figure structure is designed based on the characteristics of the shape of the object being clamped. Based on the figures number, it is possible to divide this type into two, three or even more figures. There is unparalleled grasp flexibility and stability in the hands of the human. A great effort has been paid in order to replicate the function and the shape of the human hands (Long, et al., 2020).

(Lv, et al., 2022) developed a novel synchronization motion approach provided by the mapping hybrid technique of the upper-limb and hand gesture motion. The proposed approach faces the issues that exist in the scheme of mapping the motion which has to be customised according to the operator's kinematic configuration. The robot is awakened by the operator from any initial pose without extra calibration procedure, therefore, the relieving unnecessary pre-training and operational complexity are reduced. This led to making the approach presented in this study for the gripper is to be user-friendly to master teleoperation skills. Experiments with the grasping of the robotics take verify the proposed GULIM approach's outperformance compared with the conventional direct approach of mapping.

(Cook, et al., 2002) was carried out for the purpose of presenting technical aspects of the manipulator of a robot which was mainly developed for the purpose of facilitating the young children who have disabilities to be able to grasp objects. In this study, the crc robot has been adapted. The emphasis of this study is on the control technical aspects of the interface development as well as the communication environment between the robot arm and the children. The design of the system considered that there is a user control for each child in addition to a procedure of control that is adapted individually. Large push buttons are included in control interfaces besides head-controlled switches, laser pointers and keyboards. It has been found based on the results that it is possible for young disabled children to utilise the system of the robotic arm in order to complete the functional play-related tasks. The software which has been developed in this study allow them to accomplish a set of tasks via the activation of signal switches. A set of preprogramed movements could be replayed by the children via the press of a signal switch.

In (Micera, 2006), Better and more sophisticated technologies have been created in recent years for disabled people for the recovery and substitution of sensory-motor, mainly to breakthroughs in robotics and mechatronics. User acceptability is tightly linked to various factors in all of these technologies, including the subject's residual abilities, the robot's mechatronic features, and the interface used to connect them. Various "human-interface-device" combinations, which are known as Hybrid Bionic Systems (HBSs), can be identified, each with different qualities in terms of hybridness, connectivity, and augmentation. In HBSs, the interface must be adjusted to the features of the robotic object to be controlled as well as the preferences and demands of the end-users. The subject of hand function replacement following amputation has been the focus of this research in this work. In this work, three HBSs with varying levels of complexity, flexibility, and sensorization are provided to demonstrate how varying levels of hybridness and connection for various devices and applications can lead to acceptable and effective systems. The following are some examples of case studies: 1) Direct peripheral nervous system interfaces were used to manage a flexible and highly sensorized prosthetic hand; 2) electromyographic data were recorded with surface electrodes to operate a compliant adaptive prosthesis, and 3) a foot interface to control a two-degrees-of-freedom prosthesis. The first findings so far appear to support the notion that choosing the right interface when building an HBS can improve its effectiveness and usefulness.

(Skoglund & Iliev, 2009) presented a novel method of skill acquisition from the demonstration of humans. Usually, the robot manipulator morphology has a great difference from the arm of the human, therefore, it is not possible to simply copy the motion of the human. Instead, it is required for the robot to execute its vision with the operator's skill demonstrated. Once acquiring the skill by the robot, it is required from the root to make this skill in addition to other similar skills without starting a new process of learning. Through the utilisation of a planner of motion that works in a hand-state which is an object-related world-frame, this study presented that the skill reconstruction is simplified.

In (Yang, et al., 2005), An active hand artificial device called the Inherently Ompliant light Weight Active (IOWA) hand was designed and prototyped. This hand artificial device features three joints in each of its five actuated fingers. Each joint is constructed using a revolutionary, versatile mechanism based on transverse and axial compression spring loading, as well as cable conduit systems. Because rotating motion is transformed into tendon-like activity, the actuators can be situated far away from the arm. It was demonstrated that many numerical methodologies for the study of a mechanical spring under tension, shear loading, and bending moment conditions may be obtained for motion analysis for each finder section control. Compared to experimental data these numerical models were also proved to be accurate. While the mechanical design and kinematics of the hand were given, researchers came to the opinion (without completing any clinical testing) that this sort of low intrinsically sensitive hand could have a significant impact on providing greater capabilities to a disadvantaged individual. It was also proved from the prototype that precise management of the mechanical connections leading to each section of each digit is possible.

In the design of the hand prosthesis, there are some important parameters that significantly influence the performance of the hand which are the capabilities of gripping various kinds of objects, the forces of the grasping which provide the holding stability of the objects and the cosmetic appearance which resembles the hand of the human. The design is challenged by all these mentioned parameters. (Wattanasiri, et al., 2018) presents a gripper with five-fingered which has multiple patterns for griping with the utilisation of one actuator only for the purpose of completing the most important functions in daily life. The system proposed in this study has the ability to achieve significant force for gripping from the actuator's large size. The gripper has the ability to perform two patterns for gripping and one natural position which is dominant in most the activities. Various patterns for the movement are completed through the utilisation of several sets of four-bar linkages mechanism and this leads to providing various motions to the figures when there is opposite actuation for the mechanics. This study describes the achieved performance mechanism synthesis and hand design.

(Cotugno, et al., 2016) Investigated whether or not the displacement of the opposing thumb in humans is a factor that plays a decisive role in the formation of the grasp. Researchers observed, by statistical analysis of the unpredictability of performance capture data taken from the GRASP database, which the displacement of the thumb has a leading impact on the shape of the grip. This was the case regardless of the particular item that was being grabbed in the hand. Researchers have been attempting to build robotic multi-fingered grippers that can emulate the functions of human hands, such as item handling and grasping, while creating these grippers. One of the earliest examples of multi-fingered grippers built expressly for use in robotics was a kind of robotic gripper that included a large number of fingers. It was found that a multi-finger gripper was "among the first instances" of such a device. The human hand has recently been a topic of study in the area of robotics. This is due to the fact that the human hand is one of the most dexterous multi-finger grippers in nature. This is due to the fact that it provides users with full command over the things with which they are engaging. The needs of the human hand are taken into account in the design of commonplace objects and pieces of equipment. If the ideas that are the foundation of human grasping were transferred to robots in a manner that was faithful to their nature, then as a consequence, robots may be able to use a wide range of products that were created for human use without the need for any further modifications to the robots themselves.

(Bicchi, et al., 2011) Focused on the hand as a cognitive organ and the manner in which its physical embodiment allows and governs the hand's behaviours, capacities, and cognitive functions. It's an account of an ongoing worldwide collaboration project dubbed "THE Hand Embodied". Actuators and sensors in the "hand," the abstract cognitive object that represents the feeling of active touch, are the physical embodiments of this sense, and the project's title alludes to the "hand" in both of these senses. There is an emphasis here on the hand as a cognitive organ and the way in which its physical embodiment permits and regulates it. This post was inspired by an account of an ongoing global collaborative initiative known as "THE Hand Embodied". The physical manifestations of this sense are the actuators and sensors in the "hand," the complicated and confusing object that conveys the sensation of active touch, and the project's title refers to the "hand" in both meanings. The study takes an in-depth look at a global research project. The constraints on our potential to understand and control our hands and other sensorimotor instruments during basic cognitive activities like exploring, grasping, and manipulating must be considered if this perspective is to be fully realized. Rather than just limiting alternatives and effectiveness, these restraints are the key elements that influenced and successfully determined how cognition developed into the particular, wonderful shape that they are able to observe here on Earth.

Chapter Three: Research Methodology

3.1. Overview

The proposed study mainly concerns regarding outlining the methodological approaches of the proposed project so as to be able of satisfying the aim discussed in chapter one. The following figure presents the flow chart of these approaches, where each approach is to be discussed in details in the following sub sections.

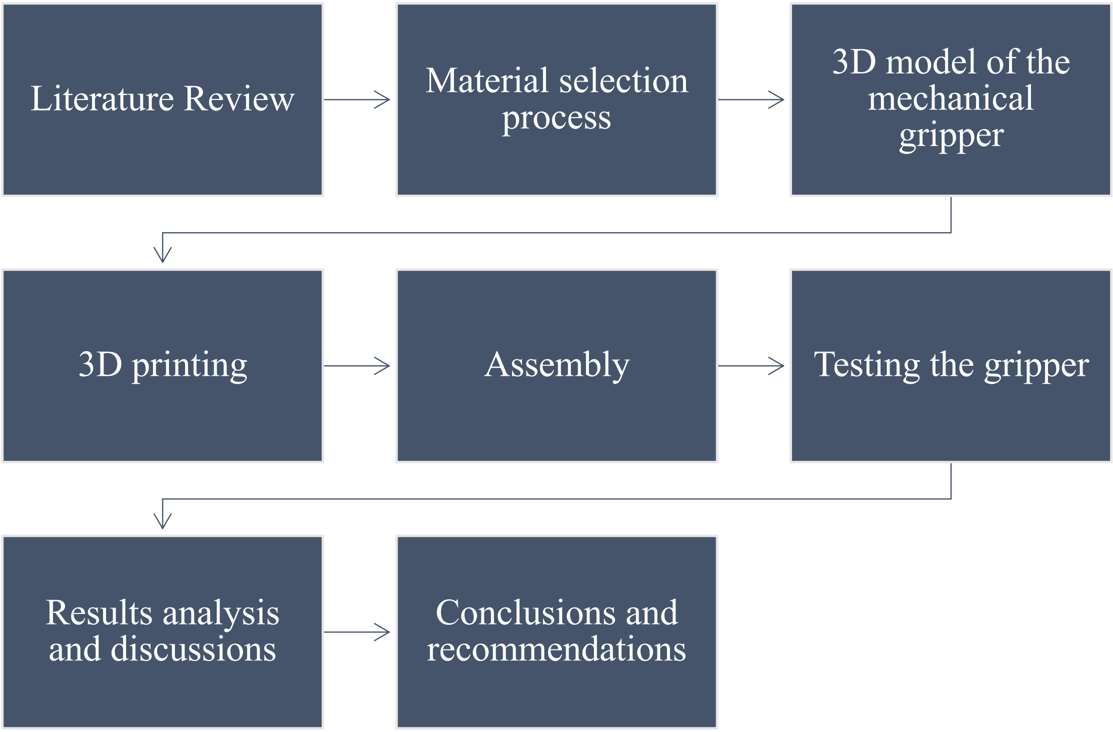


Figure 3-1.Outlines of the research methodological approaches.

3.2. Literature Review

This step was mainly concerned regarding reviewing the related studies and latest methods had been developed so as to start from where other researchers ended. The literature review would help also in strengthening the theoretical background of researchers and readers so as to keep in touch with the project's achieved progress. The decision was taken to pay an attention to studying the gripper types in addition to the operation of the grasping mechanism. Chapter two presents the entire data collection had been considered in the proposed study.

3.3. Material selection process

This section considers discussing the material selection process that should be considered using CES software package. As being the very first step, it is vital to consider that, the material should be used in 3D printing the gripper achieves such high performance index that can be expressed as the ratio between the favorable properties to the unfavorable properties. The material should be characterized by the follows;

1. High mechanical properties.
2. High manufacturability.
3. High impact resistance.
4. High stiffness (to achieve higher friction force that allows carrying heavy objects).
5. Low environmental impact.
6. Low price.
7. Low density.

$$performance\ index = \frac{Yield\ strength * impact\ resistnace * stiffness}{CO2\ footprint * price * density}$$

By applying the equation of the performance index, figure 3.2 was plotted by CES to suggest the materials that provide different performances.

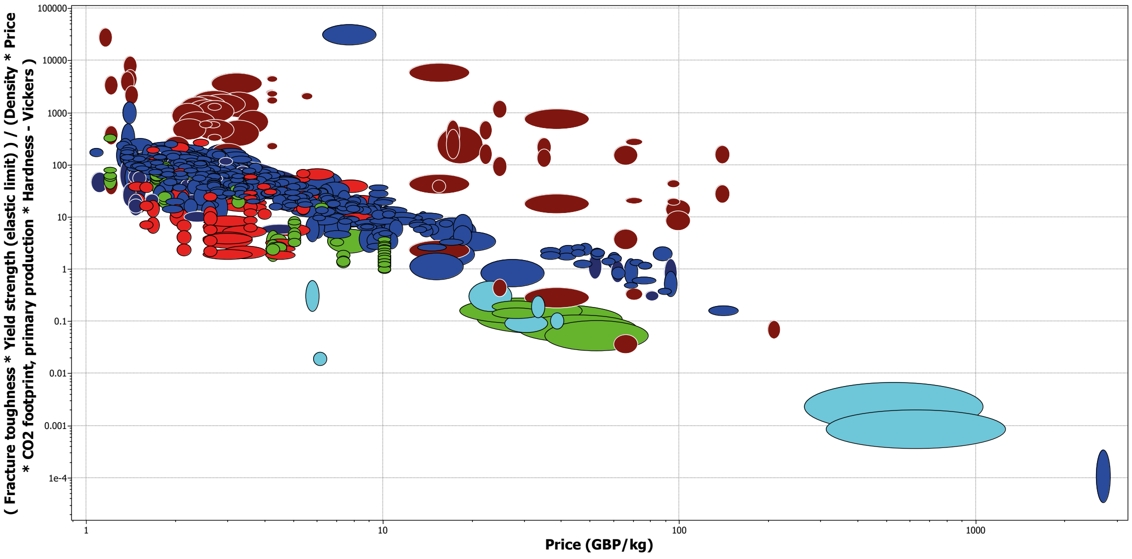


Figure 3-2. Suggestions proposed by CES for the materials achieve different performances regarding the concerning application.

Three different materials that are characterized by their 3D printability had been selected, which are;

1. ABS
2. PVC
3. Epoxy resin

The latter three materials had such properties that are presented in tables A-1, B-1 and C-1 respectively.

By comparing with the three materials, it was predicted that;

- ABS material is estimated to achieve the highest economic benefit as it is shown in figure 3.3 below;

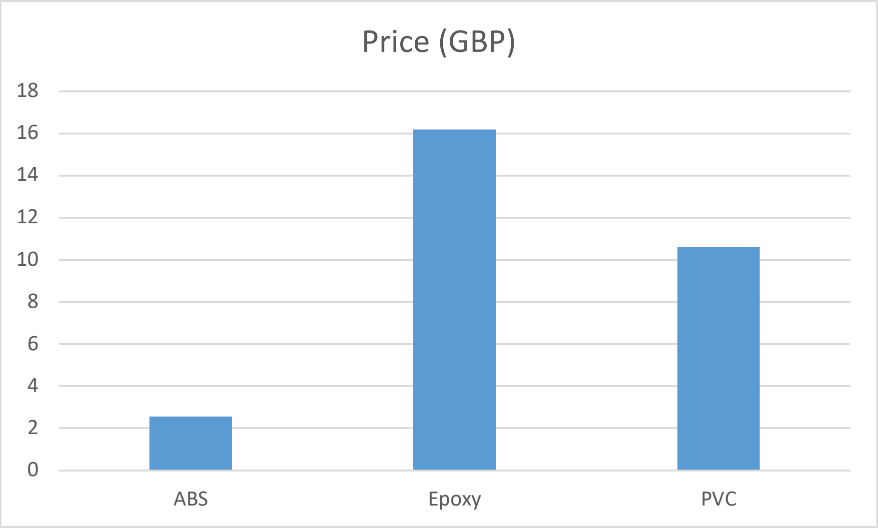


Figure 3-3. Comparison among the prices of each material considered in the study.

- The lowest density achieved by the PVC material followed by ABS while epoxy was predicted to obtain the maximum weight of the gripper. Figure 3.4 shows the comparison among the materials in accordance with the density.
- The maximum yield strength was achieved by the epoxy material as well as the maximum fracture toughness. However, the mechanical performance is not the main criteria that would be considered in the study. As there are other parameters of interest that had been discussed in this chapter. Figures 3.5 and 3.6 shows the comparison among the materials.

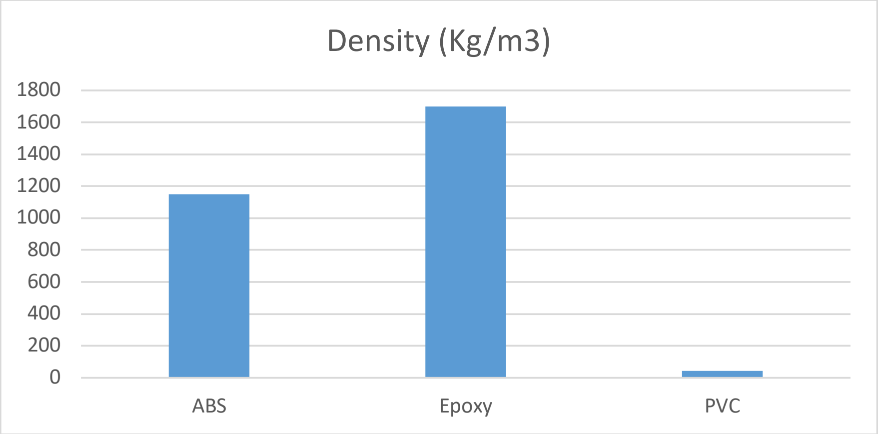


Figure 3-4. Comparison among the densities of each material considered in the study.

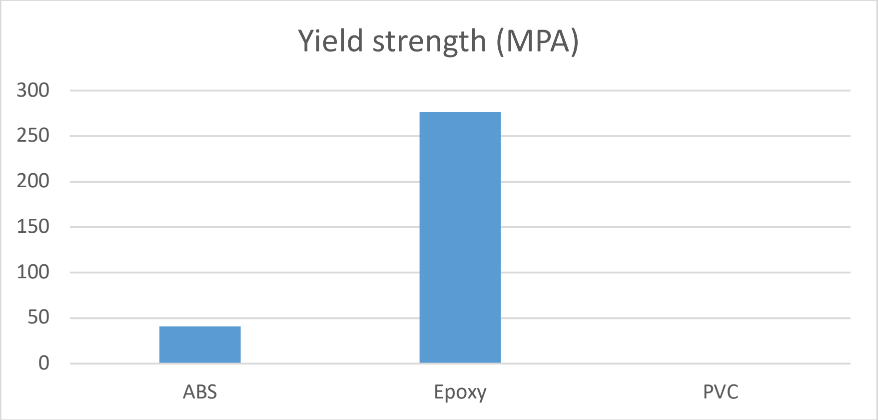


Figure 3-5. Comparison among the Yield strengths of each material considered in the study.

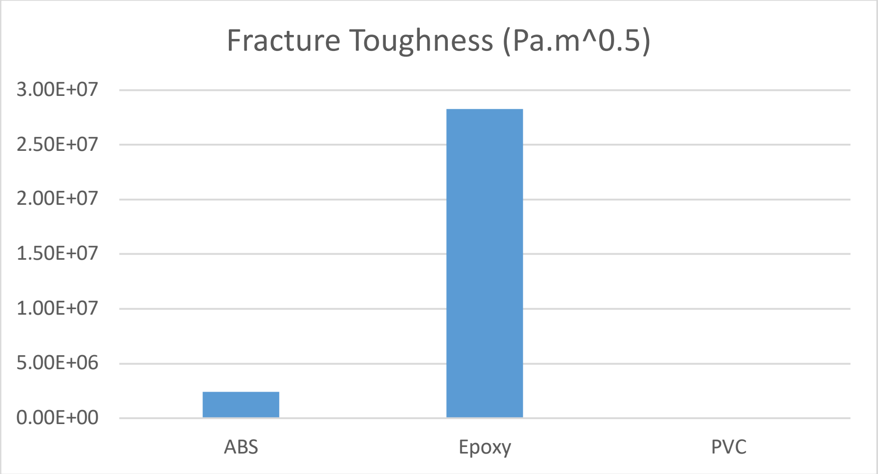


Figure 3-6. Comparison among the Fracture Toughness of each material considered in the study.

- The lowest environmental impact was achieved by the ABS material, which encourage selecting it as being the most suitable material.

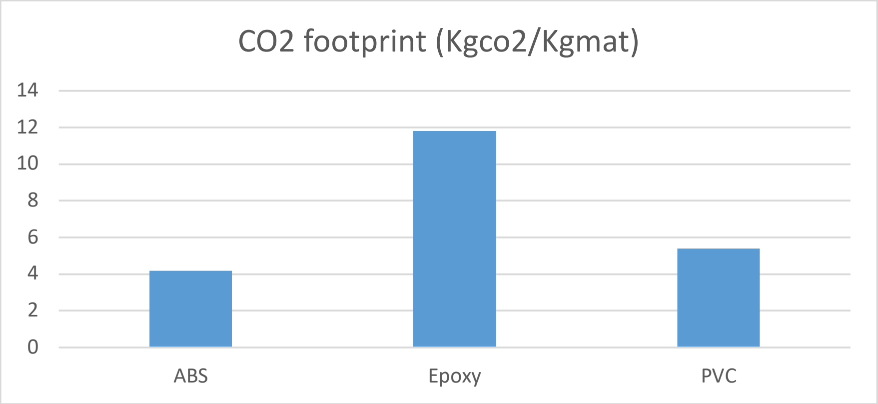


Figure 3-7. Comparison among the CO2 footprint of each material considered in the study.

Regarding to the latter comparisons had been applied, the decision was taken to select ABS material that is characterized by its high economic and environmental benefits in addition to its low hardness and moderate mechanical performance.

3.4. 3D model of the mechanical gripper

This step mainly concerns regarding 3D model of the schematic drawing had been considered in the study (in the proposal of the project shown in figure 3.8).

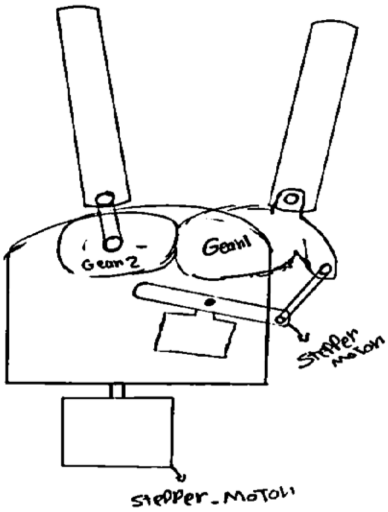


Figure 3-8. Schematic drawing of the gripper.

Chapter Four: Modelling gripper and FEA analysis

This chapter mainly concerns regarding presenting the 3D model for each constructing part for the design assembly for the gripper arm. The decision was taken to consider utilizing Solidworks software package in satisfying the research criteria. The following figure presents the 3D assembly of the gripper arm using Solidworks software package, where each constructing component would be discussed in details in this chapter.

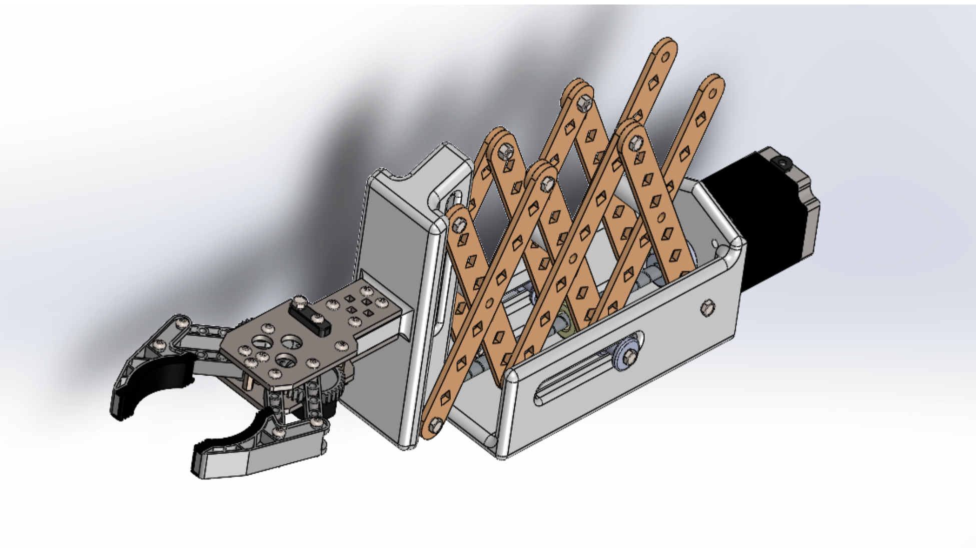


Figure 4-1. 3D assembly of the gripper arm.

4.1. Bracket

The bracket of the gripper arm dimensional description and 3D part is presented in figure 4.2, where this part mainly designed to support all the constructing parts exist in the gripper arm.

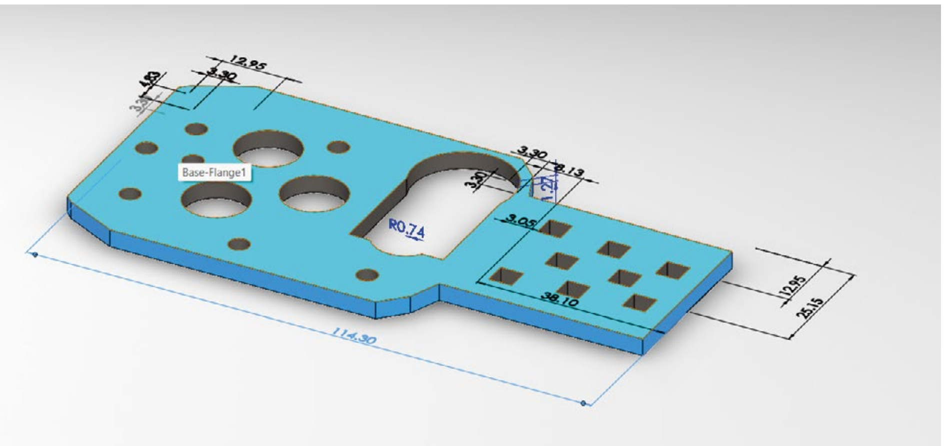


Figure 4-2. 3D model and dimensional description of the bracket.

4.2. Claw gear linkage

The claw gear linkage shown in figure 4.3 connects the bracket to the gripper itself to allow closing the two grippers to pick a cup.

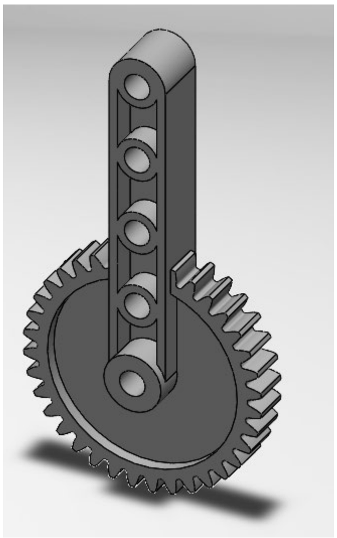


Figure 4-3. 3D model for the claw gear linkage.

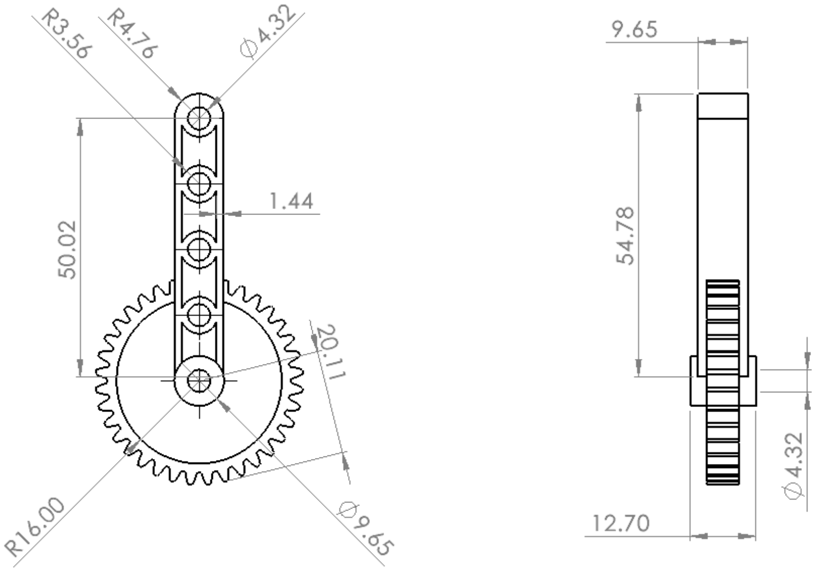


Figure 4-4. Dimensional description the claw gear linkage.

4.3. Claw linkage

The bracket and gear are connected together with a claw linkage that is presented in figure 4.5, where this linkage connects the gripper finger to the gear.

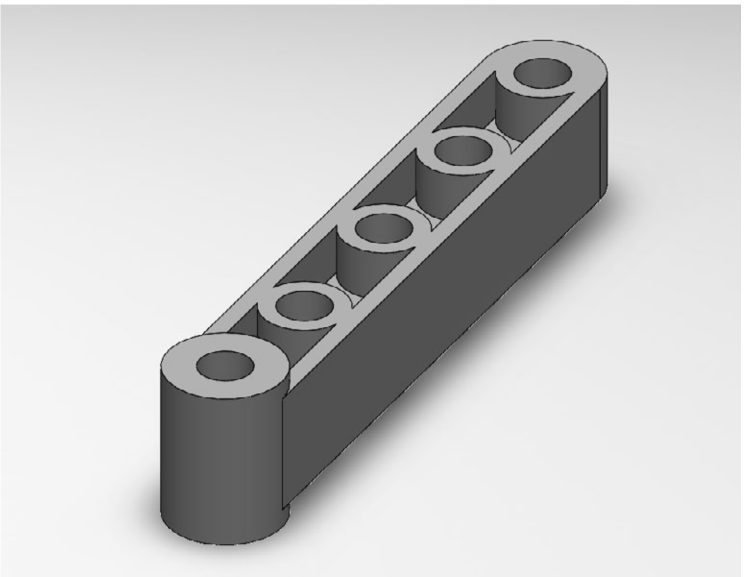


Figure 4-5. 3D model for the claw linkage.

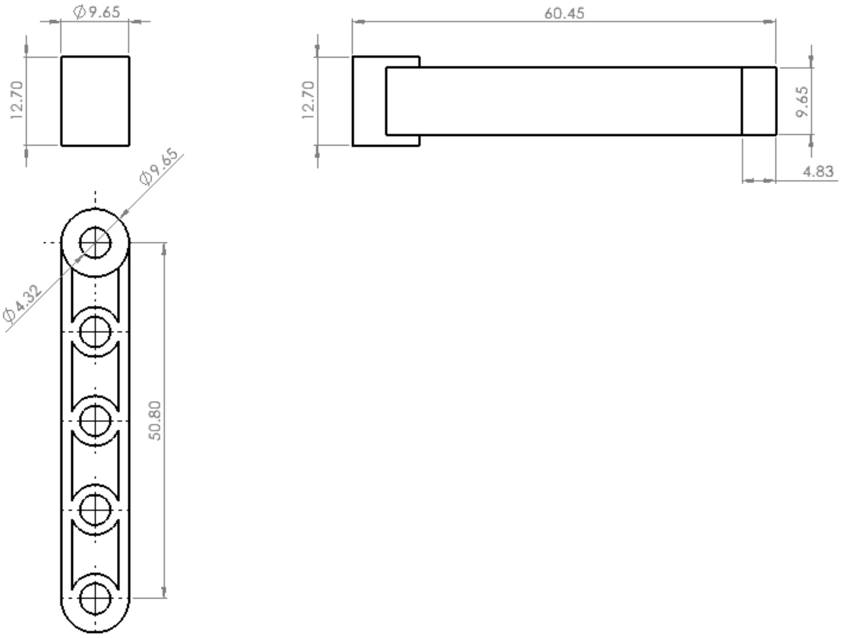


Figure 4-6. Dimensional description of the claw linkage.

4.4. Claw finger

The claw linkage is presented in the following figure, where the link the gripper itself was decided to be manufactured from ABS material according to the decision taken in the material selection process.

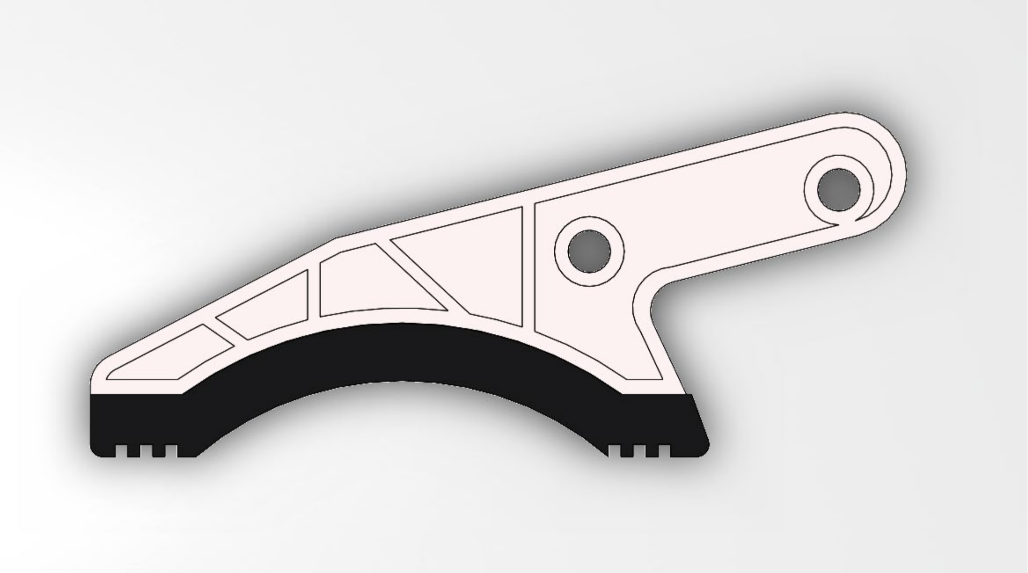


Figure 4-7. 3D model for the claw gear linkage.

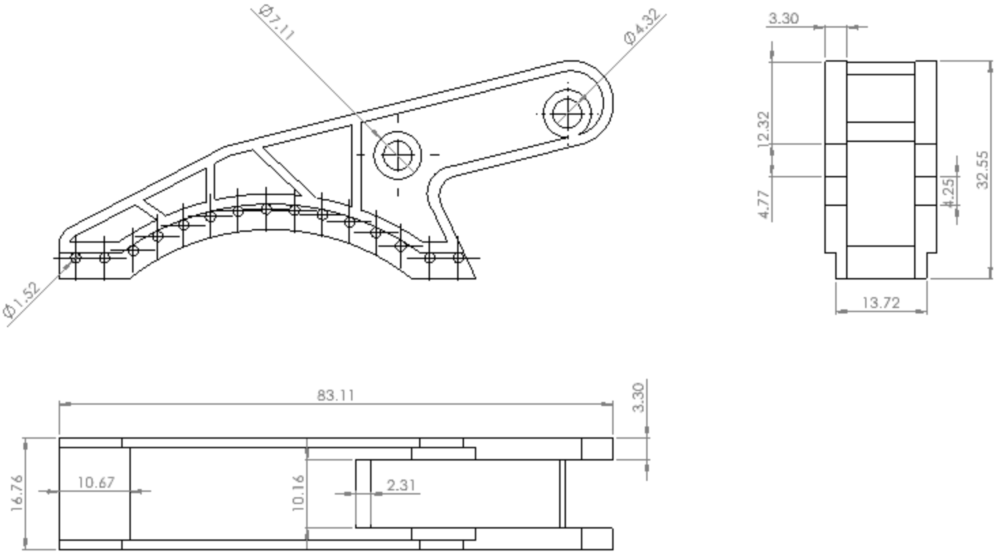


Figure 4-8. Dimensional description for the claw gear linkage.

4.5. Base

The base of the gripper arm is presented in figure 4.9, where all components are installed on it using bolts and screws.

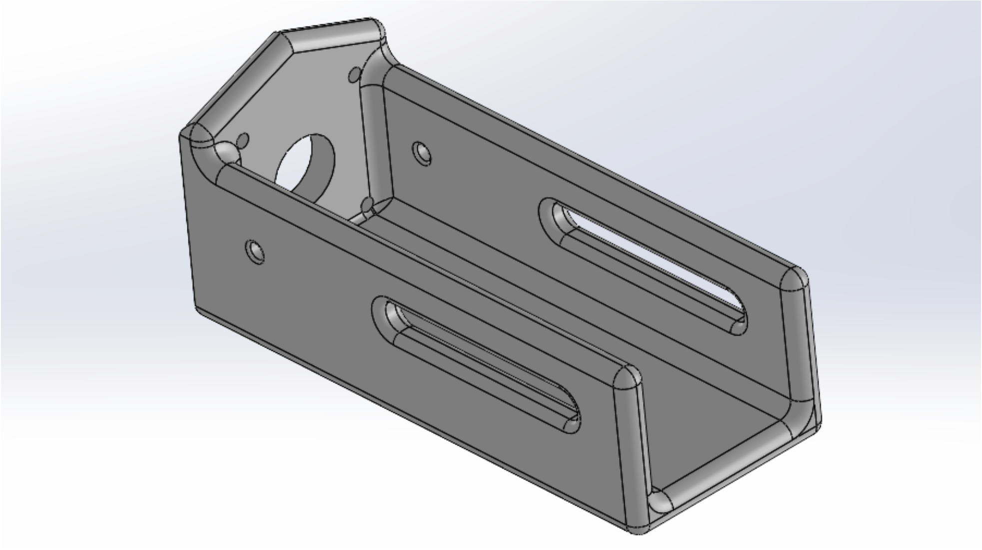


Figure 4-9. 3D model for the base.

4.6. Gripper holder

The gripper holder 3D model is presented in the following figure, where the claw gear, linkage and finger are installed on it. This component was designed mainly to allow linear motion.

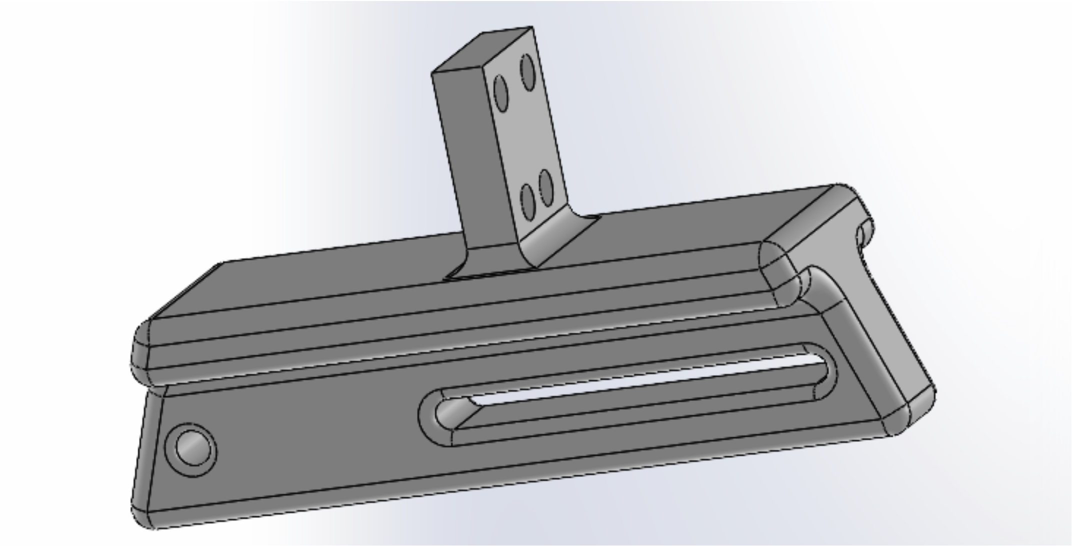


Figure 4-10. 3D model of the gripper holder.

4.7. Linear motion Link

To convert the rotational motion of the DC motor to a linear motion, a mechanism was designed that is assembled from a group of links that are presented in the following figure.

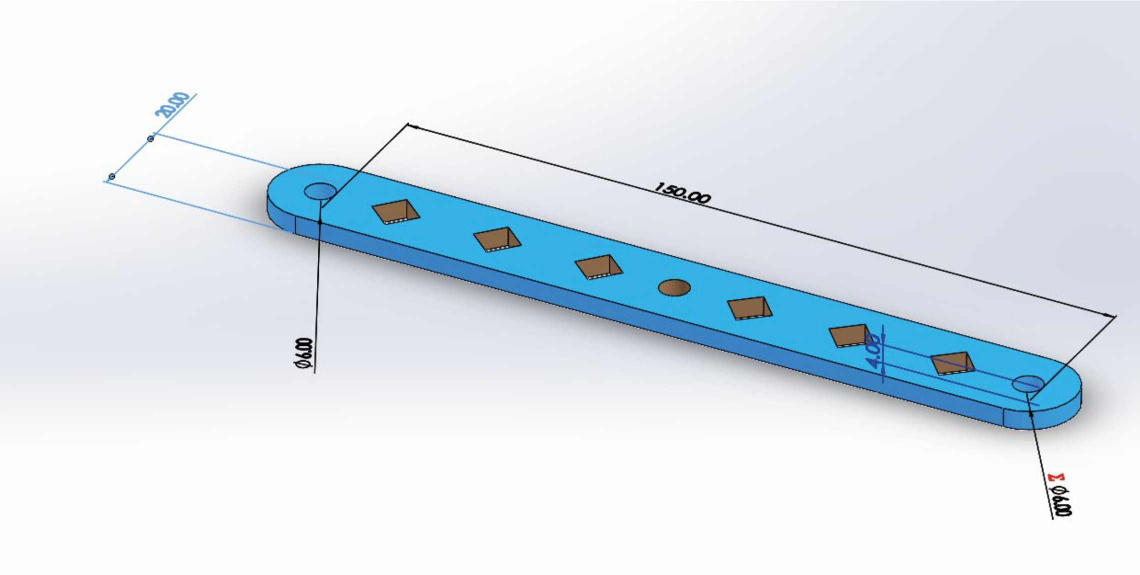


Figure 4-11. 3D model of the link.

Chapter Five: 3D printing and control

3.1. 3D printing

The 3D models of each constructing component were 3D printed so as to be able of manufacturing the gripper arm. Aiming to be able of 3D printing each part, the solid part of each constructing component was decided to be saved as a STL file. Figure 5.1 shows the Claw gear linkage saved as a STL file.

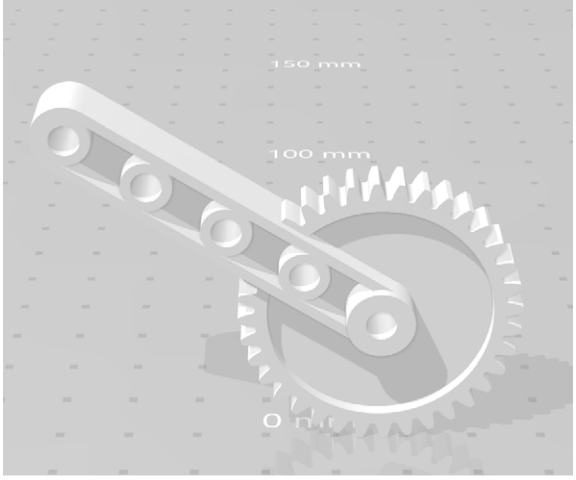


Figure 5-1. Claw gear linkage saved as a STL file.

The following figure presents the claw gear linkage had been 3D printed using PLA material.

Figure 5-2. 3D printed claw gear linkage.

The gear is to be connected to the gear that is connected to the stepper motor, figure 5.3 shows this gear. On the other side, the 3D printed gear is presented in figure 5.4.

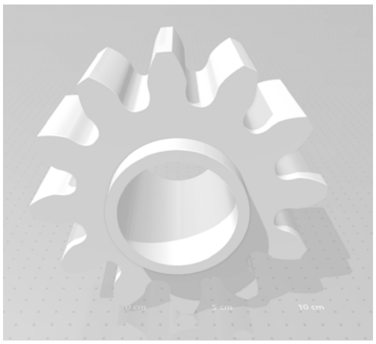


Figure 5-3. Gear saved as a STL file.

Figure 5-4. 3D printed gear connected to the stepper.

Figure 5.5 shows the STL of the linkage while figure 5.6 shows the 3D printed part.

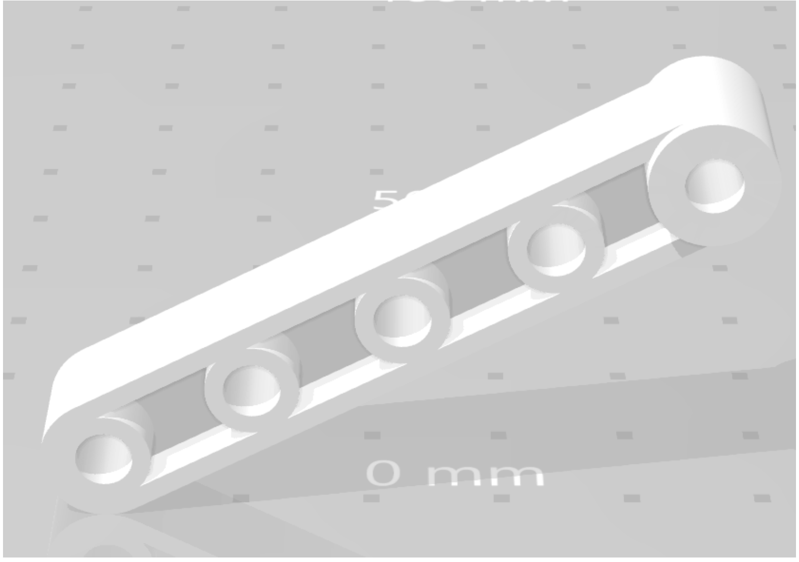


Figure 5-5. Linkage saved as a STL file.

Figure 5-6. 3D printed linkage.

Both of figures 5.7 and 5.8 shows the STL files for the gripper finger, while figures 5.9 and 5.10 shows the 3D printed parts.

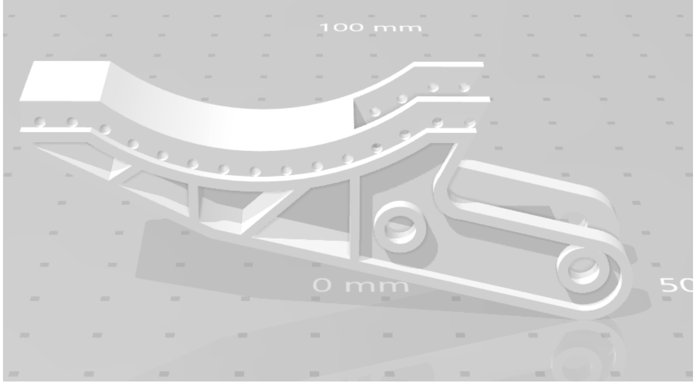


Figure 5-7. Claw gripper saved as a STL file.

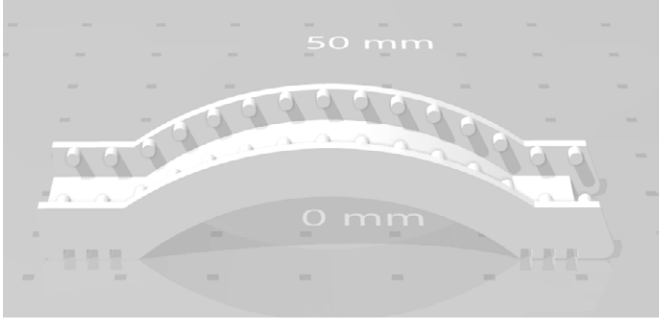


Figure 5-8. Claw finger saved as a STL file.

Figure 5-9. 3D printed claw gripper.

Figure 5-10. 3D printed claw finger.

Figure 5-11. The 3D printed parts required to be assembled to fabricate the gripper arm.

3.2. Assembly

The 3D printed constructing elements had been shown and in the latter section had been assembled to construct the gripper arm required to be designed. Figures 5.12 and 5.13 present the gripper arm at the retraction and extension modes.

Figure 5-12. Gripper Arm had been 3D printed and assembled (in the retraction mode).

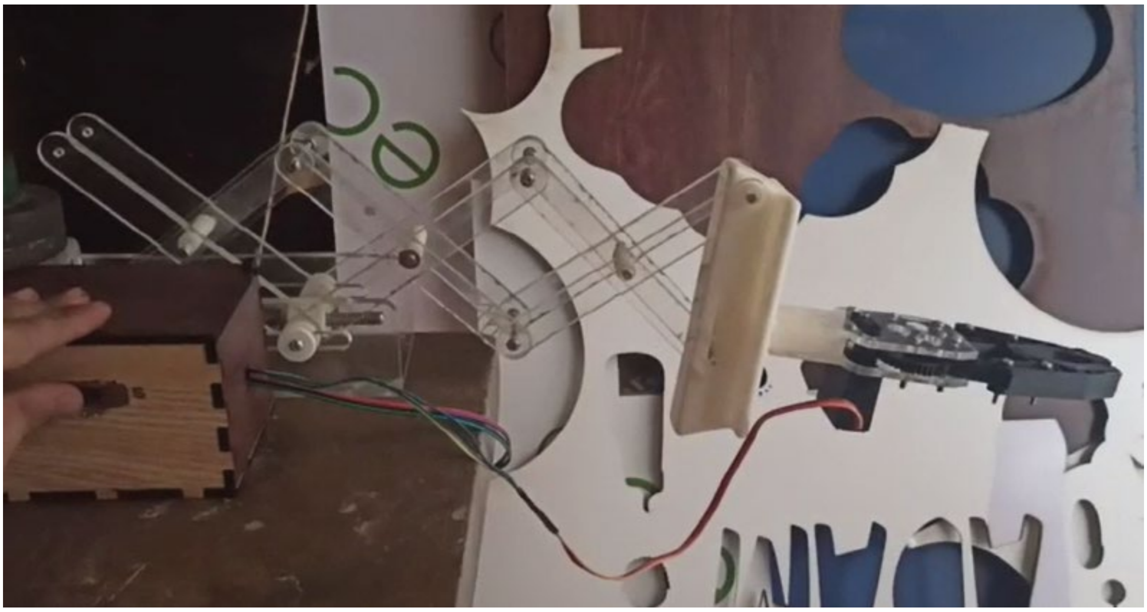


Figure 5-13. Gripper Arm had been 3D printed and assembled (in the extension mode).

3.3. Control system

The main objective of this section is to clarify the control system of the gripper arm with a detailed explanation of the control system as well as the codes. The control system was divided into two systems, which are presented as follows;

3.3.1. Stepper circuit

The stepper circuit was mainly consisted from a stepper motor that is connected to the Arduino as it is presented in figure 5.8. The stepper was decided to be controlled using three main orders, which are the short (S), Long (L) and stop (S) orders. The code of the control circuit had been written to the Arduino is presented as follows;

```
const int dirPin = 2;
const int stepPin = 3;
const int stepper1=4;
const int stepper2=5;
const int stepsPerRevolution = 20;

void setup()
{
  // Declare pins as Outputs
  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
  pinMode(stepper1, INPUT);
  pinMode(stepper2, INPUT);
}
void loop()
{
  // Set motor direction clockwise
  if(stepper1==HIGH){
  digitalWrite(dirPin, LOW);

  // Spin motor slowly
  for(int x = 0; x < stepsPerRevolution; x++)
  {
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(2000);
  }
}
else if(stepper2==HIGH){
    digitalWrite(dirPin, HIGH);

  // Spin motor slowly
  for(int x = 0; x < stepsPerRevolution; x++)
  {
    digitalWrite(stepPin, HIGH);
    delayMicroseconds(2000);
    digitalWrite(stepPin, LOW);
    delayMicroseconds(2000);
  }
```

```
}
else {
  exit;

}
}
```

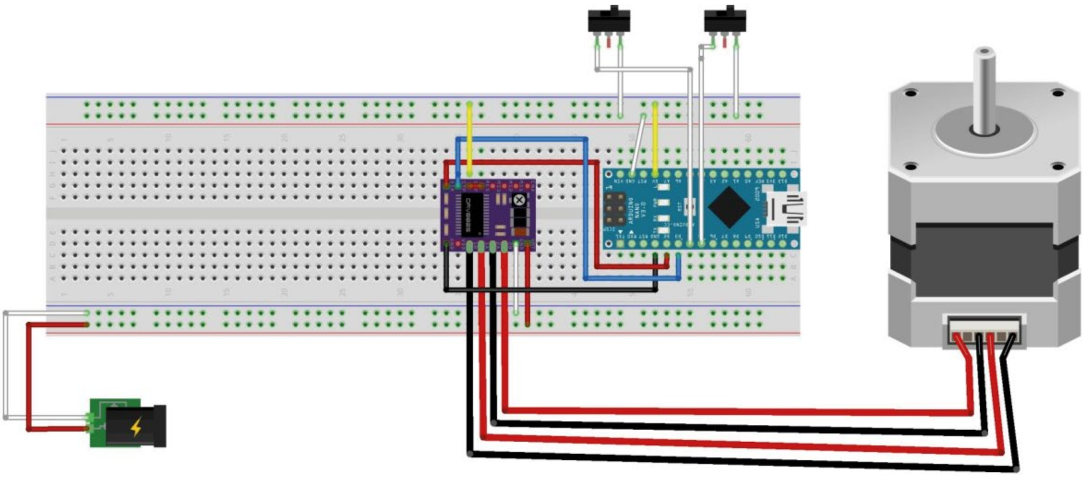


Figure 5-14. A graphical representation of the stepper control circuit.

3.3.2. Servo circuit

The servo circuit was mainly consisted from a servo motor that is connected to the Arduino as it is presented in figure 5.9. The servo motor was decided to be controlled two main orders, which are the open (O) and close (C) orders. The code of the control circuit had been written to the Arduino is presented as follows;

```
/*
 Controlling a servo with two Push buttons with Arduino
 when Left  push button is pressed, the servo start moving to the left until
it reaches 180( or zero) degrees
 when Right  push button is pressed, the servo start moving to the right
until it reaches 180( or zero) degrees
At any instance if the button is released, servo stops

 May 22, 2018 at 01:00
 Written by Ahmad S. for Robojax.com at Ajax, Ontario, Canada
 Watch video for this code at https://youtu.be/7woqNH_qby4
 This code is taken from http://robojax.com/learn/arduino
*/

#include <Servo.h>

Servo myservo;  // create servo object to control a servo

int angle =65;    // initial angle  for servo
int angleStep =5;
```

```
#define LEFT 12   // pin 12 is connected to left button
#define RIGHT  10  // pin 2 is connected to right button

void setup() {
  // Servo button demo by Robojax.com
  Serial.begin(9600);          //  setup serial
  myservo.attach(9);  // attaches the servo on pin 9 to the servo object
  pinMode(LEFT,INPUT_PULLUP); // assign pin 12 ass input for Left button
  pinMode(RIGHT,INPUT_PULLUP);// assing pin 2 as input for right button
  myservo.write(angle);// send servo to the middle at 90 degrees
 Serial.println("Robojax Servo Button ");
}

void loop() {
  // Servo button demo by Robojax.com
  while(digitalRead(RIGHT) == LOW){

    if (angle > 0 && angle <= 180) {
      angle = angle - angleStep;
       if(angle < 65){
        angle = 65;
       }else{
      myservo.write(angle); // move the servo to desired angle
      Serial.print("Moved to: ");
      Serial.print(angle);   // print the angle
      Serial.println(" degree");
       }
    }

  delay(100); // waits for the servo to get there
  }// while
 // Servo button demo by Robojax.com

  while(digitalRead(LEFT) == LOW){

    // Servo button demo by Robojax.com
    if (angle >= 0 && angle <= 180) {
      angle = angle + angleStep;
      if(angle >165){
        angle =165;
       }else{
      myservo.write(angle); // move the servo to desired angle
      Serial.print("Moved to: ");
      Serial.print(angle);   // print the angle
      Serial.println(" degree");
       }
    }
      delay(100); // waits for the servo to get there
  }//

  }
```

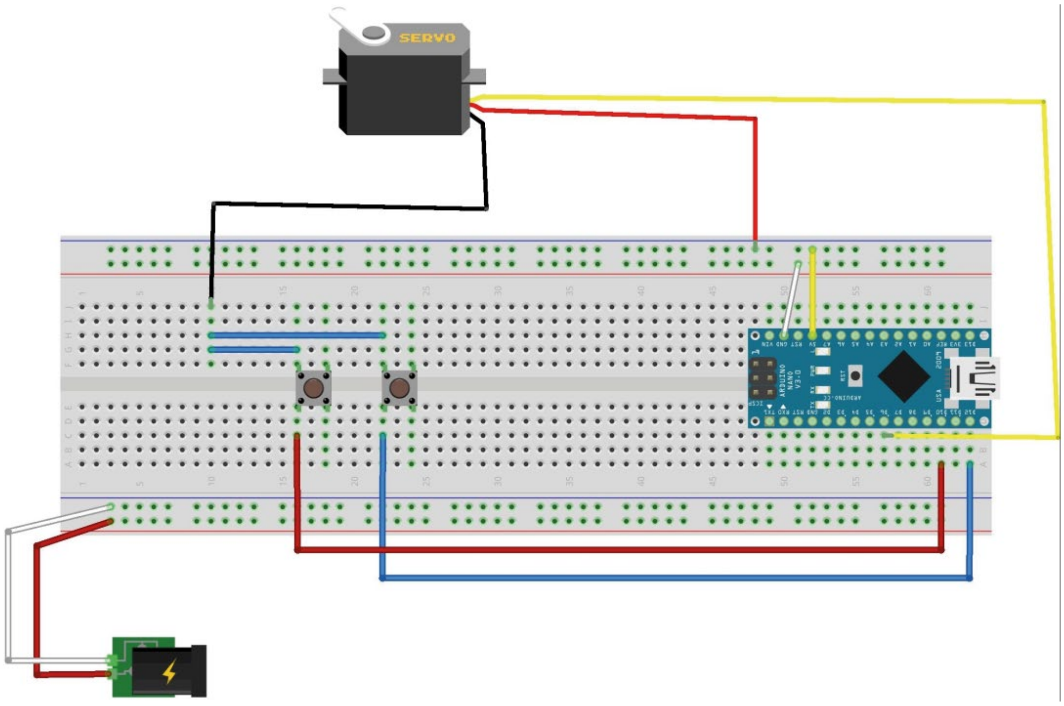


Figure 5-15. A graphical representation of the servo control circuit.

The control circuit shown and discussed in latter section was decided to be included in a box to avoid errors may generate due to losing electrical connections among pins and the Arduino. The following figure shows the control box made of wood.

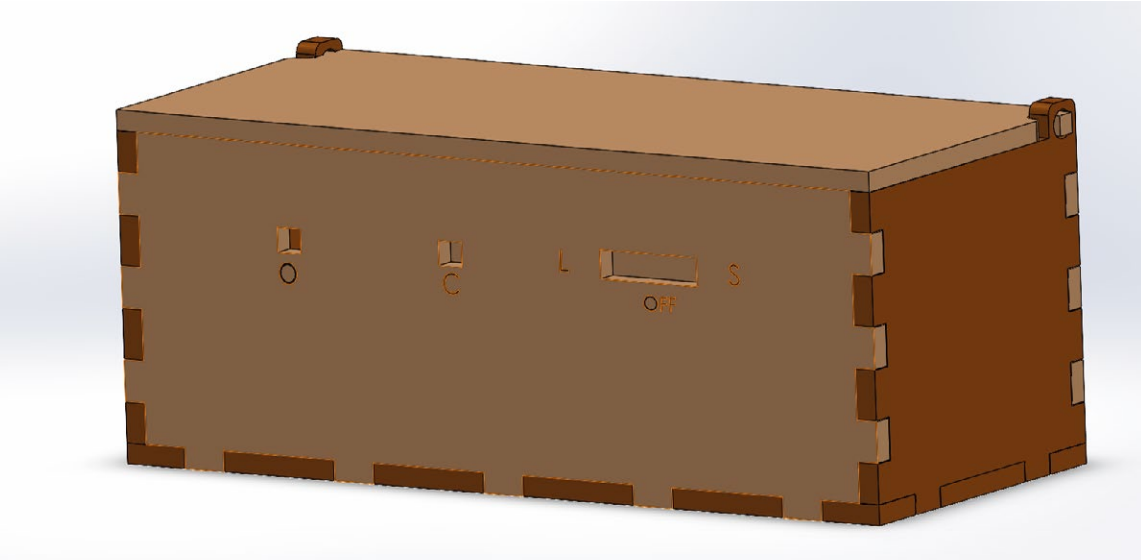


Figure 5-16. 3D model of the wooden control box includes all control components and wirings.

The following figure presents the full control system for the gripper system, where the stepper motor is responsible for the linear motion while the servo motor is responsible for the finger motion.

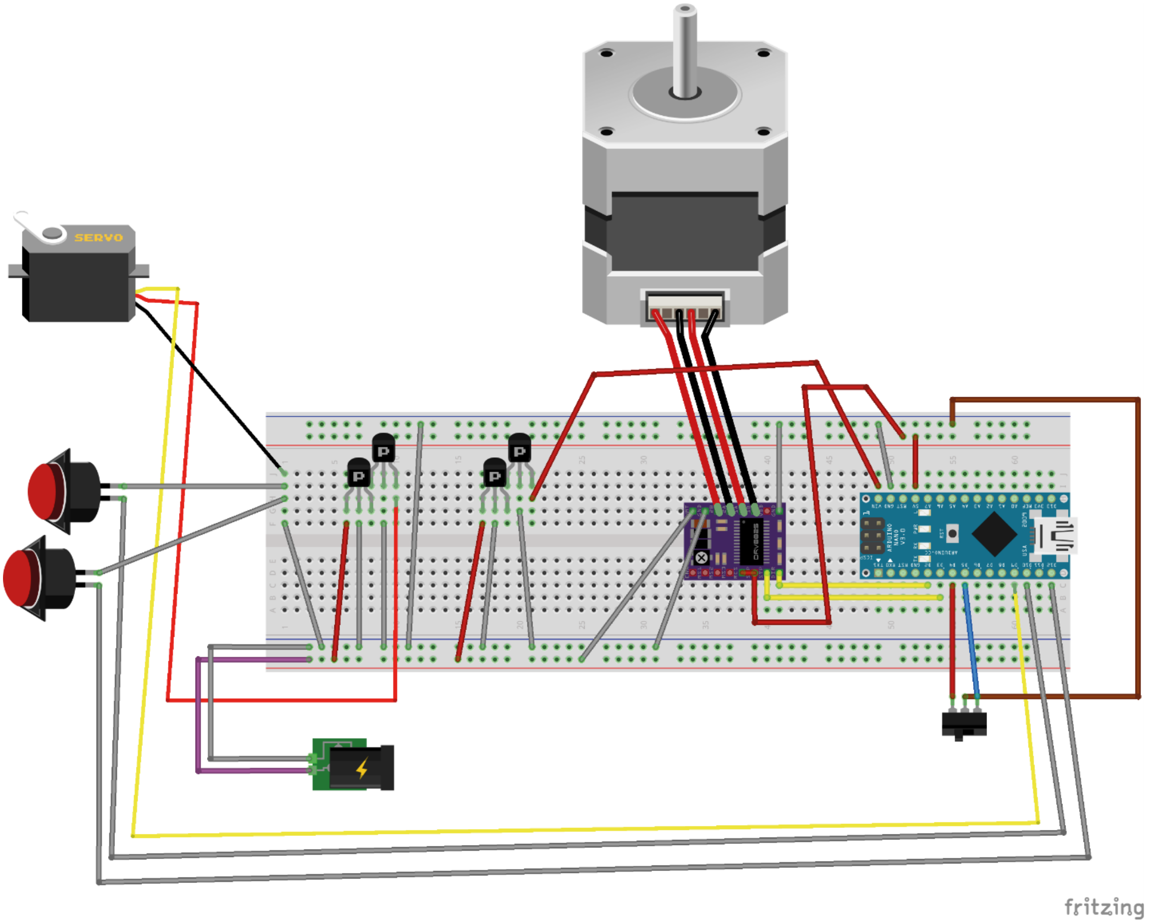


Figure 5-17. The entire control system of the gripper system.

Chapter Six: Experiment and test

The gripping system had been manufactured and assembled was decided to be tested aiming to investigate its effectiveness regarding holding such heavy objects to help disabled persons and elders achieving higher level of self-dependency. This was decided to be achieved through preparing a cup that may be full of tea, milk, water, etc. and investigating the stability achieved by the gripper arm. It is worthy to mention that, the gripper arm was planned to be installed on a wheelchair as it is shown in figure 6.1.

Figure 6-1.3D model for the installation of the gripper arm on a wheelchair for disabled person.

The gripper arm was decided to be tested to investigate the effectiveness regarding achieving high level of self-dependency. The testing scenarios are presented as follows;

1. Allowing the gripper arm to be extended to hold an empty cup that weighs 25 gram and holds for 5 minutes then retracted to the original point.
2. Allowing the gripper arm to be extended to hold a cup that weighs 25 gram with water weighs 25 grams (25 ml) and holds for 5 minutes then retracted to the original point.
3. Allowing the gripper arm to be extended to hold a cup that weighs 25 gram with water weighs 100 grams (50 ml) and holds for 5 minutes then retracted to the original point.
4. Allowing the gripper arm to be extended to hold a cup that weighs 25 gram with water weighs 150 grams (150 ml) and holds for 5 minutes then retracted to the original point.
5. Allowing the gripper arm to be extended to hold a cup that weighs 25 gram with water weighs 200 grams (200 ml) and holds for 5 minutes then retracted to the original point.
6. Allowing the gripper arm to be extended to hold a cup that weighs 25 gram with water weighs 250 grams (250 ml) and holds for 5 minutes then retracted to the original point.

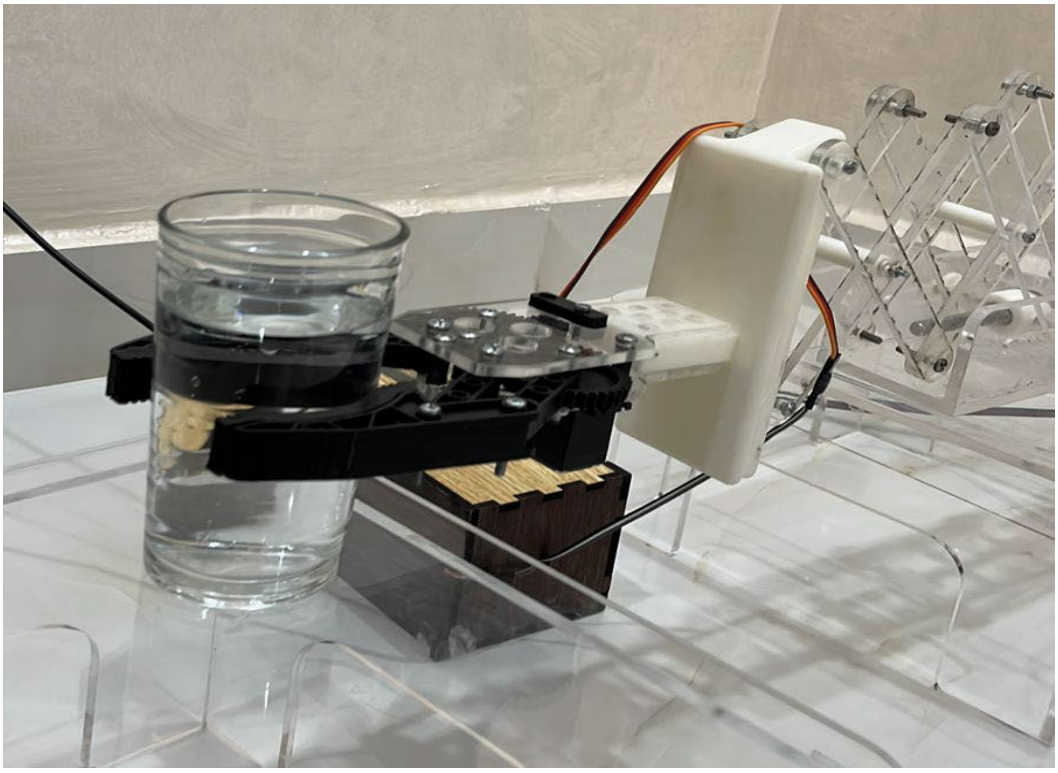


Figure 6-2. Testing the effectiveness of the proposed design of the gripper system.

Chapter Seven: Results analysis and discussions

Regarding the designed and manufactured gripper system, the decision was taken to consider testing it for different operating scenarios. The holding mechanism of the cup using the gripper system depends mainly on the friction takes place, which is presented graphically in the following figure.

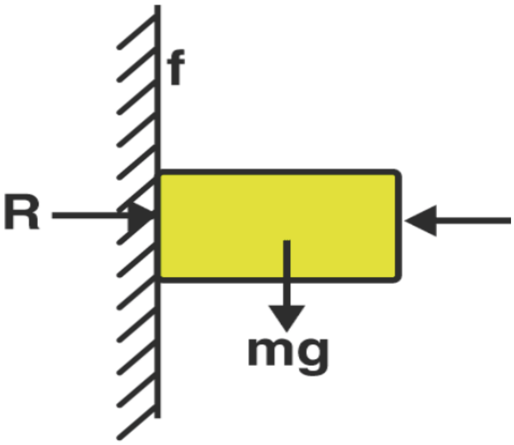


Figure 7-1. Schematic representation of the friction force.

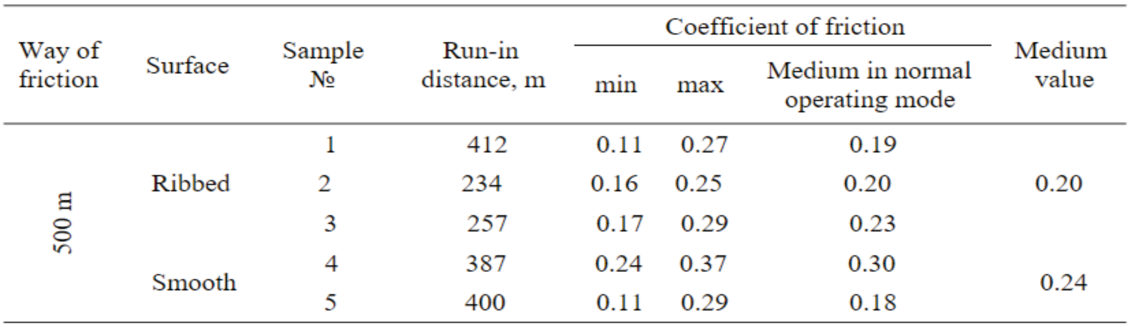
Where the friction force can be calculated using the following mathematical correlation;

$$F = \mu * N$$

Where, F is the friction force (N), μ is the friction coefficient and N is the weight of the object (N).

The coefficient of friction for the ABS material had been considered to 3D print the gripper finger was investigated laboratorial according to (Slavkina & Goncharova, 2020) and presented in the following table.

Table 7-1. Friction coefficients for different surfaces made of ABS material (Slavkina & Goncharova, 2020).



Way of friction	Surface	Sample №	Run-in distance, m	Coefficient of friction			Medium value
				min	max	Medium in normal operating mode	
500 m	Ribbed	1	412	0.11	0.27	0.19	0.20
		2	234	0.16	0.25	0.20	
		3	257	0.17	0.29	0.23	
	Smooth	4	387	0.24	0.37	0.30	0.24
		5	400	0.11	0.29	0.18	

Hence, the coefficient of friction can be assumed 0.24, then the friction forces for the different testing scenarios are presented as follows;

Table 7-2. Expected friction forces and weights for the considered testing scenarios for the gripper system.

Scenario No.	Friction force	Weight
1	0.04 N	0.25 N
2	0.18 N	0.75 N
3	0.42 N	1.75 N
4	0.48 N	2 N
5	0.6 N	2.5 N
6	0.72 N	3 N
7	0.84 N	3.5 N

It was investigated that, increasing weight of the cup resulted in increasing the friction force noticeably as it is presented in figure 7.2.

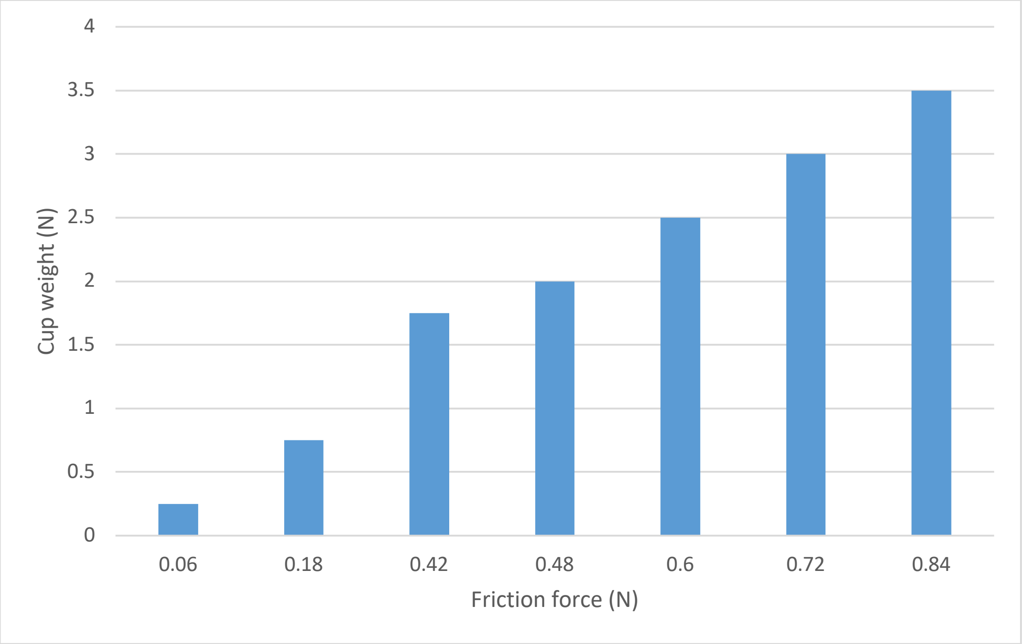


Figure 7-2. The expected effect of the weight of the cup on the friction force on the gripper finger.

It is worthy to mention that, in case of increasing the weight of the cup to reach 350 grams (3.5 N), the slippage occurs after 2 minutes that refers to the critical operation of the gripper system that should not be exceeded.

Chapter Eight: Conclusions and recommendations

8.1. Concluded points

Recently, the development of the manufacturing industry has been divided into three major categories. Small production, medium production, and massive production are the three categories. It is not possible for small production that is entirely automated to keep up with the socially growing demands for Low-Volume, High-Mix manufacturing. The cost of labour has increased significantly in manufacturing where all workers are human. When considering this issue, it is necessary to build a more flexible system in order to improve the reconfigurability and dexterity of the current manufacturing system by taking into account the coordination and combination of the above two aspects, with the goal of increasing overall effectiveness. It has been demonstrated that by providing robots with sufficient flexibility, it is possible to improve product quality and thus reduce costs. Some issues have arisen as a result of the use of robots in manufacturing industries. Because it is difficult for the robot to effectively deal with assembly parts that have complex shapes. They frequently rely on external sensors to assist with assembly work. Human workers, on the other hand, are highly skilled at completing tasks of high complexity with their hands. As a result, the manipulators of the robot must be able to perform these tasks in the same way that human workers do. As a result, special attention was paid to the robot's end effectors, such as the gripper. It is impossible to consider the human hand as a compound gripping system that incorporates both handling tools and sensors. The human hand has the ability to provide flexibility for the grasping process, adaptability, and stability, as well as other manipulation capabilities with the aid of sensor feedback and foreknowledge under the control of the brain. All robotics must interact with various sensors such as hearing sensors, visual sensors, tactile sensors, and so on. In addition to facilitating the implementation and development of closed-loop control policies, robotics must interface with the complex and variable physical environment. Significant efforts have been made to mimic the advantage aptitudes of human hands through the use of various sensors in order to grasp various types of objects with the tough sense as well as visual perception. In addition to grasping the object, the gripper will be able to analyse the information between the object and the gripper through the integration of several sensors. Furthermore, based on the fusion sensory data, online decision making is possible. As a result, the gripper can be regarded as a data source. The sensors' integration has the potential to provide powerful functionality such as interactivity, visual acuity, touch, and stability. The integration of control and drive technology, in addition to the integration of sensors, will result in a more intelligent gripper.

The development of soft grippers addresses the issue of rigid grippers that lack adaptability, flexibility, and/or compliance. This type of gripper could be powered by a variety of methods, including shape memory alloy (SMA), cable, hydraulic, pneumatic, and motors. The soft gripper is powered by a pneumatic design special ventilation chamber that employs deformable material. As a result, aside from the air cavity design, the selection of elastic material is the most important aspect of gripper design. There are two major types of pneumatic actuator structures: multi-chamber and fiber-reinforced. Negative or positive pressure is used to deform the gripper to produce the grasping motion. Figure 2a depicts a soft robotic gripper with a pneumatic network that was designed by the Harvard University Whiteside research group using elastic silicone rubber and manufactured using 3D printing technology. This gripper has demonstrated small loading capacity, mutual accommodation with the environment, flexible movement, and large deformation. Another study created a soft robotic gripper with four figures that can be adjusted in length based on the shape and size of the object that needs to be trapped. The fibre restraint concept has been used to design a fiber-reinforced actuator that is made of both rigid and super-elastic material. Using a fiber-reinforced actuator

The evolution of robotics is critical to the future of the industry. It is difficult to imagine a modern manufacturing organisation without investing in automation of production processes and manipulation. Automation of the production process of gaining tending flexible manufacturing systems using industrial robots and manipulators. The robot's end effector is the most important component because it is in charge of carrying out many tasks. The robotic arm is designed to be able to manipulate its surroundings; for example, the robot can control the assembly line workpieces. And the arm's controller is programmed to teach it how to perform this task by memorising a specific sequence of a group of movements and repeating the same motions every time. As a result, the primary goal of this project is to design and control a flexible robot end effector for the purpose of performing specific industrial tasks. This project aims to create and control a flexible robot arm that is expected to assist disabled people and the elderly in satisfying a higher dependency level, thereby improving their psychological health.

Several studies were conducted in order to optimise the performance of the gripper system, and it was decided to consider 3D printing the 3D modelled gripper system using ABS material, which was predicted to achieve the highest performance when compared to either PLA or Polyester materials. The geometrical description for each constructing part of the gripper system was presented in detail. The stepper circuit was primarily composed of a stepper motor connected to the Arduino. The stepper was decided to be controlled by three main orders: short (S), long (L), and stop (S). The control circuit's code had been written to the Arduino. The servo circuit was primarily comprised of a servo motor connected to the Arduino. The servo motor was decided to be controlled by two main orders: open (O) and close (C). Several testing scenarios were chosen to investigate the manufactured gripper system. It was discovered that increasing the weight of the cup significantly increased the friction force. It is worth noting that when the weight of the cup is increased to 350 grammes (3.5 N), slippage occurs after 2 minutes, indicating a critical operation of the gripper system that should not be exceeded.

8.2. Recommendations

For the future scientific works, it is recommended to consider the following;

1. Simulating the performance of the gripper system using simulation tools such as ANSYS software and compare the simulation results with the experimental results.
2. Optimizing the design of the gripper system using optimization technologies such as topology optimization tool exists in Solidworks software package. The optimization process would help in reducing the mass of the gripper mas with acceptable mechanical safety leading to achieve higher environmental and economic benefits.
3. Investigating the effect of changing the material on the gripping effectiveness.

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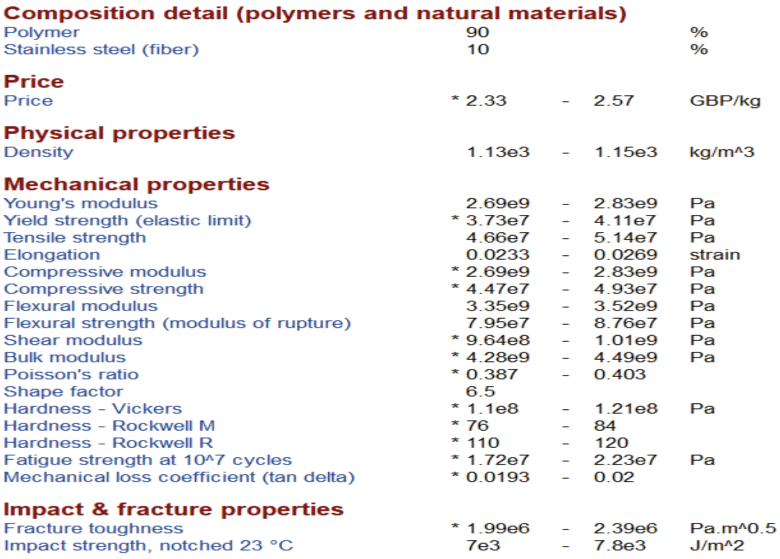
Appendix A: Properties for ABS material



Composition detail (polymers and natural materials)

Polymer	90			%
Stainless steel (fiber)	10			%

Price

Price	* 2.33	-	2.57	GBP/kg

Physical properties

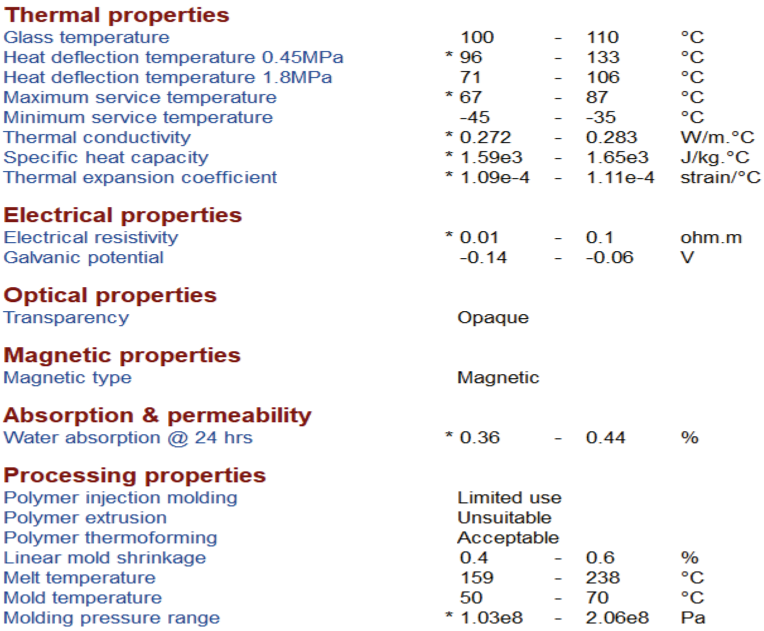
Density	1.13e3	-	1.15e3	kg/m^3

Mechanical properties

Young's modulus	2.69e9	-	2.83e9	Pa
Yield strength (elastic limit)	* 3.73e7	-	4.11e7	Pa
Tensile strength	4.66e7	-	5.14e7	Pa
Elongation	0.0233	-	0.0269	strain
Compressive modulus	* 2.69e9	-	2.83e9	Pa
Compressive strength	* 4.47e7	-	4.93e7	Pa
Flexural modulus	3.35e9	-	3.52e9	Pa
Flexural strength (modulus of rupture)	7.95e7	-	8.76e7	Pa
Shear modulus	* 9.64e8	-	1.01e9	Pa
Bulk modulus	* 4.28e9	-	4.49e9	Pa
Poisson's ratio	* 0.387	-	0.403	
Shape factor	6.5			
Hardness - Vickers	* 1.1e8	-	1.21e8	Pa
Hardness - Rockwell M	* 76	-	84	
Hardness - Rockwell R	* 110	-	120	
Fatigue strength at 10^7 cycles	* 1.72e7	-	2.23e7	Pa
Mechanical loss coefficient (tan delta)	* 0.0193	-	0.02	

Impact & fracture properties

Fracture toughness	* 1.99e6	-	2.39e6	Pa.m^0.5
Impact strength, notched 23 °C	7e3	-	7.8e3	J/m^2



Thermal properties

Glass temperature	100	-	110	°C
Heat deflection temperature 0.45MPa	* 96	-	133	°C
Heat deflection temperature 1.8MPa	71	-	106	°C
Maximum service temperature	* 67	-	87	°C
Minimum service temperature	-45	-	-35	°C
Thermal conductivity	* 0.272	-	0.283	W/m.°C
Specific heat capacity	* 1.59e3	-	1.65e3	J/kg.°C
Thermal expansion coefficient	* 1.09e-4	-	1.11e-4	strain/°C

Electrical properties

Electrical resistivity	* 0.01	-	0.1	ohm.m
Galvanic potential	-0.14	-	-0.06	V

Optical properties

Transparency	Opaque

Magnetic properties

Magnetic type	Magnetic

Absorption & permeability

Water absorption @ 24 hrs	* 0.36	-	0.44	%

Processing properties

Polymer injection molding	Limited use			
Polymer extrusion	Unsuitable			
Polymer thermoforming	Acceptable			
Linear mold shrinkage	0.4	-	0.6	%
Melt temperature	159	-	238	°C
Mold temperature	50	-	70	°C
Molding pressure range	* 1.03e8	-	2.06e8	Pa

Durability

Water (fresh)	Excellent
Water (salt)	Excellent
Weak acids	Excellent
Strong acids	Limited use
Weak alkalis	Acceptable
Strong alkalis	Excellent
Organic solvents	Unacceptable
Oxidation at 500C	Unacceptable
UV radiation (sunlight)	Poor
Flammability	Highly flammable

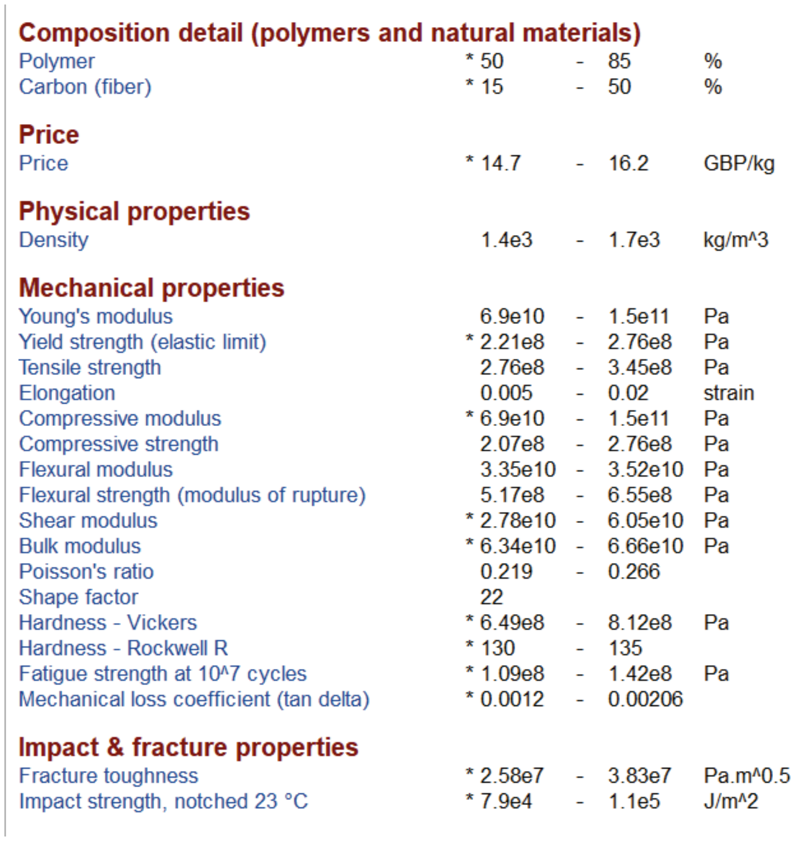
Primary production energy, CO2 and water

Embodied energy, primary production	* 9.02e7	-	9.94e7	J/kg
CO2 footprint, primary production	* 3.79	-	4.18	kg/kg
Water usage	* 0.172	-	0.19	m^3/kg

Processing energy, CO2 footprint & water

Polymer extrusion energy	* 5.8e6	-	6.41e6	J/kg
Polymer extrusion CO2	* 0.435	-	0.481	kg/kg
Polymer extrusion water	* 0.00482	-	0.00723	m^3/kg
Polymer molding energy	* 1.8e7	-	1.99e7	J/kg
Polymer molding CO2	* 1.35	-	1.49	kg/kg
Polymer molding water	* 0.0123	-	0.0185	m^3/kg
Coarse machining energy (per unit wt removed)	* 8.66e5	-	9.57e5	J/kg
Coarse machining CO2 (per unit wt removed)	* 0.065	-	0.0718	kg/kg
Fine machining energy (per unit wt removed)	* 4.39e6	-	4.85e6	J/kg
Fine machining CO2 (per unit wt removed)	* 0.329	-	0.364	kg/kg
Grinding energy (per unit wt removed)	* 8.3e6	-	9.17e6	J/kg
Grinding CO2 (per unit wt removed)	* 0.622	-	0.688	kg/kg

Appendix B: Properties for epoxy resin



Composition detail (polymers and natural materials)

Polymer	* 50	-	85	%
Carbon (fiber)	* 15	-	50	%

Price

Price	* 14.7	-	16.2	GBP/kg

Physical properties

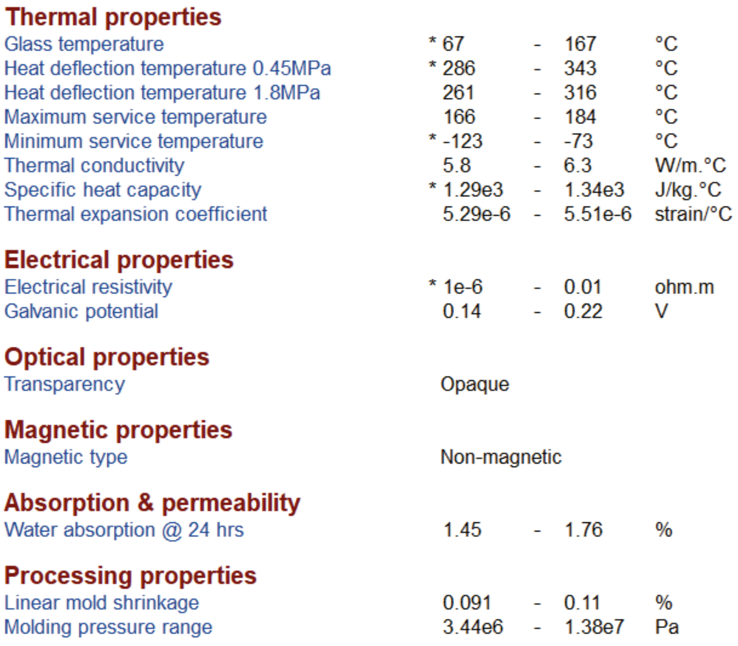
Density	1.4e3	-	1.7e3	kg/m^3

Mechanical properties

Young's modulus	6.9e10	-	1.5e11	Pa
Yield strength (elastic limit)	* 2.21e8	-	2.76e8	Pa
Tensile strength	2.76e8	-	3.45e8	Pa
Elongation	0.005	-	0.02	strain
Compressive modulus	* 6.9e10	-	1.5e11	Pa
Compressive strength	2.07e8	-	2.76e8	Pa
Flexural modulus	3.35e10	-	3.52e10	Pa
Flexural strength (modulus of rupture)	5.17e8	-	6.55e8	Pa
Shear modulus	* 2.78e10	-	6.05e10	Pa
Bulk modulus	* 6.34e10	-	6.66e10	Pa
Poisson's ratio	0.219	-	0.266	
Shape factor	22			
Hardness - Vickers	* 6.49e8	-	8.12e8	Pa
Hardness - Rockwell R	* 130	-	135	
Fatigue strength at 10^7 cycles	* 1.09e8	-	1.42e8	Pa
Mechanical loss coefficient (tan delta)	* 0.0012	-	0.00206	

Impact & fracture properties

Fracture toughness	* 2.58e7	-	3.83e7	Pa.m^0.5
Impact strength, notched 23 °C	* 7.9e4	-	1.1e5	J/m^2



Thermal properties

Glass temperature	* 67	-	167	°C
Heat deflection temperature 0.45MPa	* 286	-	343	°C
Heat deflection temperature 1.8MPa	261	-	316	°C
Maximum service temperature	166	-	184	°C
Minimum service temperature	* -123	-	-73	°C
Thermal conductivity	5.8	-	6.3	W/m.°C
Specific heat capacity	* 1.29e3	-	1.34e3	J/kg.°C
Thermal expansion coefficient	5.29e-6	-	5.51e-6	strain/°C

Electrical properties

Electrical resistivity	* 1e-6	-	0.01	ohm.m
Galvanic potential	0.14	-	0.22	V

Optical properties

Transparency	Opaque

Magnetic properties

Magnetic type	Non-magnetic

Absorption & permeability

Water absorption @ 24 hrs	1.45	-	1.76	%

Processing properties

Linear mold shrinkage	0.091	-	0.11	%
Molding pressure range	3.44e6	-	1.38e7	Pa

Durability

Water (fresh)	Excellent
Water (salt)	Excellent
Weak acids	Acceptable
Strong acids	Unacceptable
Weak alkalis	Limited use
Strong alkalis	Excellent
Organic solvents	Limited use
Oxidation at 500C	Unacceptable
UV radiation (sunlight)	Good
Flammability	Self-extinguishing

Primary production energy, CO2 and water

Embodied energy, primary production	* 1.77e8	-	1.95e8	J/kg
CO2 footprint, primary production	* 10.7	-	11.8	kg/kg
Water usage	* 0.66	-	0.73	m^3/kg

Processing energy, CO2 footprint & water

Compression molding energy	* 3.33e6	-	3.68e6	J/kg
Compression molding CO2	* 0.266	-	0.294	kg/kg
Compression molding water	* 0.00631	-	0.00946	m^3/kg

Recycling and end of life

Recycle	✗			
Recycle fraction in current supply	0.1			%
Downcycle	✓			
Combust for energy recovery	✓			
Heat of combustion (net)	* 3.02e7	-	3.18e7	J/kg
Combustion CO2	* 2.59	-	2.72	kg/kg
Landfill	✓			
Biodegrade	✗			

Appendix C: Properties for PVC material

Composition detail (polymers and natural materials)

Polymer	100			%

Price

Price	* 9.62	-	10.6	GBP/kg

Physical properties

Density	36	-	44	kg/m^3
Relative density	* 0.026	-	0.031	
Cells/volume	* 1e9	-	1e10	/m^3
Anisotropy ratio	* 1	-	1.5	

Mechanical properties

Young's modulus	2.3e7	-	2.9e7	Pa
Yield strength (elastic limit)	* 3.7e5	-	4.3e5	Pa
Tensile strength	5.3e5	-	5.5e5	Pa
Elongation	* 0.02	-	0.03	strain
Compressive modulus	* 2.25e7	-	2.64e7	Pa
Compressive strength	* 3.7e5	-	4.3e5	Pa
Flexural modulus	2.3e7	-	2.9e7	Pa
Flexural strength (modulus of rupture)	5.5e5	-	6.5e5	Pa
Shear modulus	1e7	-	1.6e7	Pa
Shear strength	1.85e5	-	2.15e5	Pa
Bulk modulus	* 2.3e7	-	2.9e7	Pa
Poisson's ratio	* 0.29	-	0.31	
Shape factor	2.4			
Hardness - Vickers	* 3.63e5	-	4.22e5	Pa
Fatigue strength at 10^7 cycles	* 2.96e5	-	3.44e5	Pa
Mechanical loss coefficient (tan delta)	* 0.05	-	0.15	
Densification strain	* 0.95	-	0.959	

Impact & fracture properties

Fracture toughness	* 2.1e3	-	2.8e3	Pa.m^0.5

Thermal properties

Glass temperature	74	-	88	°C
Maximum service temperature	92	-	97	°C
Minimum service temperature	-200			°C
Thermal conductivity	0.028	-	0.03	W/m.°C
Specific heat capacity	1.12e3	-	1.14e3	J/kg.°C
Thermal expansion coefficient	2e-5	-	2.4e-5	strain/°C

Electrical properties

Electrical resistivity	* 1e11	-	1e13	ohm.m
Dielectric constant (relative permittivity)	* 1.04	-	1.05	
Dissipation factor (dielectric loss tangent)	* 6e-4	-	7e-4	
Dielectric strength (dielectric breakdown)	* 5.39e6	-	5.47e6	V/m

Optical properties

Transparency	Opaque

Magnetic properties

Magnetic type	Non-magnetic

Absorption & permeability

Water absorption @ 24 hrs	* 4.75	-	5.76	%

Durability

Water (fresh)	Excellent
Water (salt)	Excellent
Weak acids	Excellent
Strong acids	Excellent
Weak alkalis	Excellent
Strong alkalis	Excellent
Organic solvents	Limited use
Oxidation at 500C	Unacceptable
UV radiation (sunlight)	Good
Flammability	Self-extinguishing

Primary production energy, CO2 and water

Embodied energy, primary production	* 7.65e7	-	8.44e7	J/kg
CO2 footprint, primary production	* 4.91	-	5.41	kg/kg