DEVELOPMENT OF A 6-DOF 3D PRINTED INDUSTRIAL ROBOT FOR TEACHING AND LEARNING

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KUALA LUMPUR

2019

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RESEARCH REPORT SUBMITTED TO THE FACULTY OF ENGINEERING, UNIVERSITY OF MALAYA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING (MECHATRONICS)

2019

UNIVERSITY OF MALAYA

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ABSTRACT

The trend in modern manufacturing has led to a paradigm shift from the conventional high method to heavily automated processes. This comes with a high cost for those who want to meet up to the increasing pace of this revolution as the machines and the knowledge to control them is becoming expensive. Two major areas that have contributed in shaping this achievement of the industry 4.0 are additive manufacturing and robotics. With the drop in the prices of 3D printers and availability of off-the-shelf (OTS) electronics components, the industrial experience is brought nearer to those who cannot afford it, especially students who need learn the adequate skill-sets in order to efficiently perform in this fourth industrial revolution. To this end, this project aims at building a low-cost 3D printed robotic arm for teaching and learning purpose. The robotic arm was printed using three different kinds of 3D printers, with two most common materials. The forward and inverse kinematics of the robotic arm were derived from using a well-known and easy to understand method. Finally, the robotic was controlled using the Arduino mega 2560 which sends pulse width modulation (PWM) signals to the motors through a serial connection. A simple pick and place experiment using two different objects was conducted using the robotic arm. Also, the joint accuracies of three major joints were calculated. As an educational tool, it is hoped that students will learn the principles of 3D printing, robot kinematics and some level of control.

Keywords: 3D printing, Robot education, Robot Kinematics, Robot Control.

ABSTRAK

Trend dalam pembuatan moden telah membawa kepada peralihan paradigma dari kaedah tinggi konvensional kepada proses automatik yang berautomatik. Ini datang dengan kos yang tinggi bagi mereka yang ingin bertemu dengan laju revolusi ini kerana mesin dan pengetahuan untuk mengawalnya menjadi mahal. Dua bidang utama yang memberi sumbangan dalam membentuk pencapaian industri ini adalah pembuatan dan robotik. Dengan kejatuhan harga pencetak 3D dan ketersediaan komponen elektronik (OTS) yang ada, pengalaman industri semakin dekat kepada mereka yang tidak mampu, terutama para pelajar yang perlu mempelajari set kemahiran yang mencukupi agar dapat cekap melaksanakan dalam revolusi perindustrian keempat ini. Untuk tujuan ini, projek ini bertujuan untuk membina lengan robotik 3D kos rendah untuk tujuan pengajaran dan pembelajaran. Lengan robot telah dicetak menggunakan tiga jenis pencetak 3D yang berbeza, dengan dua bahan yang paling biasa. Kinematik ke hadapan dan terbalik lengan robotik diperoleh daripada menggunakan kaedah yang dikenali dan mudah difahami. Akhirnya robot itu dikawal menggunakan Arduino mega 2560 yang menghantar isyarat modulasi lebar pulsa (PWM) ke motor melalui sambungan siri. Satu pilihan mudah dan percubaan tempat menggunakan dua objek yang berbeza telah dijalankan menggunakan lengan robot. Juga, ketepatan sendi dari tiga sendi utama dikira. Sebagai alat pendidikan, diharapkan para pelajar akan mempelajari prinsip pencetakan 3D, kinematik robot dan beberapa tahap kawalan.

Kata Kunci: Percekatan 3D, Pendidikan Robot, Kinematik robot, Kawalan robot.

ACKNOWLEDGEMENTS

Alhamdulillah for the blessing of life and health which without them both I wouldn't be able to reach the end of this program. I am always grateful to Allah for all the favours He showers upon me.

I would like to exprees my deepest appreciation to my project supervisor, Associate Prof. Yap Hwa Jen from the department of Mechanical Engineering for not only allowing me work with him, but also sharing his bank of experience with me. He has always been there to guide and correct me throughout the course of this project.

To my wife and first child (daughter) whom am yet to see, I can't thank you enough for your patience and perseverance for the time I have spent away from home for this program. You both have been my greatest motivation.

To my parents and siblings who have always advised and prayed for my success, may you all be blessed with your heart desires.

I want to extend my gratitude to Bayero University Kano for giving me the study fellowship to undergo this masters degree and TETFUND for sponsoring this degree.

Finally, to my course mates and all the staff of the faculty of engineering, university of Malaya, I am grateful for all the wonderful times we have shared.

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LIST OF SYMBOLS AND ABBREVIATIONS

OTS	:	off-the-shelf
DOF	:	degree of freedom
DH	:	Denavit-Hartenberg
AM	:	Additive manufacturing
CAD	:	Computer Aided Design
3D	:	three dimensional
STEM	:	Science, technology, engineering and mathematics
LEGO	:	
PC	:	personal computer
ROS	:	Robot operating system
GUI	:	Graphical user interface
CNC	:	Computer numerically controlled
PCB	:	Printed circuit board
MIS	:	Minimally invasive surgery
CDIO	:	conceive, design, implement, and operate
SCARA	:	Selective compliance assembly robotic arm
UKM	:	University Kebangsaan Malaysia
KUKA	:	Keller Und Knappich Augsburg
ABB	:	ASEA Brown Boveri
MATLAB	:	Matrix Laboratory
STL	:	Standard Tessellation Language
GCODES	:	format for writing CNC programs
CURA	:	Named after the surname of the inventor CURA
PLA	:	Polylactic Acid

ABS	:	Acrylonitrile Butadiene Styrene
ɑ	:	small greek letter alfa
d	:	small letter d
α	:	capital greek letter alfa
θ	:	greek letter theta
HTM	:	Homogeneous transformation matix
PWM	:	Pulse width modulation
IK	:	Inverse kinematics
FK	:	Forward kinematics

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CHAPTER 1: INTRODUCTION

1.1 Introduction

As the world drive towards a new age of technology particularly the industry 4.0 and IoT, the demand for competent in terms of technical and communication skills engineers is rapidly on the increase. However, the supply for such qualified engineers is falling short of the demand. New devices, machines, software, and various technologies are being born on a daily basis, which places a huge responsibility on schools and vocational centres to train and produce engineers and technician to use these new technologies and also try to catch up the pace.

One of the areas where the above mentioned training and development need urgent attention is in the field of robotics. Robots have been touching human lives for almost six decades now since the first robot was put to service in 1961 at General Motors plant. These robots impacted our lives behind the scene as we only enjoyed the already made parts without knowing how they were made. This was due to the fact that the first of the robots to be put to use were the industrial robots. In recent times, robots have become parts and parcel of our lives as they can be seen in almost works of lives ranging from industries, to domestic, to entertainment, and many other aspects of lives. Various applications of these robots will be given in chapter two where industrial robots will be discussed.

Over the years, there's been several definitions of what a robot is actually is. Although the most widely known definition is the one given by the robotics institute of America which defines a robot "as a reprogrammable, multi-functional manipulator (or device), designed to move materials, parts, tools, or specialized devices through variable, programmed motion for the performance of a variety of tasks". The foregoing definition suits the industrial robot better. As there have been multiple developments in the area of robotics, a more precise definition of a robot will be “any machine that is capable of performing actions automatically when instructions are given to it”

A robot can have degrees of freedom (DOF) ranging from one (1) to six (6), being the common and standard ones, which allows it to perform various forms of movements. There are those with more than six degrees of freedom known as the redundant robots as they have more than enough freedom to carry out different movements. The most common types of robots are the 6-DOF and 7-DOF. A robot with 6-DOF is capable of moving in a translational in all three perpendicular axes of movements and respective rotational movement taking each axis into account. This allows so much flexibility for the robot which enables it to carry out varieties of functions. The applications where a 6-DOF robotic arm can be seen being put to use include; pick and place in industries, teaching and learning, writing, surgical operations and applications, hazardous working conditions, spot welding, painting etc.

From the kinematic point of view, a robot can either be a serial, parallel or hybrid robot. The serial robots were first developed and have been used in different applications. The parallel robots came afterwards. Both kinds of robots have their advantages and disadvantages depending on the application they are being used for. Also, the modelling of robot kinematics comprises direct and inverse kinematics which are used to solve for robot parameters such as position, orientation, and velocity of the end effector with respect to the base coordinate and other parts of the robot. This kinematics can be obtained either by an analytical or numerical method. Although the numerical methods give more accurate results, they are best suited for redundant robots and they come with computational errors(Xu et al., 2019). The DH [Denavit and Hartenberg] convention is the classical and mostly used method in solving the kinematics of a robotic arm. Another method being used is the screw theory as proposed by (An, Lee, Lee, Seo, & Lee, 2017). These classical methods have their peculiar shortcomings of which the biggest one is the singularity (Xu et al., 2019).

Additive manufacturing (AM) is building process where objects or parts are generated given their computer-aided design (CAD) model or any form of AM file by successively adding material layer by layer (Li, Haghighi, & Yang, 2018). Additive manufacturing has many advantages over the conventional traditional methods especially in the area of producing parts with complex geometry, material management and time-to-market reduction (Li et al., 2018). Even though there are some limitations that hinder the growth of additive manufacturing such as low strength, accuracy and surface finish, it is still becoming widely accepted and used in the modern manufacturing industries, there are various methods of additive manufacturing among which are; stereolithography (SLA), laminated object manufacturing (LOM), inkjet systems, selective laser sintering (SLS), fused deposition modelling (FDM). In recent times, additive manufacturing is becoming widely known as 3D printing. Since emerging technologies are heavily tapping from the advantages of additive manufacturing and 3D printing, the adoption of the aforementioned is swiftly growing.

Being a technique which was discovered for over two decades, additive manufacturing is gaining greater attention in the field of manufacturing in the sense that it is no longer restricted to making functional prototypes nowadays but also building tools, jigs and fixtures, replacement parts, concept models, molds and castings, e.t.c. which can serve as much as the previously made types. With the increasing popularity of 3D printers, so much attention is now focused on competences of 3D modelling techniques and other related techniques (Huang & Lin, 2017).

In the area of education, robots have been playing important roles to develop young competent engineers to fit in today's world of rapidly growing technology. With the increased interest and recent widespread of the Science, Technology, Engineering, and Mathematics (STEM) programs, robotics education being an important component of STEM is a promising tool to get students engage in the STEM programmes. The inflow of researchers and students into robotics education over the past few years cannot be overemphasized. Quite a number of researches have shown that educating students of nowadays using robots will not only boost their interests of programming, computational thinking and robotics but also improve their science literacy. Robotics education can serve to enhance students in three major ways which are; being an object of study, being a tool for cognition, and be a means of teaching, development and upbringing of students (Ospennikova, Ershov, & Iljin, 2015). In many countries, robot education is in the process of being incorporated into the school curricula so that students in preschool, primary school, high school, and college can get involved in robotics from an early stage in life.

Controlling the conventional robotic arms require a high skilled operator who has been specially trained. Due to the complexity of the programming and operation, it becomes a herculean/difficult task for high young students in schools to learn how to program these robots. In order to solve this problem, several approaches have been adopted. One of the popular ones is the LEGO mindstorm which was aimed at teaching the basic concept in adaptive control (Michael, Frank, & Torsten, 2012). The open PC-based robot control platforms and sensor and motion interfaces have also pivoted the control aspect of robotic manipulators. Recently, the robotic operating system (ROS) which serves to be an open source platform has become not only a standard open platform but also a widely accepted platform for research and robotics education (Berger et al. 2011).

This robot used in this project was build using a 3D printer which is a form of additive manufacturing. Thus, this marriage between robotics and 3D printing which exploits the benefits of additive manufacturing and combining it with robotics will give birth to a system which will serve to be useful in robotic and manufacturing education. The robot is expected to ease learning for students in the area of robot development, kinematics, controlling of robots, electronics components and programming. The model is expected to fulfil some industrial tasks alongside being an aid for teaching and learning. It is majorly focused on the pick and place application which is common industrial task used during packaging and palletizing.

1.2 Problem Statement

Some of the problems that lead to the undertaking of this project are listed below.

- Standard robots that are manufactured by robotics industries come at a very high cost. This makes it almost impossible for schools to obtain one. In order for schools to have access to similar robots, there should be a low-cost robot which will function as the standard robots. These robots should not only be affordable, but also available.
- Another problem is the space constraints due to the sizes and weights of these standard robots. Most schools don't have the space to store such huge robots. Even though there are smaller robots with lower payload, their weights are much compared to the robot that is built in this project.

- The technical knowledge that is needed to control or operate these standard robots also comes with the cost of training coupled with the fact that most of these industrial robots comes with their specific/peculiar teach pendants. So the flexibility of operation is limited as compared to the robot that is built in this project. This is because it is more efficient to teach children through pictures and toys. So, the GUI of this project will serve as a picture, while the model itself will serve as toy, thus making the learning process a fun.
- The student robot ratio that can be obtained by using a 3D printed robot will be higher than buying a standard robot from a robot manufacturer. With the low-cost robot, schools can buy more units, thus giving the students the opportunity to get hands on the robots and work with them.

1.3 Objectives of the Research

The objectives of this research are stated below;

1. To develop the kinematics for the 6-DOF industrial robot for teaching and learning.
2. To fabricate the robotic arm using additive manufacturing technology equipped with controller system.
3. To control the robotic arm using the Arduino microcontroller.

1.4 Scope of the Research

This research project is limited only to the kinematic modelling of the joints to obtain the position of the gripper or end-effector. The dynamic modelling to obtain forces and torques is not included. The electronics components that have been used are off-the-shelf (OTS) components which can be obtained from any electronics shop.

1.5 Report Organization

This report is divided into six (6) chapters. Chapter one introduces the projects by giving concise information of what is expected in the coming chapters. The objectives and scope of the project are listed under this chapter. In chapter two, a literature review of previous works that are directly and indirectly related to this project is presented. The major areas that were given preference in the literature review are; Industrial robots, Additive manufacturing (3D printing precisely), and Robot education. Other areas that were also reviewed are; Robots kinematics and Robot programming. The methodology used in developing the robot and also in the programming is described in chapter three. The mathematical computation of the kinematics and the printing of the robot are featured in this chapter. Chapter four comprises the experiments conducted, and the results obtained. Here the finished project is implemented. The results obtained in chapter four are discussed in this chapter. The conclusion of the project and recommendations for future works are given all in chapter five. This is the final chapter of the project.

CHAPTER 2: LITERATURE REVIEW

2.1 Industrial Robots/Robotic Arm

The origin of most robots we see in all areas today dates back to the early industrial robots designs. Much of the technological advancement that has made robots more friendly to humans and adaptable for wide variety of applications came as a result of the manufacturing of industrial robots. Industrial robots take the largest share in terms of the commercial applications of robotics technology in recent times. All the important fundamentals related to the control of robot germinated with the development of industrial applications in mind. Giving these applications special attention is of paramount importance if we are to understand the origin of robotics science. That will make us appreciate many unsolved problems that prevented and is still preventing the wider use of robots in manufacturing. An overview of robots is given in figure 2.1. The first sets of robots were the stationary industrial robots with little or no intelligence. They were equipped with CNC machines and used in production. Over the years, several improvements have taken place to revolutionize the robotic industry. Today we have intelligent robots that are capable of sensing a phenomenon and perform the appropriate task to change that phenomenon. Today's robots are equipped with sensors, actuators, and other high order electronics and computer interfaces.

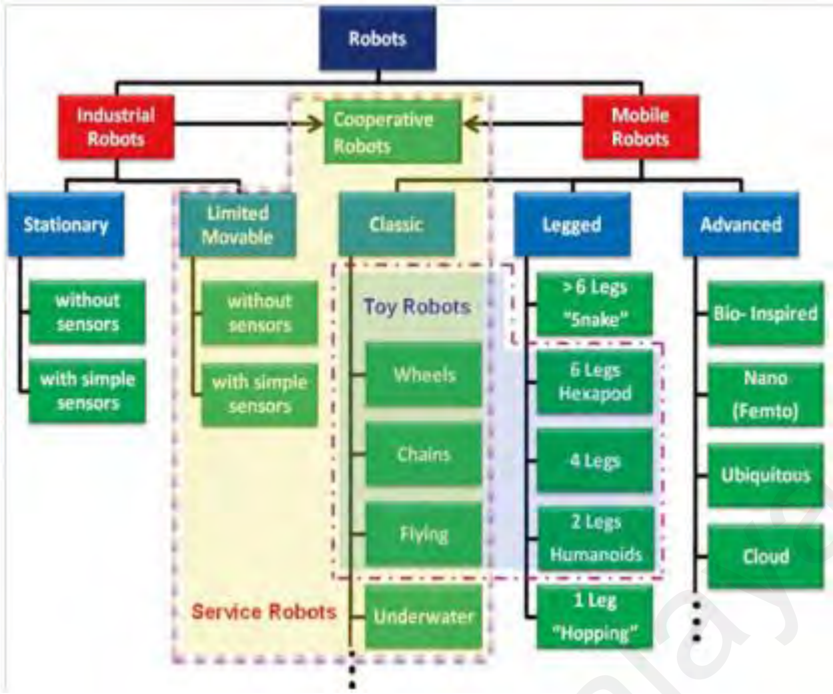


Figure 2. 1; Overview of Robots (Source;(Linert & Kopacek, 2016))

The trend in the manufacturing industry today is that most of these industries are replacing most of the jobs that were previously done by humans with robots. Such jobs are those of high labour cost and low productivity. Examples of these jobs ranging from unsafe jobs like lifting of heavy parts, spot welding, loading and unloading, to jobs requiring great degree of speed and accuracy or both, like inserting parts in a printed circuit board (PCB), painting, and continuous welding.

An industrial robot is the one having the above described characteristics but is made to be used mostly in the factory environment for the purpose of manufacturing. Typical areas where industrial robots are used include; assembly, painting, welding, inspection, ironing, pick and place, to mention only a few. The level of speed, precision and endurance is quite high. Figure 2.2 shows industrial robots being used for different applications in the factory.

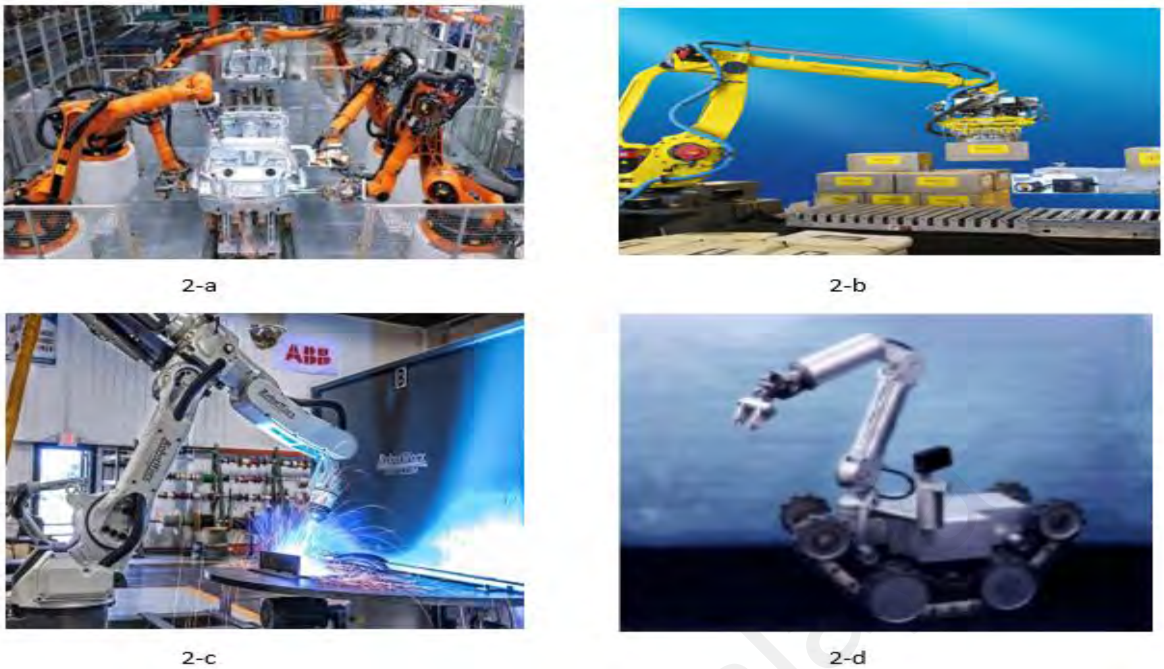


Figure 2. 2; Industrial robots in use for different applications

Industrial robots are regarded as the fundamental of competitive manufacturing, which has the sole aim of combining quality, high productivity, and adaptability at minimal cost. It was reported in 2007 that more than one million industrial robots were installed, with automotive industries taking the lead in usage with involvement of more than 60% (The International Federation of Robotics, 2007). Nevertheless, high-growth industries (in electronics, life sciences, food, solar cells, and logistics) and emerging manufacturing processes (coating, gluing, precision assembly, laser-based processes, etc.) will continuously depend on advanced robot technology. As reported by (Michael et al., 2012), industrial robots play a significant role in high degree automation and aids in the reproduction of parts in an economical way due to its speed and precision(Aburaia, Markl, & Stuja, 2015). In order to meet the industrial demand of capable robot engineers and also close the gap between practical applications and theory, there is an imminent need to produce students who are both competent in the theoretical and practical aspect of robotic (Michael et al., 2012).

National and International standards are now being used to define safety precautions and to quantify robot performance, define geometry, and media interfaces. Most robots are operated within enclosed and secure barriers to keep people out of harm's way at a safe distance. Recently, human–robot can directly collaborate due to improved safety standards, creating an avenue for human factory workers and robots to share the same workspace.

A robotic arm can either be a serial or parallel manipulator. Serial manipulators stand out to be the most common kinds of industrial robots. They are designed in a kinematic chain-like structure having series of links connected by motor-actuated joints that runs from a base to an end-effector. This connection qualifies them as being a kinematic chain. A kinematic chain can be either an open-loop or a closed-loop chain. Often, their structure is similar to an anthropomorphic arm structure described as having a "shoulder", an "elbow", and a "wrist". With these mentioned features, it is clear that the industrial serial robot is similar to the human hand. This is where it derived its name as the robotic arm. In this text, industrial serial robot and robotic arm will be used interchangeably. The number of joints in a robotic arm can be from three to six depending on the manipulation that is required. For an object to be placed in an arbitrary position and orientation in the workspace, a robotic arm will usually have six joints, which translates into six degrees of freedom (Wikipedia., 2018). The upper part of the assistive robot in the work of (Mohamed & Capi, 2012) consisted of a 6-DOF arm on each side of the humanoid robot.

On the other side, a parallel manipulator which is a close rival of the serial manipulator is a mechanical system that uses several computer-controlled serial chains to support a single platform, or end-effector. It is possible that the best known parallel manipulator is formed from six linear actuators which are meant to support a movable base for devices such as flight simulators. Due to their closed-chain configuration, they have a high stiffness and a superior dynamics performance. Among the available types of parallel manipulators, the most commonly used type for high-speed pick-and-place tasks is the Delta-type robots. They are also useful in medical-assistance positioning applications. Parallel robots have some advantages over the serial robots, some of which advantages are high rigidity, low weight and the ability to handle loads greater than its own weight. Besides, parallel robots features some downsides which include; link interlocking and limited workspace (Amogh, Aditya, & Rajeevlochana, 2018).

2.1.1 Components of a Robotic arm

The robotic arm just like every other robot has five (5) basic components which are; controller, manipulator, end-effector, drives, and sensors. In other articles, the power supply is also considered as being part of the components. The controller which is made of silicon chip serves as the brain of the robotic arm. It is the CPU where all the commands needed to control the actuators are generated. The manipulator is the actual arm which comprises the shoulder, wrist and the elbow. To one end of the manipulator is the base, and to the other end is the end effector. The manipulator makes it possible for the arm to carry out tasks. The end effector performs the actual task as it is synonymous to the human hand. Some end effectors are made in such a way that they can accommodate various kinds of tools. The drive system mainly comprises the actuators while the sensors are used for detection. The sensors and drive system are mutually dependent in their actions (Adamu, 2018).

2.1.2 Classification of robotic arm

There are quite a number of ways in which the industrial robots can be classified which may be dependent on the type of configuration of the arms, the drive system, the type of jobs they perform, kinematic structure, (Tsai, 1999) or even their size. Some robots do not fit into any of the mentioned categories, thus classifying them create some level of confusion.

Based on the configuration, a robotic arm can be rectangular where the movements are strictly linear. It is cylindrical if the base rotates only about the vertical axis and the other parts are only allowed linear movements. A spherical robotic arm is an upgrade over the where the base has two degrees of rotation combined with the linear rotation of the arms. The final classification based on the configuration is the articulated robotic arm which is a specialized type. It has three large axes and three small axes for a 6-DOF robot. It is capable of performing motion in every direction with little or no restriction. Figure 2.3 shows the classification of robots based on their configurations.

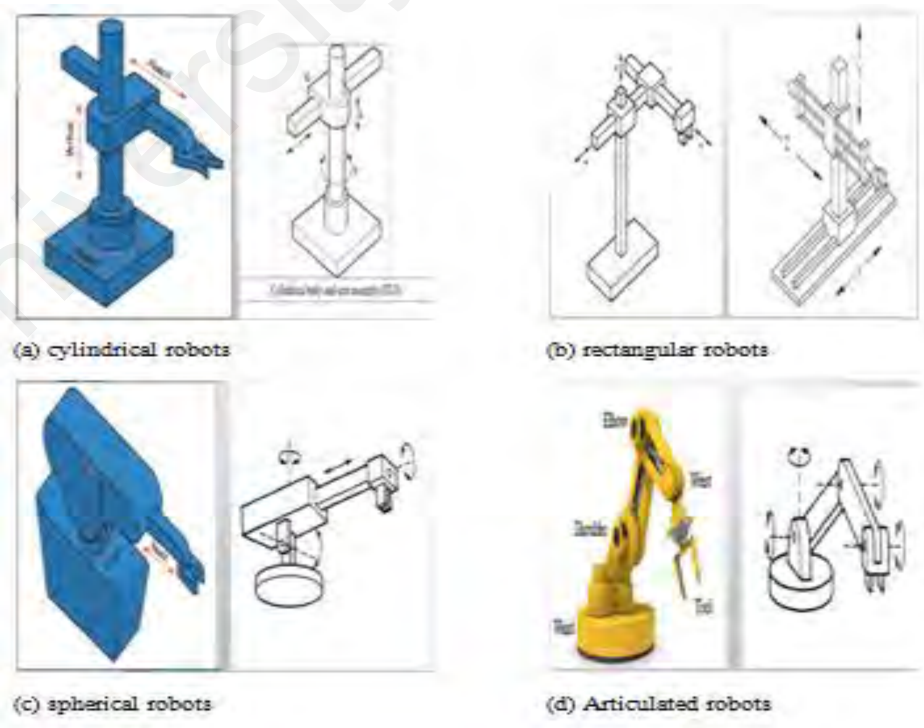


Figure 2. 3; classification of industrial robots

Other classification methods are rarely used. Size is one of those, where a robotic arm can be classified as either a small, medium or large arm. The last but not the least type of classification is the drive system. A robotic arm can be driven in different ways from hydraulic, pneumatic, to electrical drive systems (Adamu, 2018).

2.2 Application of Robotic Arm

Industrial robots find their usage more extensively in the manufacturing industries (Amogh et al., 2018). As the usage of robots in all works of life keeps increasing, researches are being conducted on a daily basis to see how these robots can be build with optimum safety, comfort, and efficiency so that human and other animals alike can make use of these machines without much fear. Poor safety and comfort can lead to severe casualties. Robots are now heavily used in automobile, aerospace, medical, agricultural, and other industries. Some of them are used in homes for domestic purposes. One of such areas where robots are being put to use is in assisting the elderly people who are weak and can no longer perform some of the tasks they used to. to this course, (Mohamed & Capi, 2012) developed a humanoid robot that is meant to assist the elderly people. Their robot was designed not only to help the elderly, but also to interact with people in places like homes and hospitals. In agriculture, robots perform important roles as lightening of farmer’s load and improved efficiency. Although the development of agricultural robots are still in their initial stage, (Ali & Noboru, 2016) proposed a new 5-DOF robotic arm to aid harvesting of heavy crops. Underwater exploration is not left out in the usage of robotics. The trend of equipping underwater vehicles with robotic arm is also getting plenty of attention. To this regard, a modular small-sized underwater robotic arm by (Barbieri, Bruno, Gallo, Muzzupappa, & Russo, 2018) was developed and tested. In an argument presented by (Zhang, Yan, & Zhang, 2018), they pointed out the fact that a robotic arm with 6-DOF may be extravagant for some practical industrial jobs such as pick and place, and workpiece feeding. So, they restricted their work to the design and analysis of a 3-DOF cylindrical coordinate-based-manipulator. In order to meet a small volume, low cost specifications, they used the cylindrical coordinate mechanism principle in their design. Their robot arm comprises one revolute joint and two prismatic joints. The results they obtained from their experiments were not very accurate, but they were able to prove that the 3-DOF arm and complete favourably with the 6-DOF in some easy tasks. In minimally invasive surgeries (MIS), haptic devices are being used to assist surgeons. Besides, errors in the computations or programming of these haptic devices can lead to fatal accidents.

In the area of minimally invasive surgery (MIS), Serial Haptic Master devices with large DOF have the advantages of large workspace and improved dexterity. But if the device is improperly designed, then these advantages can be a source of contributing dynamics effects and kinematic errors. Consequently, there is a high risk of damaging delicate tissues due to accidents which are likely to result from improper transmission of forces from the surgeon in the surroundings of the surgical site. Since the manipulator has to reach different points within the workspace, the kinematics of the device is greatly responsible for the efficiency of the procedure since it can help to avoid infinite motion. If the structure parameters and trajectories are poorly selected, then the errors in workspace will be imminent, all because of the presence of singular points. Consequently, the efficient transformation of energies from the joint space to the task (Cartesian) space cannot be carried out.

Some of the challenges facing the design and development of a lightweight and strong robotic arm are not far from the issues of power supply, actuators, structural parts, and power transmission.

2.3 Additive Manufacturing (3D printing)

Additive manufacturing as described in the introductory part is a technology that is gaining wide acceptance in the manufacturing industry. New applications are seriously taking advantage of this technology. Meanwhile, the pace at which these applications are growing creates a rather wide gap between the education and skills development, as shown by several published work on additive manufacturing and 3D printing. This gap could hinder adoption if the 3D printing technology. With limited number of review to address this problem, especially in the area of teaching and learning, (Ford & Minshall, 2019) brought several dispersed researches together to come up with an all-encompassing invited literature review to address the problem. Their focus was on where and how 3D printing is being used and can be used in the educational system. Taking schools, universities, and libraries into consideration, their review, the areas where 3D printing can be of importance were categorized into six. They include; teaching students, teaching teachers/instructors, using it as a support technology, supporting outreach activities, making artefacts that will aid learning, and finally in creating assistive technologies. It comes with numerous advantages such as complex parts creation, among others. Advantages of additive manufacturing over the traditional manufacturing can be found in (Attaran, 2017). However, it comes with some disadvantages of which the major ones are poor surface finish due to stepping and low dimensional accuracy. In order to try and overcome the limitations of this method, (Li et al., 2018) proposed a hybrid additive-subtractive manufacturing process using a 6-DOF robot arm which is equipped with several changeable heads and integrated manufacturing platform. Form their results, they were able to improve the surface quality, reduce the production time and most importantly eliminate the need for a support structure. The last improvement was possible because of the flexibility of the 6-DOF robotic arm. The robot arm and the gripper designs in (Barbieri et al., 2018) also took advantage and made heavy use of additive manufacturing technique (3D printing). Another form of 3D printing using inkjet technology was implored by (Schreiber, Manns, & Morales, 2019) to design a soft gripper which will almost serve as a universal gripper. This is possible because their design could be used to handle materials of unforeseen geometry by compliantly deforming to the required geometry. By limiting to a small budget, (Gutierrez S.C. & Meseguer, 2017) designed and manufactured a lightweight robotic arm using a 3D printing technology.

Some of the disadvantages of 3D printing include health and safety of the operator due to the fumes produced by the filaments (with that of ABS being more than PLA), high cost of consumables for those with limited budget, intellectual property (IP) concerns. But, with the expiration of the last major patent in 2009, the danger of infringing on IP went down and more printers have hit the market since then. This brought down the prices of 3D printers. Another downside of using 3D printers is their slow nature in producing parts; this gets the user bored most times. Printers of nowadays like Prusa mk3 have a great speed improvement and the problem is being managed.

3D printing has chiefly transformed the STEM and technical education in different ways. Teaching materials produced using this technique has proven to facilitate learning in various fields of science ranging from medical science to engineering. With the growing popularity of 3D printers, spatial ability is one of the key elements one needs to have in order to comfortably handle a 3D printer. There are several other 3D modelling techniques of which the spatial ability is a subset. In this field, (Huang & Lin, 2017) attempts to develop an educational framework which is focused on improving the spatial ability of college students. They used a method referred to as CDIO (conceive, design, implement, and operate) and performed some experiments by using printed solid models to prove the validity of the framework. As the needed skills to prepare beginners for industrial expectations are gotten mostly in vocational and technical schools, (Huang & Lin, 2017) believe that making use of their CDIO method will help in achieving this goal. Teachers also stand to benefit from using this framework, which by extension will raise learning efficacy and also innovative thinking.

2.3.1 Areas where 3D printing has helped education

Quite a number of researches have demonstrated how the 3D printing technology has benefited the educational system. Students' interest and engagement have increased, creativities are being inspired, skills are being developed, and learning is becoming more interesting. Feedbacks from students who have experienced the use of 3D printers supports the previous claim. Enthusiastic students take photos of made parts to show friends and parents which gets other kids motivated and join the 3D printing class. The four pedagogical environments where 3D printing is being used include; schools, universities, special education settings, and libraries (Ford & Minshall, 2019). Because literatures covering the use of 3D printing in primary and middle schools are few(Ford & Minshall, 2019), schools in this subsection will be used to generalise primary, secondary and high schools for the purpose of simplicity.

In schools (Ford & Minshall, 2019), engineering projects involving design and development (e.g design of prosthetic hands, gears, mechanical systems, etc) have shaped the way the students think. Their understanding of science and mathematics is being improved coupled with development of skills in creativity. However, it should be noted that students may be faced with vices that will make them lose interest in projects using 3D printing. Some of the problems can arise from fatigue, mental tiredness, frequent panic, and frustration. Frustration can result of the product not working as expected and poor experiment environment. Outreach activities bringing together students from all educational levels have been reported in many publications. These outreach programmes running from days into weeks task the participants with using 3D printers to build robots and other similar projects. Training of educators and workshops are encouraged by (Ford & Minshall, 2019) in order to prepare school teachers for the technology. This will reduce too much reliance of school children on outreach programmes and schools will then have 3D printing incorporated into their curriculum.

In universities (Ford & Minshall, 2019), Mechatronics projects involving students building a RepRap 3D printer have been carried out. The students then download and fabricate different 3D models afterwards. In some cases, 3D printing has been used to introduce masters students of industrial engineering to additive manufacturing. Business students also benefit from this. Other significant areas are where the 3D printers are used to create models to facilitate lab and classroom learning. Elsewhere, Masters students have used 3D printed part in fan and turbo compressor experiments while capstone students in aerospace engineering have created wing spoilers with it. Anatomy, chemistry, and history students have gained more understanding of courses by using printed parts to aid learning. Artefacts, bones, and others printed specimens are cheaper than the real ones and be studied just like the original ones. Students have nevertheless argued that even though these printed parts support learning, they cannot replace the original specimens. (Ford & Minshall, 2019) concluded that the universities are the highest users of the 3D printing technologies and promising fields are spanning from it.

3D printing technology has found its way into the world special education as it has served well in creating parts used for cognitive, visual and motor experiments. Nevertheless, there are reported cases of students losing interest due to hard to complete tasks, and insufficient time. Therapists also are having hard time accepting the technology as they feel they should be consumers of the work rather than being givers of the knowledge.

In teaching robotics, 3D printers have served well as they have been wonderfully used to produce the chassis of low-cost haptic devices and educational robots. Students have had the opportunity to modify robotic designs and have them printed using the 3D printers. It is stated (Ford & Minshall, 2019) that the areas that make heavy use of the technology are Mechatronics engineering and STEM subjects. In projects, Mechatronics students make use of 3D printing to build part or the entire skeleton of their robots. Students also showcase their ideas by modifying and sharing their robots design among friends and course mates.

Due to the novelty of this technology, teachers do not have much upper hand than the students as there is only few published work in this area. So both teachers and students are left at the mercy of internet sources which are more up-to-date and accurate than the publications(Ford & Minshall, 2019). What this means in essence is that the teachers learn alongside the students which places him on the pedestal of a mentor than a leader. 3D printing technology does not come with specific programme packages for many teachers who do not really understand engineering or how engineering works, making it an area that needs to be torch lighted. As 3D printing creates an avenue to harmonize students from different technical background, educators find it challenging to handle the students. This is because the instructors will need to adapt to the various needs of different students which proves difficult. One of the methods that has proven successful in tackling this issue is grouping students of complementary backgrounds together. And this has generated projects with novel results.

On a final note, additive manufacturing is not expected to fully replace the existing traditional manufacturing methods. However, it will help revolutionize the manufacturing industry when it is coupled with the traditional method (Attaran, 2017).

2.4 Robot Education

Robotics being an exceptional engineering science that covers the design, modelling, and controlling of robots, is swiftly taking charge of the routine of peoples' daily lives today (Raza, Khan, & Abbas, 2018). Robots these days go from industrial to education, to medical sciences, to military, to space exploration, and other numerous fields.

The introduction of robotics into the educational system has really gone a long way to show how students can learn faster when they use an actual tool to support the theories they learn in class. However, it is at its initial stage of development and the application it yet to be fully efficient(Ospennikova et al., 2015). In order to fully engage students of science, technology, engineering, and mathematics (STEM), robotics education has shown great prospects in attracting the interest of researchers, teachers, and students alike from kindergarten up to university level over the past few years (Xia & Zhong, 2018). Some studies have suggested that using robots in schools could improve the science literacy in students (Shih & Chen, 2013). Robotics is also believed to created opportunities for primary school pupils to develop language skills in addition to the technical skills (Scaradozzi, Sorbi, Pedale, Valzano, & Vergine, 2015). Opinions of (Gomoll, Hmelo-Silver, Šabanović, & Francisco, 2016) and (Master, Cheryan, Moscatelli, & Meltzoff, 2017) show particularly that the interest and self-efficacy of girl students will be boosted through robotic education. Another review (Benitti, 2012) showed the potentials of using robotics as an educational tool. This will help students get a better understanding of STEM concepts as seen in his results. At higher levels of learning, (Raffaele, Riccardo, & Claudio, 2014) suggests that teaching activities be organised in such a way that not only the basic knowledge of robotics will be learnt, but also advanced skills of automation and control software. Advancements in the field of robotics place high demand of well trained and skilful graduates who will handle such technologies (Manzoor, Ul Islam, Khalid, Samad, & Iqbal, 2014). To this regard, a 5-DOF SCARA robot was developed by (da S. Neto, de Mendonça, & de Sena, 2015) which is meant as a teaching tool. Their goal was for the robot to be implemented in stock organization which is a branch of accounting. The standard SCARA robot comes with 4DOF; however, they were able to add a horizontal linear prismatic joint which brought about the fifth axis in their design. In another work (Manzoor et al., 2014), a robotic framework was presented for training, vocational, and academic purposes. The framework aids the proper understanding of robot manipulators. Their work was focused on a 6-DOF robotic arm. The arm was equipped with cameras and sensors. They demonstrated the efficacy of their proposed platform by conducting two experiments. Moreover, FASTBot robot trainer was used as a tool to create awareness for school children and to also train them components of robotics like sensors, Mechatronics, embedded systems etc (Balaji, Balaji, Chandrasekaran, khan, & Elamvazuthi, 2015). This they believe will guide the students in choosing a career path. A description of how the field of wheel mobile robots have evolved is given in (Zdesar, Saso, & Gregor, 2017), targeted on the masters programme offered in their university. Their effort was to balance the inductive and traditional teaching methods by presenting the challengers facing the duo. They presented works that argued how the inductive learning (which involves giving students a particular task and allowing them freedom to seek for answers) is better than the traditional learning (which involves teaching the basics before giving students tasks to perform). The results showed that inductive learning aids better retention of what is taught as against the traditional learning. Through project-based learning, students have acquired working skills, robot design knowledge, and application of theoretical knowledge (Timo, Jari, Petro, & Tiusanen, 2011). In the competitions, students from agric based courses designed the chassis of the robots while automation-based students handled the programming aspects.

There are so many ways robots can benefit the educational system. Yet, it still remains a mystery to many researchers and educators how these robots can actually be of benefit to the system (Cheng, Sun, & Chen, 2018). To unravel the mystery, (Cheng et al., 2018) carried out a study which highlights the essential areas where robots can be of benefit to the educational system. Using three approaches, they investigated the educational system at all levels to find out their requirements as per robots. Five main areas were discovered to be the essential areas where the robots should be deployed and used. They include; robotics education, language education, teaching assistant, guided learning through feedback, and social skill development and special education. By collecting data through the three approaches they adopted, they came up with six users' group covering all ages. The results they obtained were further categorized into 14 general areas where direct application of robots is involved. More details in (Cheng et al., 2018). The major area of interest for this project is the application of robots in robotics education. From the findings of (Cheng et al., 2018), educational robotics was the second most important area where robots can be deployed. Figure 2.4 clearly shows this point. In terms of actual usage, educational robotics has the highest number of users cutting across all ages with high schools and colleges having more engagement than other groups. Figure 2.5 explains more.

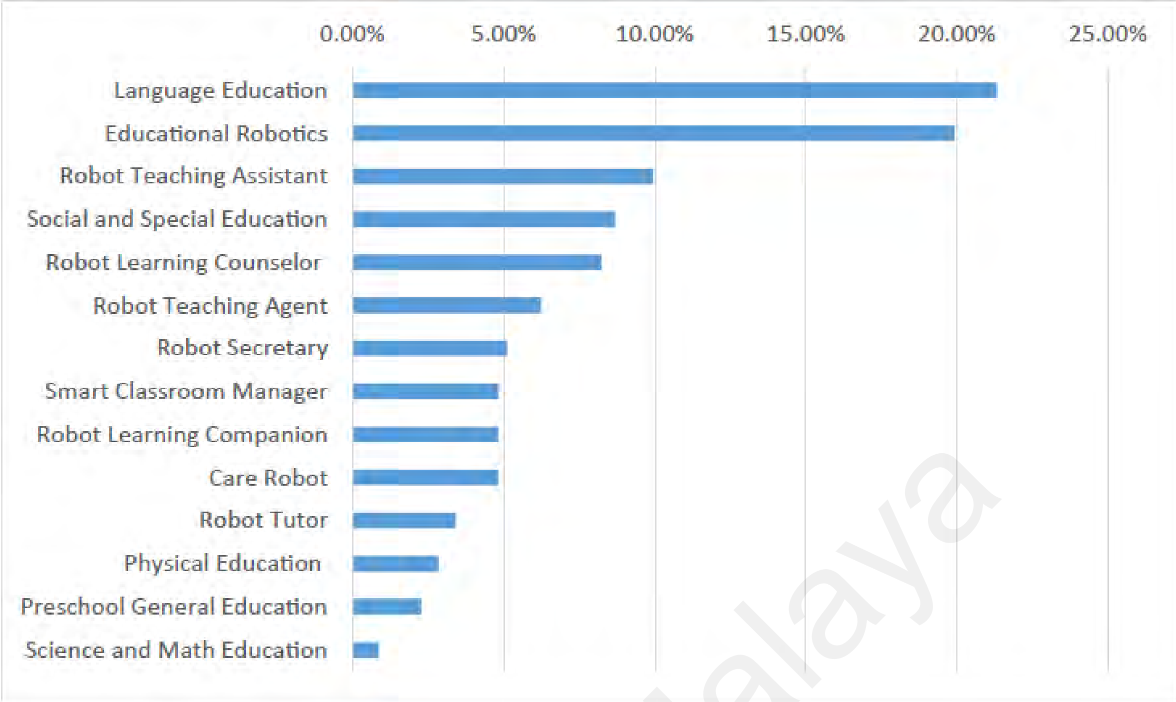


Figure 2. 4; The ranking list of the 14 general applications (source; (Cheng et al., 2018))

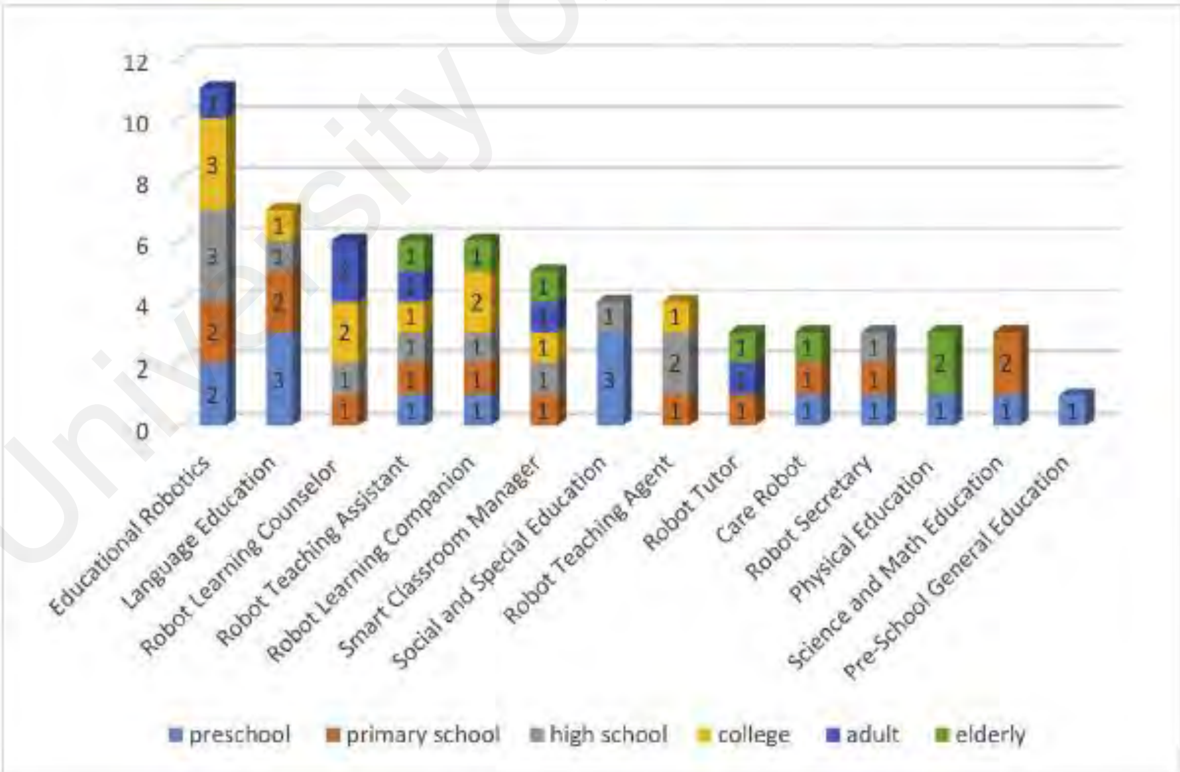


Figure 2. 5; The ranking list of the 14 categories across the six age groups (Cheng et al., 2018)

2.4.1 Creativity in Robotics

They technical creativity of students is being developed by involving robots in the educational system. There is more to robotics than just robotics as pointed out by (Linert & Kopacek, 2016), they believe robotics is more about creativity and challenging one's creative ability. The technical environment of the modern world is being transformed through innovation, thus these technical changes needs to be visible in student educational content(Ospennikova et al., 2015). The results of their review (Xia & Zhong, 2018) also supports the fact that robotics education can improve students' STEM knowledge, skills, and attitudes. Furthermore, (Scaradozzi et al., 2015) have registered improvement of teachers and primary school pupils after implementing the robotics course in the curricula. Curiosity by pupils coupled with enthusiasm of teachers has made them work together, build and program robots in groups, and develop problem solving skills. This is mostly achieved through project-based leaning and competitions. However, (Zdesar et al., 2017) argued that when students are taking several courses together with the project-based learning, the project might become boring due to time constraints. Also, (Timo et al., 2011) suggested that students should not be allowed too much freedom as this lowers motivation and decreases learning experience due to disorientation.

2.4.2 Some Regions of Active Robotic Education

Looking at Russia, (Ospennikova et al., 2015) stated that the interest and creativity of students learning robotics has been on the increase since 2009 even though robotics education has been on for two decades now. Several published works of teachers, research specialists, engineers, and pedagogues of education all show how robotics education has been engulfed in the school education. In Finland, (Timo et al., 2011) through a field robot competitions have shown how robots education can be enhanced through competitions. With detailed specifications to work on agricultural fields, students' teams from different schools have built robots from scratch to carry out field operations. A number of 44 students have so far benefitted from this programme (Timo et al., 2011). Another research which supports the view that competition plays an important role in robotics education is (Akagi et al., 2015). At the university of Bologna, Masters students taking automation were introduced to learning how to write efficient code and also gain knowledge of mobile robots using LEGO mindstorms Kits (Raffaele et al., 2014). Collaborations between universities and lower schools in Russia have been reported (Sergey, Natalia, Ilya, & Alexander, 2017b) where the two institutions are brought together in order to share ideas and learn robotic skills. Students taking bachelor programs at St. Petersburg State University and high school students of St. Petersburg Phys&Maths Lyceum have been reported in this aspect (Sergey, Natalia, Ilya, & Alexander, 2017a). The academic curriculum is so tight that students can't learn all they need in a robotic course, so supplementary courses are offered during the summer period. One of such programmes are Robocamp as reported in (Sergey et al., 2017b). University students taking engineering courses are also advised to take teacher lessons as they will make better robotics teachers. In Italy, robotics is being introduced into the primary curricula (Scaradozzi et al., 2015) which give the teachers the opportunity to be trained. They then pass the acquired knowledge and skills over to their students whom have shown positive improvements in area of collaboration and teamwork. Malaysia is not left out in the interest burst of robotics education as a curriculum to include robotics into the Malaysian schools was developed (Ramli, Yunus, & Ishak, 2011). They held a three weeks program which provided students with hands-on experience on how to build simple robots from known platforms. In the program which was sponsored by the Malaysian government, students were selected from all over the country via an IQ test which was conducted at UKM.

2.4.3 Some Selected Views on Robot Education

(Ospennikova et al., 2015) points out that in order to prepare modern graduates for the rapidly changing environment, three objectives needed to be achieved which are; updating the content of polytechnic education so that it reflects robotics technology, introduce courses that will prepare students for robot manufacturing, and creating better awareness to the consumers of these robots by carrying out of proper training. (Ospennikova et al., 2015) argue that in robotics educations, interdisciplinary projects should be in the top important trends. (Ramli et al., 2011) believe learning robotics school children will develop critical thinking skills which is vital for the future generation of scientists and engineers. They also concluded that experiments and competitions for students, and training and workshops for teachers will go a long way in increasing the interest of school children in robotics, readiness to take up robotics subjects and enrich them with the mastery of the robotics area when they finally graduate. (Manzoor et al., 2014) resolved that their platform will be of great importance in teaching courses like robotics and others. In a systematic review which was aimed at reviewing empirical studies of K-12 robotics knowledge(Xia & Zhong, 2018), 22 journal papers were used to check how rich in content the robotics was for teaching and learning. They discovered that most of the elementary schools used LEGO robots for their practical sessions, and the time allocated for these sessions were in most cases less than two month. They also discovered that 50 percent of the papers conducted non-empirical works.

2.4.4 Robotics In School Curriculum

There are three major areas where robots can serve in educating of students: it can serve as a tool for cognition, as an object of study, and as a means of developing and tutoring(Ospennikova et al., 2015). By conducting experiments and modelling of robots, the cognitive ability of students will become stronger. Using robots as an object of study will entail developing modules that will teach students the basic and advanced knowledge of robots which will include areas like the history of robotics, the types and components of a robotic system, the various applications and the programming and control of robots among other things. Finally, as a means of teaching students, robotics being a multidisciplinary subject will force the students to acquire knowledge in fields that are different from the ones they are taking. This is made possible by working together with other students as teams which also boosts their confidence. Increasing the number of experiment and the duration for these experiment was the proposition made by(Xia & Zhong, 2018) in order to help students retain and easily remember what they have learnt from the robotics class. They believed it this will also aid the transfer of knowledge. Based on experience, (Timo et al., 2011) stated that robot competitions organized for students places more demands on the teachers than on the students. To help STEM teachers develop robotic lessons easily, (Kim et al., 2015) conducted an investigation which was focussed on pre-service STEM teachers. Their investigation was to unravel how teachers understand, engage, and use robots in teaching. They pointed out that majority of teachers are not prepared to use robotics in teaching, and most of them don't even recognise the benefit of educational robotics. So they suggested that teacher's interest and confidence should be important ingredients after the knowledge of the robotics education. As suggested by (Ford & Minshall, 2019), inputting the 3D printing into school curriculum will encourage innovation, experimentations, entrepreneurship, facilitation of multi-disciplinary approaches, and integration of technical knowledge.

2.5 Kinematic Modelling

It is a fact that kinematic modelling is one of the essential parts of robot analysis, if not the most important part. Kinematic analysis can be traced back to physics as a component of motion analysis which deals with the motion only without considering the forces causing the motion (Sugiarto & Conradt, 2017). Kinematic analysis which is concerned with how joints variable of a given manipulator is obtained is divided into two parts namely; direct (forward) and inverse kinematics. While inverse kinematics deals with finding joint values which will bring the end-effector to a desired position and orientation, direct kinematics on the other hand is used to find the position of the end-effector assuming the joint values are known beforehand (Tsai, 1999). The preceding explanation on direct and inverse kinematics can also be found in (Mark, Seth, & Vidyasagar, 2006). The derivative of these joint values can also be calculated in order to give the joint velocities. Direct kinematics is quite easy to calculate, whereas the inverse kinematic can be really complicated. Many methods for computing the kinematics of a robot manipulator have been proposed in several researches. But the most commonly used methods are; Denavit and Hartenberg method (which uses a 4 x 4 matrix method), geometric method, vector algebra method, screw algebra method, quaternion method, and 3x3 dual matrix method. Some of the mentioned methods adopt analytical approach while others adopt the numerical approach.

It has been argued that most of the proposed method are rather complex mathematically and do not have enough intuitive information on how to express geometrical meanings of kinematics (An et al., 2017). So, a different approach to the exact solution was proposed by them which was derived on the basis of screw theory. They have claimed that their method could be used on different robotic arms after successfully testing it on two separate industrial manipulators. Combining geometrical intuition with kinematic analysis will create a good and simple background for design of mechanisms and motion planning. A structural parameter identification method based on the DH method was proposed in (Gao, Sun, Na, Guo, & Wu, 2018) to bring down the non-predictive movements in robotic arms. They implemented their design on a 6-DOF robotic arm. In (Sugiarto & Conradt, 2017), a generic model for modelling robot kinematics was developed based on the factor graphs. Their model is applicable to robotic arms as well as mobile robots, and the validity of the model was tested on two fundamental robotic models.

The following subsections will highlight some works where the forward and inverse kinematics have been employed in the modelling of robots.

2.5.1 Forward Kinematics

(Mohamed & Capi, 2012) also used the DH convention to model the forward kinematics of their robots while for the inverse kinematics, they employed the geometrical method. The forward kinematics of the 5-DOF robotic arm by (Ali & Noboru, 2016) was also modelled using the DH method. The DH convention has also been adopted by (Barbieri et al., 2018) in their work of the underwater robot. Irrespective of the fact that some authors don't state the method they used in their forward kinematic analysis, going through their shows clearly that they made heavy use of the DH convention. Also for the reason of its adaptability for multi-link robotic arms, (Manzoor et al., 2014) adopted the DH method in computing the direct kinematics for their model. A robot simulator (Amogh et al., 2018) was developed by making use of the DH convention and applying them on CAD files.

2.5.2 Inverse Kinematics

One of the big problems facing the kinematic modelling of robotic arms has been the inverse kinematics(Springer, 2008). A successful control or manipulation of a robotic arm is only possible with a good inverse kinematics. The actuators will be in the joint space while the actual task to be performed will be in the Cartesian space. (Xu et al., 2019) argue that the classical methods are not sufficient for computing the inverse kinematics of modern robots that are adaptable to unstructured environment due to their redundancies. Numerical method is sometimes used but come with high computational errors while analytical method has limited usage. The inverse kinematics method used by (Manzoor et al., 2014) is similar to the geometrical analytical method although it was not clearly stated. Inverse kinematics results obtained using the RoboAnalyzer software (Raza et al., 2018) have been used to design an optimized arm for an industrial robot. After obtaining, the optimization was done using CAD models and FEA software. While considering three sub-problem with different rotational orientations, a novel inverse kinematics model based on the screw theory was presented in (Xu et al., 2019). The subject robot for their model was a 4-DOF manipulator, although they were able to test the model on six and eight degree of freedom robot manipulators. Screw theory they say can provide global description of robotic arm, which is an advantage over the DH method's singularity problem. With improved computational efficiency, general applicability, and calculation accuracy, the (Xu et al., 2019) model being a hybrid model can successfully obstacle avoidance and trajectory planning problems. Another novel work which is aimed at avoiding singularity and joint limit problem was presented (Faria, Ferreira, Erlhagen, Monteiro, & Bicho, 2018). This position-based method kinematics which takes in two parameters (arm angle and global configuration) is an algorithm which is suited for a 7-DOF serial manipulator.

2.5.3 Workspace analysis

The workspace of a robotic arm constitutes all the points that the end effector can reach in the Cartesian space. The joint parameters and the degree of freedom greatly determine what the workspace of a robotic arm will look like. With the dynamic changes in the application of robots, the workspace is now considered an important pillar in determining the performance of the robotic arm. The workspace contributes almost and much as the contributions given by the speed, accuracy and weight. Workspace analysis of a haptic device of 8-DOF consisting of four links was performed by (Iqbal & Aized, 2014). Their aim was to improve the efficiency of robots in surgical procedures by minimizing the kinematic errors encountered during manipulation. Equipped with increased dexterity and larger workspace, their improved device will avoid singularity problems.

2.6 Robot Control and Programming

The reason why industrial robots stand out against other types of machinery is mainly because of their adaptability to different tasks and programmability. So, one can conclude that robots are therefore probably the most demanding type of equipment concerning the control and software aspects (Adamu, 2018).

Robot programming has greatly moved away from being a low-level coding thing to something which is strictly based on intuition. This became the trend amongst programmers in their quest to making coding of programs easier for operators. "Robot operators are not always robot makers, and robot makers are not always the best people to program a particular task". For example, it would have been better to get a painter to program a paint robot since he is experienced in that area rather than a programmer who has no experience in painting (Adamu, 2018). Programming of robots could lead to a great deal of frustration especially if one is new to it (Kim et al., 2015). Prior experience can help alienate this emotional pressure.

General robot controllers are difficult to find. Most robot manufacturers design their custom made programme programs for their robots which are often sold as a separate device (Amogh et al., 2018). However, robot simulators have been developed by researchers and companies alike to control robotic manipulators in a virtual environment. Some commercially available ones are; RoboDK library, KUKA Sim Pro, ABB RobotStudio, etc. Having a library with more than 20 different industrial robots coupled with the fact that it is acquired for free (Amogh et al., 2018), RoboAnalyzer is another robot simulator which is widely used. The good thing about robot simulators is that they can prevent any damage to the physical robots and injury to human co-worker as errors can be seen and corrected in the simulator. Time is also saved with the simulators. (Raza et al., 2018) have also stated how the simulation of robots can help in the designing, fabricating, and inspecting robots in real working environment.

The most accepted platform for the control of robots is the LEGO MINDSTORMS (Weinberg J.B. & X., 2003). Several versions of this platform have been released over the years with the current ones being an upgrade over the previous ones. It is clearly proven in the work of (Xia & Zhong, 2018) that this platform dominates the atmosphere as long as robot education is concerned. See figure (Xia & Zhong, 2018) below. The major reason can be associated to the low budget of schools teaching robotics education. Recently, LEGO mindstorms have been greatly adopted by schools due to its computational power and low cost (Raffaele et al., 2014). The system of their proposed (Scaradozzi et al., 2015) curricula is such that students of the first two year will use the lower versions of the platform, while the last three year students will use the higher versions. They also reported cases where programs have been designed in Austin to take this platform to economically weak students to give them the chance to build 21st century skills, have access to the robotics technology, and to boost the children's' interest in science courses. Other platforms such as Robotics dream level 1, Bee-Bot, I-Cybie, and Ficsher Technik have been employed in some cases. (Master et al., 2017) developed a custom made robot for the purpose of research purpose instead of subscribing to the already available platforms. Nevertheless, the application of these platforms on a robotic arm with several degrees of freedom is not feasible enough to fulfil training requirements (Manzoor et al., 2014). They are confined to laboratory experiments and don't really relate to what is obtainable in real life practice. Another deficiency of the LEGO m packages is that it comes with a proprietary programming language and non-open robot kits (López-Rodríguez & Cuesta, 2016). It is suggested that Arduino being an open source platform stands out as a good replacement for LEGO in developing students' skills in hardware and network configuration, and high-level programming (López-Rodríguez & Cuesta, 2016). The most popularly used robotics kit in Russia as stated in (Ospennikova et al., 2015) is the LEGO MINDSTORM products. The usage of kits by Huna is also seen in some school practices. In the design of (Mohamed & Capi, 2012), the robot could be controlled using voice commands, breathe-activated command, or joystick. (Barbieri et al., 2018) performed a tele-operation in their underwater robot using the master and slave operation method. After testing their (Amogh et al., 2018) visual C custom made teach pendant application in a simulation environment, they claimed it could be used virtually control any kind of manipulator, thus, making it a generic simulation tool. The LEGO firmware which is Java based was adopted (Raffaele et al., 2014) in teaching the students how to develop structured robotic software.

Robot operating System (ROS) is a programming platform that has been in use for over a decade now. It is used to control robot manipulators and other types of robot. The steep learning curve of ROS is one of the major challenges which hinder students from implementing it in their robotics projects. This is also pointed out in (Zdesar et al., 2017). ROS is expected to reach wide users outside research environments in the near future. However, (Dieber et al., 2017) fear that ROS could be vulnerable to cyber attack, so they presented a paper which highlights the vulnerabilities of ROS and suggestions on how to solve them. They proposed and implemented security architecture on ROS. (Cheng et al., 2018). In an unrelated work, (Michael et al., 2012) uses MATLAB to design a control framework which serves as a tool for learning control of robotic systems. They demonstrated their platform on a 6-DOF robotic arm.

CHAPTER 3: METHODOLOGY

Introduction

This chapter presents the procedure that was undertaken in completing this project. Robotic model is briefly described; the equipment and materials used in building the robot are also explained. The mathematical modelling and the programming of the robotic arm is given in this chapter. Figure 3.1 is a flowchart showing the sequence of how the projected was executed.

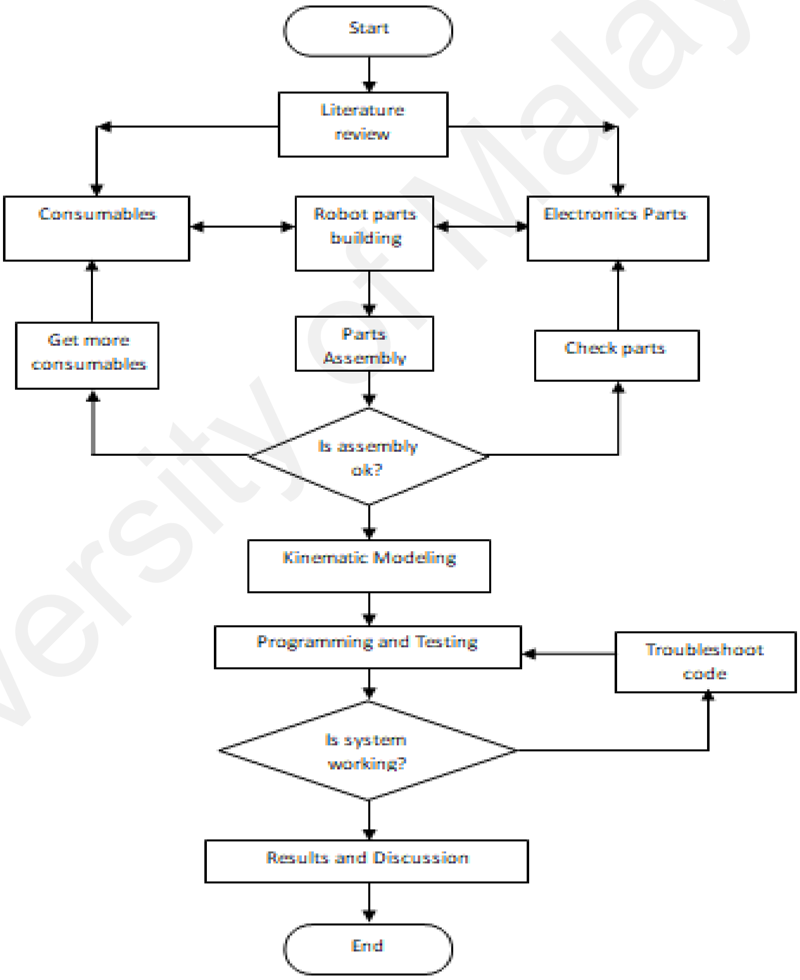


Figure 3. 1; Flowchart of the project

3.1 Robot Development

In this section, the robotic is described. The tools and equipments used in printing the robotic arm are also described. The consumables and the electronics parts used are also discussed.

3.1.1 The Robotic Arm Model

There are several design models of 6-DOF robotic arm available online. Quite a number of platforms such as thingiverse and GRABCAD make these designs available for users to either adopt or make some modifications. This has really helped innovation and sharing of ideas. The robotic arm model used in this project is from thingiverse and was designed by “wondertiger”. The robotic arm has 6-DOF including the base and the end effector (5+1 DOF) adopting the design of a standard robotic arm known as SCORBOT. The CAD model of the robot manipulator is given in figure 3.2. It consists of 35 printed parts. The non-printed parts consist of the electronics parts and fasteners. Tables for the list of parts will be provided in subchapters.

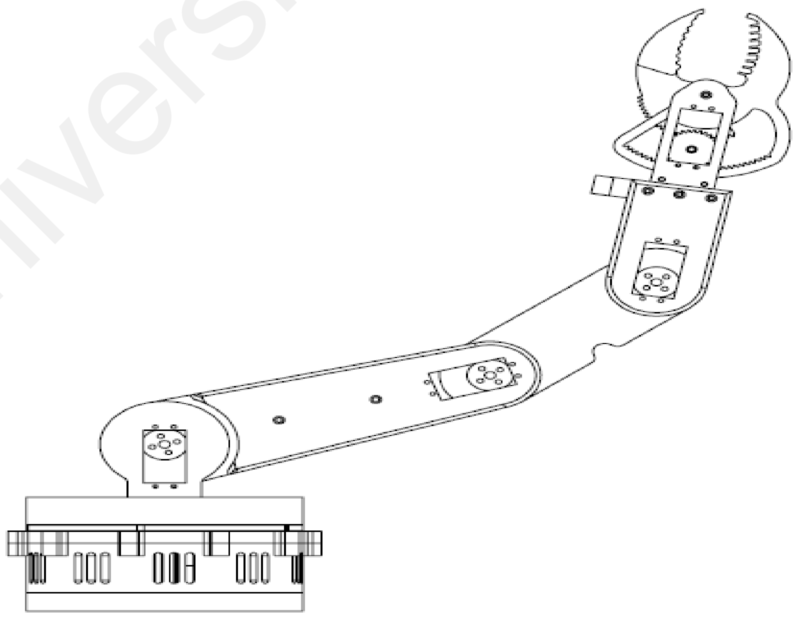


Figure 3. 2; the robotic arm model

As reported in (Xia & Zhong, 2018), the content of most robotics education researches show that about 70% is geared towards the structure and construction of the robots (see figure 3.3). Standing on this reason, it is believed that the robotic arm in this project will be used to teach students how to make their low cost robotic arm using additive manufacturing.

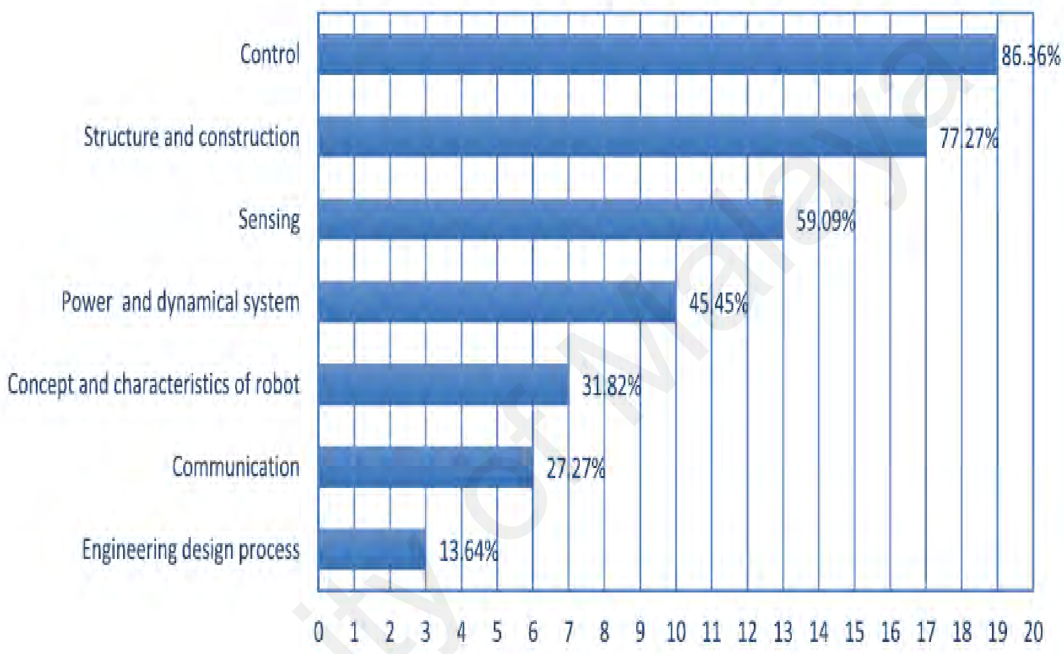


Figure 3. 3; contents of robotic education (Source;(Xia & Zhong, 2018))

3.1.2 Equipments, Software, And Materials

The equipments used for developing the robotic arm are 3D printers. Three different products of 3D printers were used to print the entire parts of the robot arm. They are; Prusa MK3, Flashforge Creator Pro, and Cr8 3D printer. The structures of the mentioned printers are shown in figure 3.4a, b, and c for Prusa, Flashforge, and cr8 respectively. In table 3.1 below, the characteristics of these printers are given.

(a) Prusa I3 Mk3 (b) Flashforge Creator Pro

(c) Cr8 3D printer

Figure 3. 4; the 3D printers that were used

Table 3. 1; features of the printers used

3D printer / Features	Prusa mk3 I3	Flashforge Creator Pro	Cr8 3D printer
1. Bed size	250x250mm	200x200mm	200x150mm
2. Nozzle size	0.5mm	0.4mm	0.4mm
3. consumable used	PLA	ABS	PLA
4. Print speed max	200mm/s	100mm/s	100mm/s
5. Quality of print	Medium	High	High

Three software were utilized in this project. The first is the SOILDWORKS software which was used in the thingiverse designs. The files in SOLIDWORKS are saved as STL files before they are further processed for printing. The STL design files needed to be converted to a format which is readable by the 3D printers. The machines are custom made to read files in .gcode format. For that reason, the two other software were used for converting the STL files to .gcodes which are readable by the printers. CURA 3D was used for both Prusa MK3 and Ceality, while the flashforge had its custom-made slicing software known as Flashprint. Figure 3.3a and b shows the usage of the CURA 3D and Flashprint respectively.

The materials used for the printing are Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) which are otherwise known as consumables. They both belong to the plastic family with PLA being thermoplastic while ABS being a thermosetting plastic. They are the most commonly used materials in 3D printing. Both materials have distinguishing properties giving one an advantage over the other. PLA has the advantages of strength and flexibility over ABS while ABS has the advantages of structural integrity and mechanical usage over PLA. The properties of the consumables are shown in table 3.2 below. The choice of which material to use depends on the working properties of the part to be built. For this project, ABS was used for parts that are either small or those that needed high precision printing like those having gear teeth. For other large parts, PLA was used because it withstands warping more than its counterpart. There is no doubt that the strength of the printed part is affected by the direction of the melted filament and the superficial melting nature. This slightly changes the expected mechanical properties from the actual ones.

Table 3. 2; properties of consumables used (ABS and PLA)

Properties	ABS	PLA
1. Young's Modulus	2.5GPa	3.5GPa
2. Density	1.4g/cm^3	1.3g/cm^3
3. printing temperature	210^{0}C to 250^{0}C	180^{0}C to 230^{0}C
4. Print bed temperature	80^{0}C to 110^{0}C	50^0 to 60^{0}C

5. Nozzle clogging	Never	Occasionally
6. Fumes	Bad and High	Little or none
7. Enclosure	Recommended	Optional
8. Elongation	3.5 – 50%	6%
9. Warping	Present in long parts	Close to no warping
10. Price*	100MYR	85MYR

* price may differ depending on the seller.

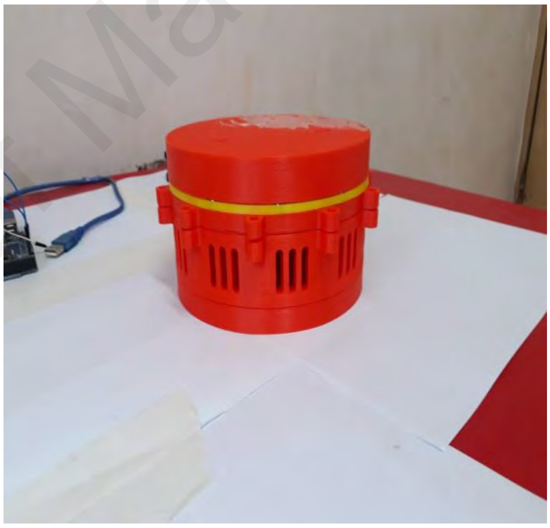
3.1.3 Printing

The robotic arm is divided into three separate components which were printed individually. They parts were finally assembled to give the robotic arm. This subsection will describe the printing of each of the components. It is worthy to note that before printing, all critical holes are oversized by 0.25mm to guarantee easy fit. In the same vein, all M3 and M4 bolt holes are undersized by 0.02mm making them 2.8mm and 3.8mm respectively.

3.1.3.1 Base

The base as the name implies serves as the base which supports the other two components (i.e arm and gripper). It is meant to have a rotation of about 330^{o}. It consists of 10 printed parts out of the 35 parts mentioned in previous section. All of the parts were printed using the Prusa MK3 printer with the exception of the gears which were printed using the flashforge printer. The cr8 3D was only used to print the rotating bearing guide. The electronics parts used in the base are; nema 17 stepper motor and a BOURNS 3590S potentiometer. Every part was printed once except for the bearing clamp which was printed twice. The images for the exploded view of the base are given in figure 3.5a and the printed parts are shown in figure 3.5b and 3.5c.

(3.5a) Images from CAD files



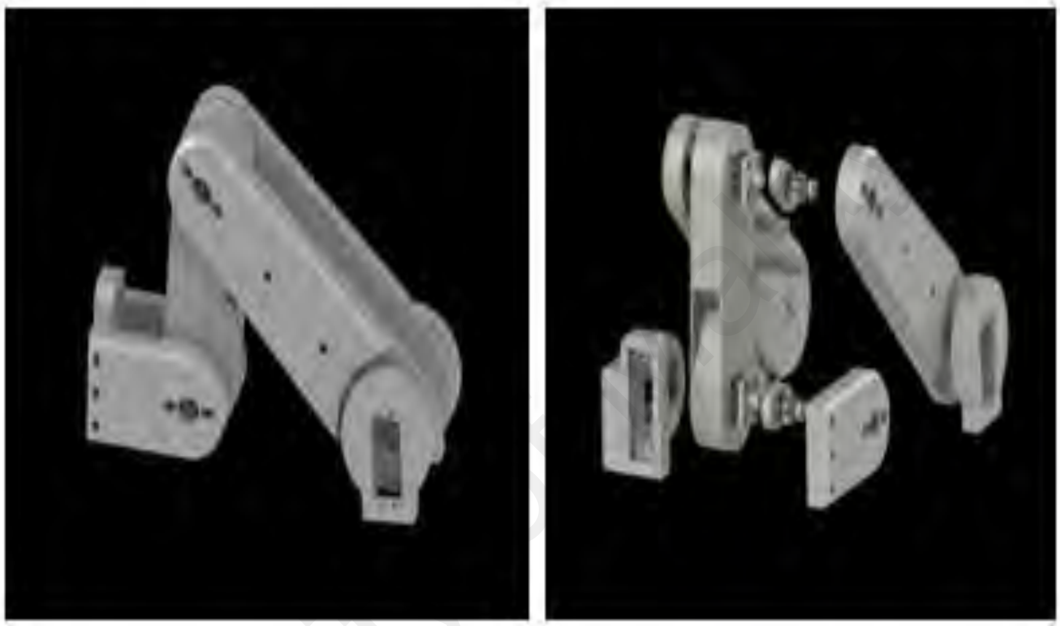
(3.5b) printed parts (3.5c) Assembled turntable

Figure 3. 5 a and b; Turntable (Base of the robot)

3.1.3.2 Arm

The arm is considered as the manipulator. It formed by links and joints which are connected in series. The arm makes it possible for the robot to reach different locations in a workspace. Consisting of the lower arm, centre arm, and upper arm, it has a total 16 printed parts. The lower and centre arms were printed using the Prusa MK3 while the upper arm was printed using the flashforge. The electronics parts used for the arm are;

(5 x MG996r) servo motors. Other hardware includes (2 x 688zz) bearings, bolts, and nuts. Parts that were printed twice are; servo mount, bearing holder, centre arm bearing guide, centre arm bearing guide clamp, and lower arm bushing. The images for the exploded view of the arm are given in figure 3.6a and the printed parts are shown in figure 3.6b and 3.6c.



(3.6a) Images from CAD files

(3.6b) printed parts- arm

(3.6c) Assembled arm

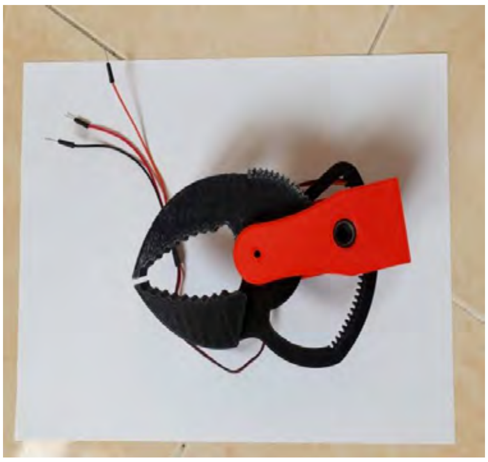
Figure 3. 6 a and b; robotic arm (manipulator)

3.1.3.3 Gripper

The gripper is the end-effector which carries out the actual task to be performed by the robot. In this design, it is assumed to have a degree of freedom. It consists of 9 printed parts. All parts having gear teeth in the gripper were printed using the flashforge while other parts were printed using the Prusa MK3. The top-bottom bearing bushing was printed twice. The electronics parts used for the gripper is 1 MG996r servo motor. The exploded view of the gripper is given in figure 3.6a and the printed parts are shown in figure 3.6b.

(3.7a) Images from CAD files

(3.7a) printed parts- gripper



(3.7b) Assembled gripper

Figure 3. 7 a and b; robotic gripper (end-effector)

3.1.4 Electronics

Designing using off-the-shelf (OTS) electronics components reduces cost but at the same time comes with difficulty in software development(Barbieri et al., 2018). Off-the-shelf components and recycled materials were used by (da S. Neto et al., 2015) in building their robot. However, they used steel instead which is quite different form this project where plastic is being used. It is suggested that low level electronics parts should be included in robotics education since they are essential parts of building a robot (Timo et al., 2011). For the above reasons and the fact that this project is for teaching and learning purpose, the electronics parts used for this project are low cost OTS electronics components that are easily accessible. They can be obtained in almost every electronics shop. Table 3.3 gives a comprehensive list of all the electronics components used for the entire project and areas where they have been put to use.

Table 3. 3; the list of electronics components used in the project

Components	Description
1. Arduino 2560	Serves as the microcontroller for the robot implementation
2. stepper motor x 1	Controls the base of the robot
3. servo motor x 6	Controls the joint angles
4. potentiometer x 1	Regulates the speed of the stepper motor
6. 12v ac-dc adaptor	Power supply for the stepper motor
7. A4988 module	Driver module to control the stepper motor
8. connecting wires (set)	Used to establish connections

3.1.5 Assembly

This serves as the final step in building the robotic arm. After printing the whole parts for individual components, they are assembled to give sub-assemblies. The base is the first sub-assembly to be coupled. The base is coupled as shown in its exploded view figure. It is worth noting that during the assembly, the potentiometer is rotated to the center (i.e 5 turns). The second sub-assembly is the arm which is also assembled as shown in its exploded view. Finally, the gripper was also assembled. These three sub-assemblies were then assembled into the complete robotic arm. The final assembly is shown in figure 3.8.

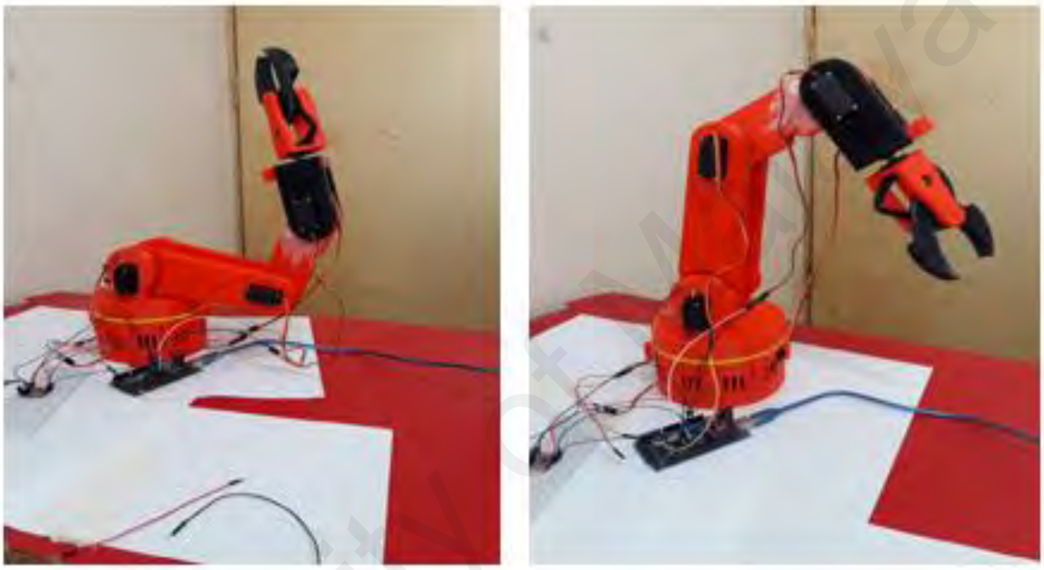


Figure 3. 8; full assembly of the robot arm

3.3 Kinematic Modelling

To fully grasp the complicated joint analysis, velocities, forces, and torques (Sergey, Natalia, Ilya, & Alexander, 2107), prior mathematical knowledge is paramount. This project will try to simplify the steps as much as possible.

There are three methods that can be used to model the kinematics of robots. Robotic arms adopt these methods. They are; analytical, numerical, and hybrid methods (combining the first two methods). In the hybrid method, the analytical method is firstly applied to compute the joint angles, and then the numerical method is applied to obtain optimal results. For a redundant manipulator, the kinematic problem can be solved by either the velocity-based or the position-based methods with the former being the standard method used. Yet it is a too difficult method due to the presence of infinite number of joints configuration. (Sugiarto & Conradt, 2017) further explains that analytical modelling makes use of standardized formulae while numerical modelling uses algorithms or learning paradigms to find optimized solutions to problems.

3.3.1 Coordinate Assignment

In this project the Denavit Hartenberg (DH) method will be adopted due to its simplicity, suitability (Tsai, 1999), and for the fact that it has been successfully used on different configurations of robotic arms. To use the DH method, Cartesian coordinates frames needs to be assigned to every joint of the robot arm. The rules governing the assignment of coordinate frame are given below;

- The z-axis is always aligned with the joint axis. The direction of rotation can be arbitrarily chosen.
- The x-axis is always assigned along a line connecting and perpendicular to two joints. The assignment starts from the trailing joint to the leading joint.
- The y-axis is obtained using the right-hand-rule.

More details on coordinate frame assignment can be found in(Mark et al., 2006) and (Tsai, 1999). The base is assigned the zeroth coordinate while the end-effector has its own system of assignment as well. Having successfully attached coordinate frames, there are four which are specially determined by the geometry of the robot axes; these parameters are a, d, α, and θ.

a; this is the distance between two joint axes. In other words, it is the length of the link.

d; this is the sliding or translational distance between two coinciding normals of a joint axis. In other words, it is the relative translation between two links.

α; this is angle between any two z-axes (adjacent to eachother) taking the x-axis as the axis of rotation.

θ; this is the angle between any two x-axes (adjacent to each other), taking the z-axis as the axis of rotation.

For every joint in a kinematic chain, three of the four parameters described above are always constant, while the fourth parameter will be dynamic depending on the joint type. For a prismatic joint, *d* will be the dynamic parameter, while for a revolute joint, θ will be the dynamic parameter. Following the previous explanation, coordinate for this project's robotic arm is shown in figure 3.9.

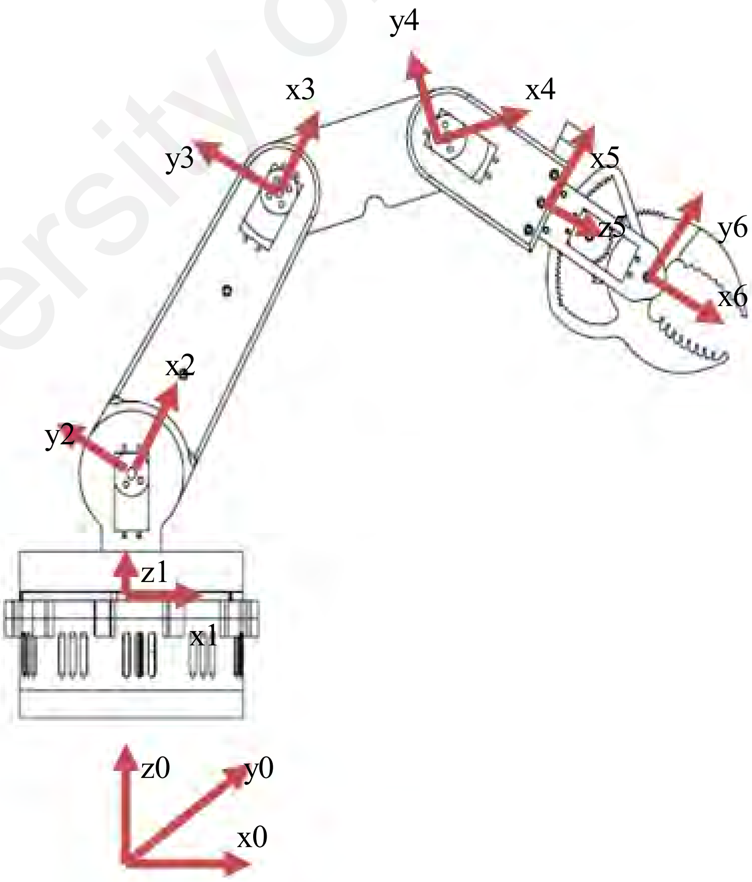


Figure 3. 9; coordinate frame assignment

The first joint axis points vertically upwards, the second joint axis is normal to the first without any offset, the third and fourth joint axes are both parallel to the second. The fifth joint axis is perpendicular to the fourth, while the end-effector axis is normal to the fifth joint.

3.3.2 Homogeneous Transformation Matrices

The DH method employs a 4x4 transformations matirix in order to transform from one coordinate frame to another. It is called the homogeneous transformation matrix (HTM) and it is of the form shown below.

$$\begin{pmatrix} {}^{A}R_{B} & {}^{A}P_{B} \\ \gamma & \rho \end{pmatrix} \quad \ldots\ldots \quad (1)$$

R is a 3x3 matrix which defines the orientation of one coordinate frame relative to another. It is basically a rotation matrix form (for example say from point A to B). *P* is a 3x1 matrix which defines the translation from one coordinate frame to another (e.g from A to B). It is a position matrix. *Gamma* is 1x3 matrix containing all zeros and *Rho* is a 1x1 matrix having a value of 1.

The HTM is composed of rotations and translations which are hugely dependent on the four parameters that were described previously. α and θ, and a and *d* represents the rotations and translations respectively. If we are to move from a said coordinate frame *i-1,* to another one say *i,* then for each of these parameters, their corresponding transformation matrices are given below.

$$Rot_{x,\alpha} = T(x,\alpha) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c\alpha_i & -s\alpha_i & 0 \\ 0 & s\alpha_i & c\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$ which is a rotation about the x-axis by an angle α_i

$$Rot_{z,\theta} = T(z,\theta) = \begin{pmatrix} c\theta_i & -s\theta_i & 0 & 0 \\ s\theta_i & c\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$ which is a rotation about the z-axis by an angle θ_i

$$Trans_{x,a} = T(x,a) = \begin{pmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$ which is atranslation along the x-axis by an angle a_i

$$Trans_{x,d} = T(x,d) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}$$ which is atranslation along the x-axis by an angle d_i

The order in which the matrices are multiplied to give the HTM is starting with the rotation about the z-axis by θ; then followed by a translation along the z-axis by *d*; then followed by a translation along the x-axis by α; and finally a rotation about the x-axis by α. Below is an equation for clearer understanding.

$$H = {}^{i-1}T_i = T(z,\theta)T(z,d)T(x,a)T(x,\alpha)$$

$${}^{i-1}T_i = \begin{pmatrix} c\theta_i & -c\alpha_i s\theta_i & s\alpha_i s\theta_i & a_i c\theta_i \\ s\theta_i & c\alpha_i c\theta_i & -s\alpha_i c\theta_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \text{……………………………………….. (2)}$$

3.4 Forward Kinematics

The DH parameters are obtained from the combination of the geometry shown in figure 3.9 and the line equivalent in figure 3.10 as shown. The parameters are arranged in table 3.4

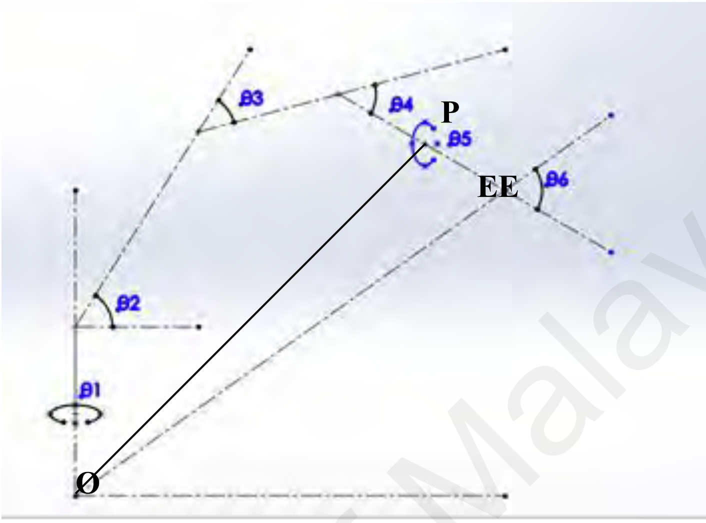


Figure 3. 10; free body diagram of the robot arm

Table 3. 4; DH parameters for the robotic arm

Joint value (i)	Rotation, z (θ)	Translation, z (d)	Translation, x (a)	Rotation, x (α)
1	θ1	d1	0	-π/2
2	θ2	0	a2	0
3	θ3	0	a3	0
4	θ4	0	a4	-π/2
5	θ5	d5	0	-π/2
6	θ6	0	a6	0

Since the forward kinematics involves finding the position of the end-effector depending on the joint angels, a general transformation matrix can be formed by multiplying the corresponding HTMs for all the joints. The values for the translations x of the links a1, a2, a3, a4, a5, and a6 corresponds to 135mm, 185mm, 118mm, 80mm, 75mm, and 70mm respectively. Knowing a point in space say Pb given in vector form Pb (Px, Py, Pz) and a fixed coordinate frame at the origin say Pa (0, 0, 0). Then the position of the end-effector with respect to the fixed frame can be computed using the equation below.

$$^{A}P = {}^{0}T_n {}^{B}P \qquad \text{.. (3)}$$

where ${}^{0}T_n$ is the overall transformation from the base frame to the end-effector frame. It is given

$$^{0}T_n = \sum {}^{i-1}A_n \text{ and i = 1, 2, ...n} \qquad \text{.. (4)}$$

The total number of joints is n.

$$^{o}T_n = {}^{0}A_1 {}^{1}A_2 {}^{2}A_3 {}^{3}A_4 {}^{4}A_5 {}^{5}A_6 \qquad \text{....................................... ....(5)}$$

Using the general transformation matrix given above, the various transformation for each joint will be computed. Since the rotation around the x-axis is a constant value, the cosine and sine values will disappear from the equations. Therefore, only the cosine and sine values for the rotation around z-axis will remain. To make our equations less clumsy, the following conventions will be adopted

$$\cos\theta_i = c_i \text{ ;} \sin\theta_i = s_i$$
$$\cos(\theta_i + \theta_j) = c_{ij} \text{ ; } \sin(\theta_i + \theta_j) = s_{ij}$$
$$\cos(\theta_i + \theta_j + \theta_k) = c_{ijk} \text{ ; } \sin(\theta_i + \theta_j + \theta_k) = s_{ijk} \text{ and so on...}$$

For joint 1, we have $^{0}A_{1} = \begin{pmatrix} c_1 & 0 & -s_1 & 0 \\ s_1 & 0 & c_1 & 0 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ …………………….. (6a)

For joint 2, we have $^{1}A_{2} = \begin{pmatrix} c_2 & -s_2 & 0 & a_2c_2 \\ s_2 & c_2 & 0 & a_2s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ …………………….. (6b)

For joint 3, we have $^{2}A_{3} = \begin{pmatrix} c_3 & -s_3 & 0 & a_3c_3 \\ s_3 & c_3 & 0 & a_3s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ ………………………. (6c)

For joint 4, we have $^{3}A_{4} = \begin{pmatrix} c_4 & -s_4 & 0 & a_4c_4 \\ s_4 & c_4 & 0 & a_4s_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ ……………………… (6d)

For joint 5, we have $^{4}A_{5} = \begin{pmatrix} c_5 & 0 & -s_5 & 0 \\ s_5 & 0 & c_5 & 0 \\ 0 & -1 & 0 & d_5 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ …………………….. (6e)

For joint 6, we have $^{5}A_{6} = \begin{pmatrix} c_6 & -s_6 & 0 & a_6c_6 \\ s_6 & c_6 & 0 & a_6s_6 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$ …………………………. (6f)

Notice that joints 2, 3, and 4 are parallel to each other. This chain can be modelled as a 3-link planar manipulator. For this reason, we compute first the transformation through these three joints by multiplying equations 6b, 6c, and 6d.

$$ {}^{1}A_4 = {}^{1}A_2\,{}^{2}A_3\,{}^{3}A_4 = \begin{pmatrix} c_{234} & 0 & -s_{234} & a_4c_{234}+a_3c_{23}+a_2c_2 \\ s_{234} & 0 & c_{234} & a_4s_{234}+a_3s_{23}+a_2s_2 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \ldots (7) $$

The overall transformation is finally obtained by multiplying equations 6a, 7, 6e, and 6f. this is given below;

$$ {}^{0}T_n = {}^{0}A_6 = {}^{0}A_1\,{}^{1}A_4\,{}^{4}A_5\,{}^{5}A_6 = \begin{pmatrix} u_x & v_x & w_x & ee_x \\ u_y & v_y & w_y & ee_y \\ u_z & v_z & w_z & ee_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad \ldots\ldots\ldots\ldots (8) $$

Where;

$$
\begin{aligned}
u_x &= c_1c_{234}c_5c_6 + s_1s_5s_6 + c_1s_{234}s_6 \\
u_y &= -c_1c_{234}c_5s_6 + s_1s_5s_6 + c_1s_{234}c_6 \\
u_z &= -c_1c_{234}s_5 + s_1c_5 \\
v_x &= s_1c_{234}c_5c_6 - c_1s_5c_6 + s_1s_{234}s_6 \\
v_y &= -s_1c_{234}c_5s_6 + s_1s_{234}c_6 \\
v_z &= -s_1c_{234}s_5 - c_1c_5 \\
w_x &= -s_{234}c_5c_6 + c_{234}s_6 \\
w_y &= s_{234}c_5s_6 + c_{234}c_6 \\
w_z &= s_{234}s_5 \\
ee_x &= a_2c_1c_2 + a_3c_1c_{23} + a_4c_1c_{234} - d_5c_1s_{234} + a_6s_1s_5c_6 + a_6c_1c_{234}c_5c_6 + a_6c_1s_{234}s_6 \\
ee_y &= a_2s_1c_2 + a_3s_1c_{23} + a_4s_1c_{234} - d_5s_1s_{234} + a_6c_1s_5c_6 + a_6s_1c_{234}c_5c_6 + a_6s_1s_{234}s_6 \\
ee_z &= d_1 - a_2s_2 - a_3s_{23} - a_4s_{234} - d_5c_{234} + a_6c_{234}s_6 - a_6s_{234}c_5c_6
\end{aligned}
$$

Equation (8) is the forward kinematics equation for the robotic arm. If a point is specified with respect to any origin, then the forward kinematics can be computed using equations (3) and (8).

3.5 Inverse Kinematics

It has been explained in chapter two that inverse kinematics involves finding the joint values that are needed to take the end-effector to a desired position in space. The figure below shows the joint values that need to be calculated. To simplify the derivations, it will be divided into two steps. The first step will be finding the joint values that will position the wrist centre, P. The second step will be finding the additional angles to position the end-effector, ee.

Step 1

The set of angles needed to position the wrist center at any position in the Cartesian plane are; θ1, θ2, θ3, and θ4. The transformation from the base frame to the wrist can be derived as follows;

$$ {}^{0}A_4 = {}^{0}A_1 {}^{1}A_2 {}^{2}A_3 {}^{3}A_4 \qquad \text{.................................... (9)} $$

An easy way to solve equation 9 is to multiply both sides of the equation by the inverse of ${}^{0}A_1$.

$$ \left({}^{0}A_1\right)^{-1} . {}^{0}A_4 = {}^{1}A_2 {}^{2}A_3 {}^{3}A_4 \qquad \text{......................... (10)} $$

It is worth noticing that the right-hand side of equation (10) is the same as equation (7). An equation similar to equation (8) is adopted for equation (9), but the position (ee) will be replaced by position $\vec{P}$. Assuming the position vector $\vec{P} = p_z, p_y, p_z$ for the wrist is specified, and then we can equate the last columns of equation (10) to yield the following equation.

$$ \begin{aligned} &P_x c_1 + P_y s_1 = a_2 c_2 + a_3 c_{23} + a_4 c_{234} \\ &-P_z + d_1 = a_2 s_2 + a_3 s_{23} + a_4 s_{234} \\ &-P_x s_1 + P_y c_1 = 0 \end{aligned} \qquad \text{.................. (11)} $$

From the third line of equation (11), the first joint angle θ1 can be obtained using,

$$\theta_1 = \tan^{-1}\left(\frac{P_y}{P_x}\right) \qquad \text{.............. (12)}$$

There are two solutions for θ1. The are θ1 and (π + θ1).

Step 2

The end-effector will now be considered. Adding the fifth joint in equation (9) will generate a transformation needed to take the end-effector to any position in the Cartesian space.

$$^0A_5 = {}^0A_1 {}^1A_2 {}^2A_3 {}^3A_4 {}^4A_5 \qquad \text{.............................. (13)}$$

Following the same procedures in step 1, we have

$$\left({}^0A_1\right)^{-1} . {}^0A_5 = {}^1A_2 {}^2A_3 {}^3A_4 {}^4A_5 \qquad \text{.............................. (14)}$$

Assuming here also that the orientation vector, $\vec{u} = u_x, u_y, u_z$ for the end-effector ee is given, then we can equate the first columns of equation (14) to yield the following equations.

$$\begin{aligned} u_x c_1 + u_y s_1 &= c_{234} c_5 \\ -u_z &= s_{234} c_5 \\ -u_x s_1 + u_y c_1 &= -s_5 \end{aligned} \qquad \text{.............................. (15)}$$

From the third line of equation 15, we obtain the fifth joint value.

$$\theta_5 = \sin^{-1}\left(-u_x s_1 + u_y c_1\right) \qquad \text{.............................. (16)}$$

For every solution of θ1, θ5 has one solution.

Substituting θ1 and θ5 in equation (15) will produce θ_{234} .

$$\theta_{234} = A\tan 2\left[\frac{-u_z}{c_5}, \frac{(u_x c_1 + u_y s_1)}{c_5}\right] \quad \text{.................................. (17)}$$

With the joint values obtained, substituting them in equation (11) will change the equation into the one below,

$$\begin{aligned} k_1 &= a_2 c_2 + a_3 c_{23} \\ k_2 &= a_2 s_2 + a_3 s_{23} \end{aligned} \quad \text{.. (18)}$$

Where $k_1 = (P_x c_1 + P_y s_1 - a_4 c_{234})$ and $k_2 = (-P_z + d_1 - a_4 s_{234})$. The sum of the squares of equation (18) will yield

$$k_1^2 + k_2^2 = a_2^2 + a_3^2 + 2a_2 a_3 c_3 \quad \text{.................................. (19)}$$

Solving for c_3, the third joint angle will be obtained thus

$$\theta_3 = \cos^{-1}\left(\frac{k_1^2 + k_2^2 - a_2^2 - a_3^2}{2a_2 a_3}\right) \quad \text{.................................. (20)}$$

θ_3 has two solutions, each for the positive and negative axis. Now substituting θ_3 in equation (18) and expanding the equation will aid finding of θ_2 as seen below

$$\begin{aligned} k_1 &= (a_2 + a_3 c_3) c_2 - (a_3 s_3) s_2 \\ k_2 &= (a_3 s_3) c_2 + (a_2 + a_3 c_3) s_2 \end{aligned} \quad \text{.................................. (21)}$$

Solving for c_2 *and* s_2, we can obtain the second joint angle θ2.

$$\begin{aligned} c_2 &= \frac{k_1 (a_2 + a_3 c_3) + k_2 a_3 s_3}{a_2^2 + a_3^2 + 2a_2 a_3 c_3} \\ s_2 &= \frac{-k_1 a_3 s_3 + k_2 (a_2 + a_3 c_3)}{a_2^2 + a_3^2 + 2a_2 a_3 c_3} \end{aligned} \quad \text{.................................. (22)}$$

$\theta_2 = A\tan 2(s_2, c_2)$ .... (23)

Since by the set convention, $\theta_{234} = \theta_1 + \theta_2 + \theta_3$, then finding θ_4 will be straightforward.

$\theta_4 = \theta_{234} - \theta_2 - \theta_3$ .... (24)

To obtain $\theta_{6,}$ similar approach used in deriving θ_5 can be adopted. In this case the equation will look like

$\left({}^0A_1{}^1A_2{}^2A_3{}^3A_4\right)^T . {}^0A_n = {}^4A_5{}^5A_6$ .... (25)

Assuming the vector $\vec{u} = (u_x, u_y, u_z)$ is specified, then equation the first columns of equation (25) will yield the following equations

$$\begin{aligned} u_x c_1 c_{234} + u_y s_1 c_{234} + u_z s_{234} &= s_5 s_6 \\ -u_x s_1 + u_y c_1 &= -c_5 s_6 \\ -u_x c_1 s_{234} - u_y s_1 s_{234} + u_z c_{234} &= c_6 \end{aligned} \quad \text{.............................. (26)}$$

If c_5 *and* c_6 are computed, then the last joint angle θ6 can be solved.

$\theta_6 = A\tan 2(s_6, c_6)$

From the whole derivations, it is seen that the robotic arm has eight real inverse kinematic solutions.

3.6 Control Of The Robotic Arm

3.6.1 Electrical connection

In controlling this robot arm, an Arduino Mega 2560 is used as the microcontroller. The Arduino board is connected to the serial interface, thereby getting its power supply from the PC. The code that controls the stepper and servo motors are written in the

Arduino IDE which is installed on the PC, which is then sent to the Arduino board to control the motors. The control signals are sent via a pulse width modulation (PWM) which is transferred to the board. The Arduino board gets 5v power supply from the PC, thus the servo motors which also run on 5v then get their supply from the board. The stepper motor which requires a higher voltage gets its supply from an external 12v power adaptor through the A4988 stepper motor driver. An A4988 stepper motor driver is used to control the stepper motor. It serves as a link between the Arduino board and the stepper motor. The 12v power supply is fed to the motor driver in order to power the stepper motor. The logic circuit of the motor driver uses 5v dc, so it gets that from the Arduino board through a serial connection. Figure 3.9 shows the electrical wiring of the project.

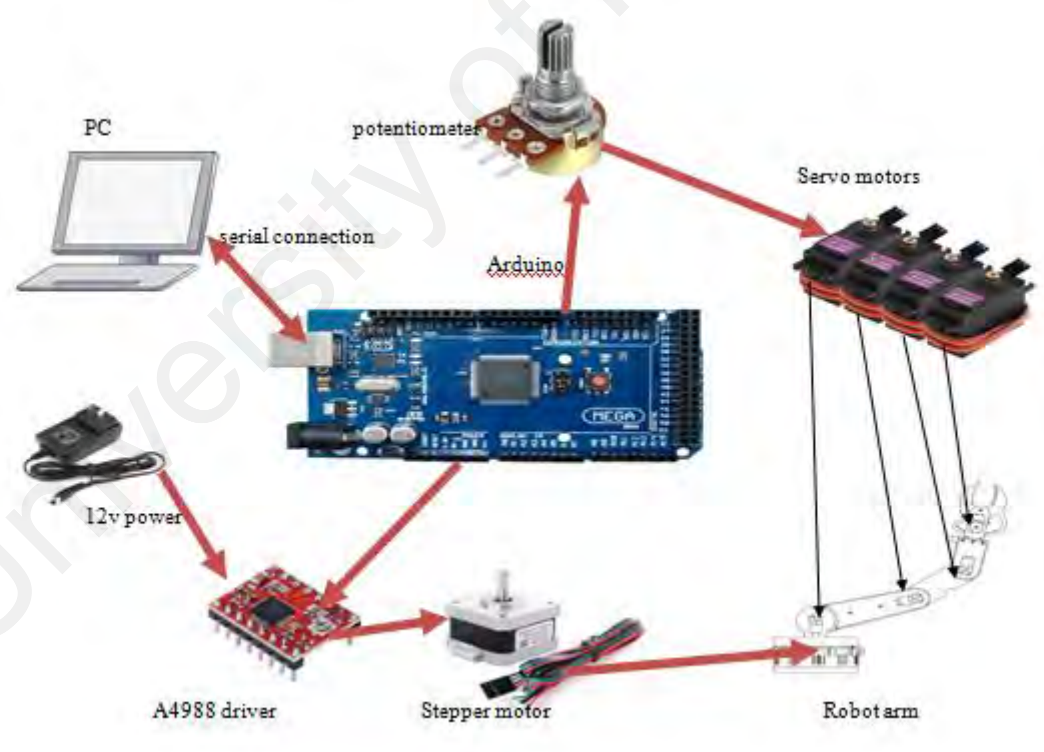


Figure 3.11; Electrical wiring of the project.

The first joint at the base is controlled by the stepper motor. All other joints are being controlled by the servo motors. The servo motors are being controlled by individual

10K ohm potentiometer. The potentiometers are tuned to change the joint angle values which then move the links in desired direction. Basically the motors are controlled by varying the operating power by PWM (Pulse Width Modulation) which are sent from the Arduino.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Project Implementation

The implementation of the project is shown in figure 4.1. The Arduino IDE interface is as shown on the PC is where the control codes are written. The code is tuned until the robot arm gets the end-effector to a desired location. For the stepper motor controlling the base, the PWM signal is sent first to the A4988 driver, which in turn sends it to the stepper motor. For the servo motors, the PWM signal is sent directly to the motors. This is because the IDE contains libraries with PWM that can directly control the servos without the use of drivers.

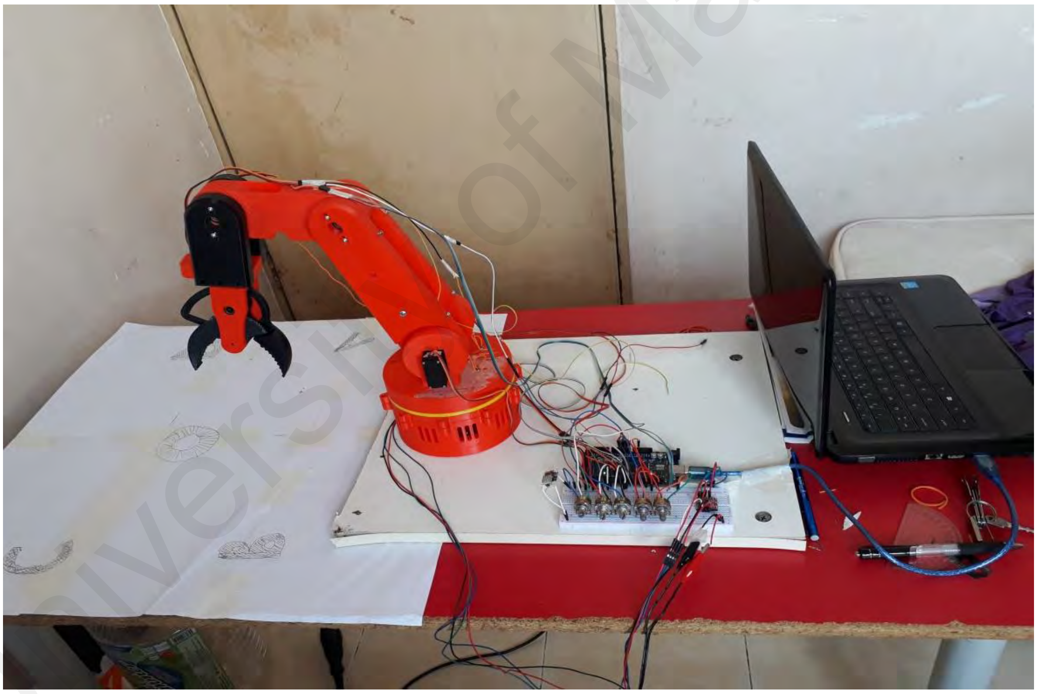


Figure 4. 1; project implementation

4.2 Joint Accuracy

The efficiency of the robot can only be ascertained if the robot follows the motion as specified by the values of the joint angles that are sent to it. In chapter three, it was pointed out that the three major angles that places the robot end-effector in any position in space are $\theta 2$, $\theta 3$, and $\theta 4$. These angles correspond to the lower arm, centre arm, and upper arm respectively. In order to determine the accuracy of these listed joint angles, input angles ranging from 15 to 90 degrees were used with an interval of 15 degrees. The measurements were done using a protractor setting the straight position of each arm as the zero mark. The resulting angles were also recorded. Graphs for each of the joint angles were plotted and their slopes represented the joint accuracy.

Lower arm

Table 4. 1 Joint values (lower arm)

Commanded Angle	Resulting Angle
15	13
30	28
45	43
60	57
75	73
90	88

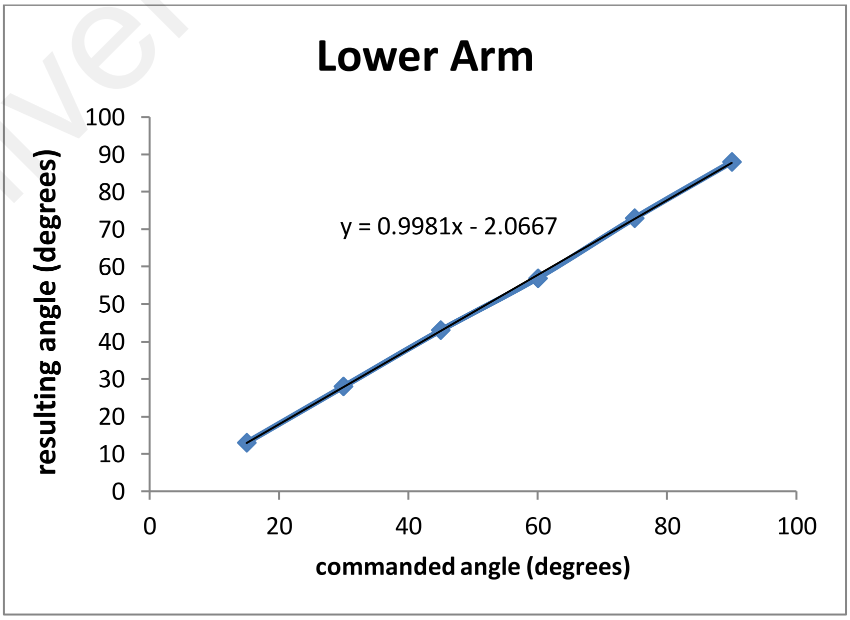


Figure 4. 2 Accuracy graph (lower arm)

Centre Arm

Table 4. 2 Centre Arm (Joint Values)

Commanded Angle	Resulting Angle
15	17
30	33
45	48
60	63
75	77
90	91

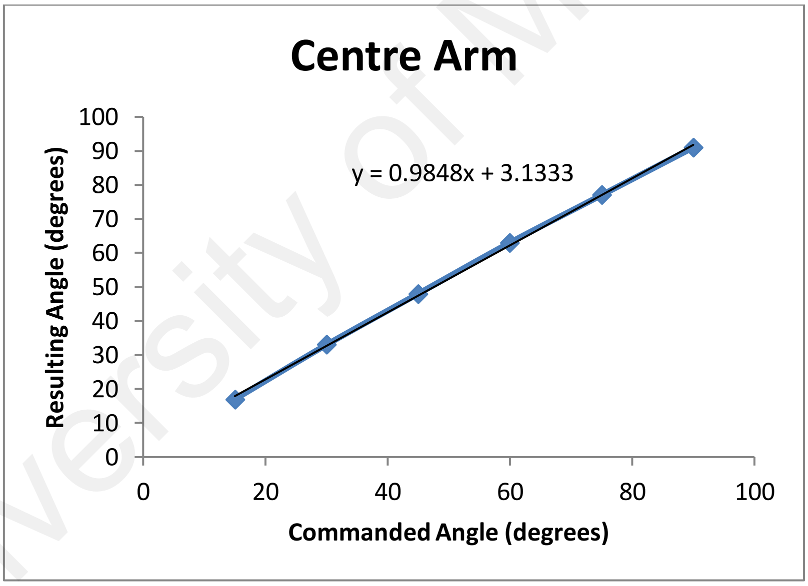


Figure 4. 3 Accuracy graph (centre arm)

Upper Arm

Table 4. 3 Upper Arm (Joint values)

Commanded Angle	Resulting Angle
15	18

30	33
45	48
60	63
75	78
90	93

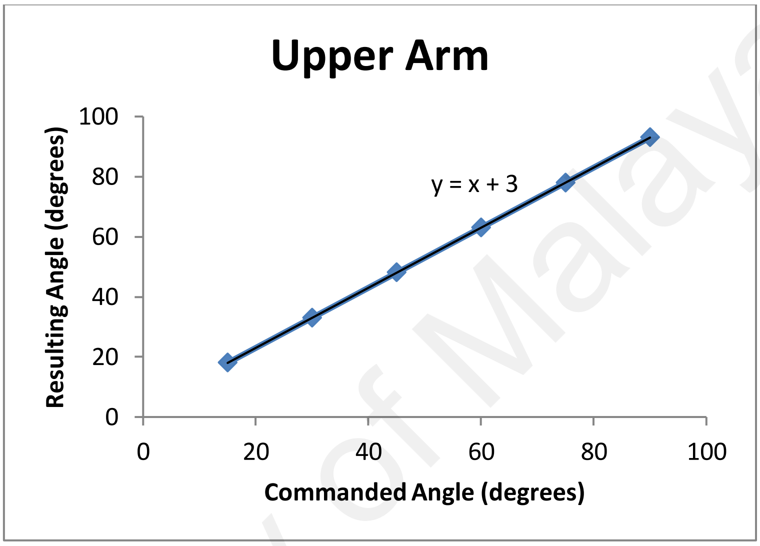


Figure 4. 4 Accuracy graph (upper arm)

The percentage accuracy of each of the joint corresponds to the slope of the graphs plotted. For the lower arm, it is seen that the joint efficiency is slightly less than unity with a value of 0.998. This is due to the variations caused by the weights of the center arm to the end-effector chain on the servo motor which prevented it from stabilizing. Also the resulting angle is lagging by about 2.06 degrees. The center arm has a slope similar to that of the lower arm with a value of 0.985. However, the resulting angle is leading the commanded angle by a value of 3.1 degrees. Finally, the upper arm is the most efficient with a slope of 1. The upper arm is also leading in the resulting angle by a value of 3 degrees

4.2 Pick and Place Experiment

In order to make school children more acquainted with the industrial related task, robotic arm comes into play(Sergey et al., 2107). Experiments performed using robotic arm mimics the industrial conditions, this will prepare the students well enough before they graduate. To demonstrate the working of the robot arm, a simple pick and place experiment is performed. The potentiometer is used to turn the stepper motor which then directs the base of the robot to the direction where the object is. Afterwards, the servo motors angles are tuned until the end-effector is lowered on the object. The end-effector then closes to pick the object. A reverse of the described motion is implemented to get the desired placing position. The end-effector is then lowered once again to drop the object. The set up for the experiment is the same as shown in figure 4.1. four coordinate points were marked as A, B, C, and D. Also a centre coordinate point O was marked. Two different objects were used for the experiment to show the versatility of the end effector and also the motion of the robotic arm. One of the objects is a plastic water bottle, while the other object is a masking tape. Attached are photos taken from the experiment. In figure 4.5, the masking tape is picked from point A, then placed at point O. It is further picked from point O, then flipped around with the help of joint 5, then finally placed at point C. In a similar fashion, the plastic bottle in figure 4.6 is firstly picked from point D, then it was flipped around and passed through point C to finally being placed at point B. The plastic bottle was not dropped at point O, unlike the masking tape.

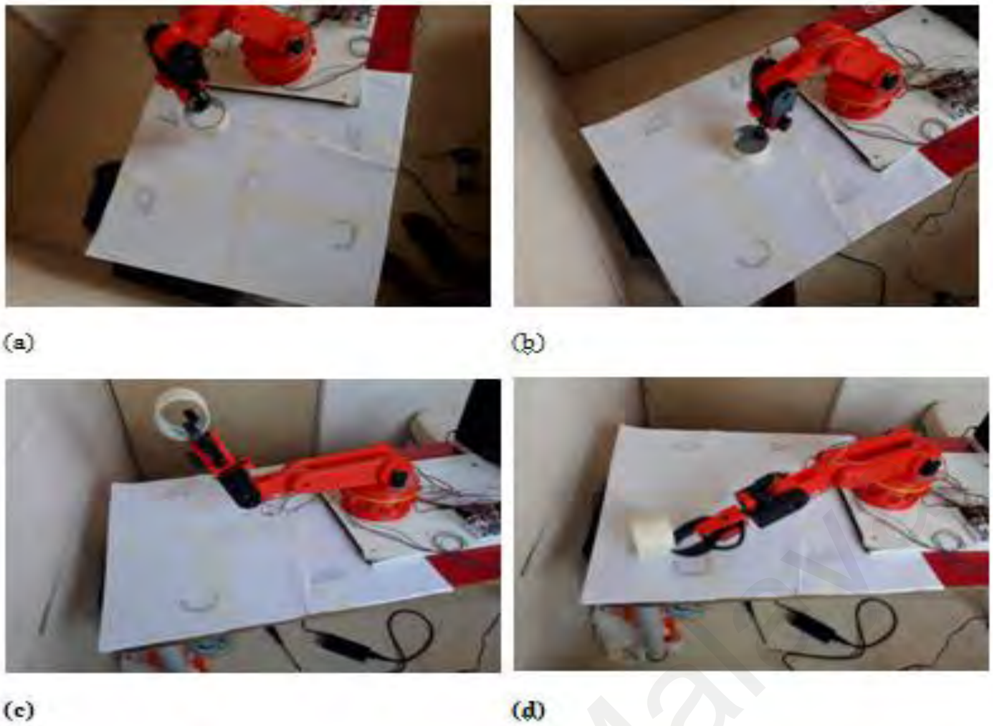


Figure 4. 5 Experiment using masking tape

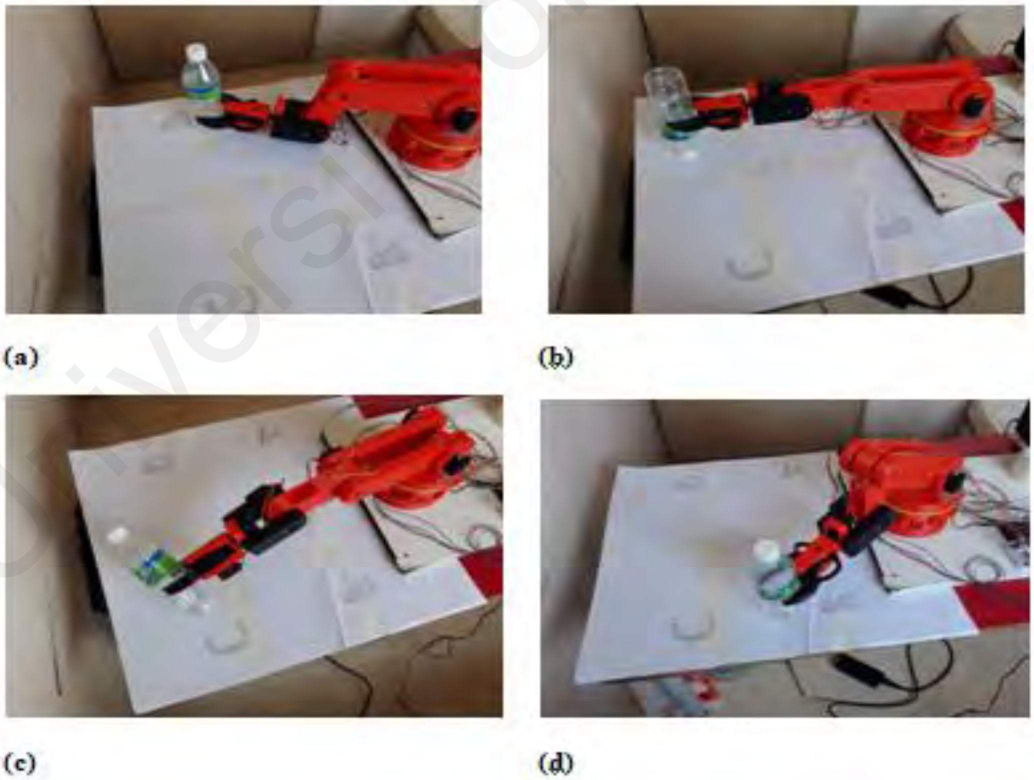


Figure 4. 6 Experiment using plastic bottle

4.4 Printed Parts

Since three different printers and two different consumables were used in this project, the parts needed to be measured to be sure of the quality of the printed parts. In terms of the dimensions, the printed parts were all measured and the results were compared to the design values. It was discovered that all the parts had no discrepancy in the dimensions as all dimensions were accurate. We can infer that the three printers are accurate in printing. In terms of the surface finish, the parts printed using the flashforge were better than those printed with the other two printers (Prusa and Cr8). This can be attributed to the speed and nozzle sizes of the printers. Finally, in terms of the weight, the infill used which ranged from 17-20 caused the robot arm to be too heavy for the RC servo motors. This really made it almost impossible to perform several different experiments with the printed robot arm. Some of the photos taken during the printing are shown in figure 4.7.

Figure 4. 7 Printing of parts

The two major challenges that were faced during the printing were warping of parts and exhaustion of filament. The small parts were all printed without any complications. But the long parts were not sticking to the printed which was as a result of the temperature gradient as it cooled down faster than the time taken for the nozzle to come back to position. This is shown in figure 4.8d. Different methods were explored from online sources, but the two methods that worked fine were; (1) applying painters tape to the print bed, which makes it easy for the parts to stick to the bed as shown in figure 4.8 b and c, and (2) applying glue stick to the printed bed which also served fine. The method most efficient was (1) above. For the exhaustion of filament, it was learned that when a new filament is immediately fixed to follow the previous one, the print was fine but with two layers having different colours as shown in figure 4.8a. However, if the new filament is delayed in fixing, then the previous part shrinks to the extent that a new filament would not stick well to it thus, damaging the printed part.

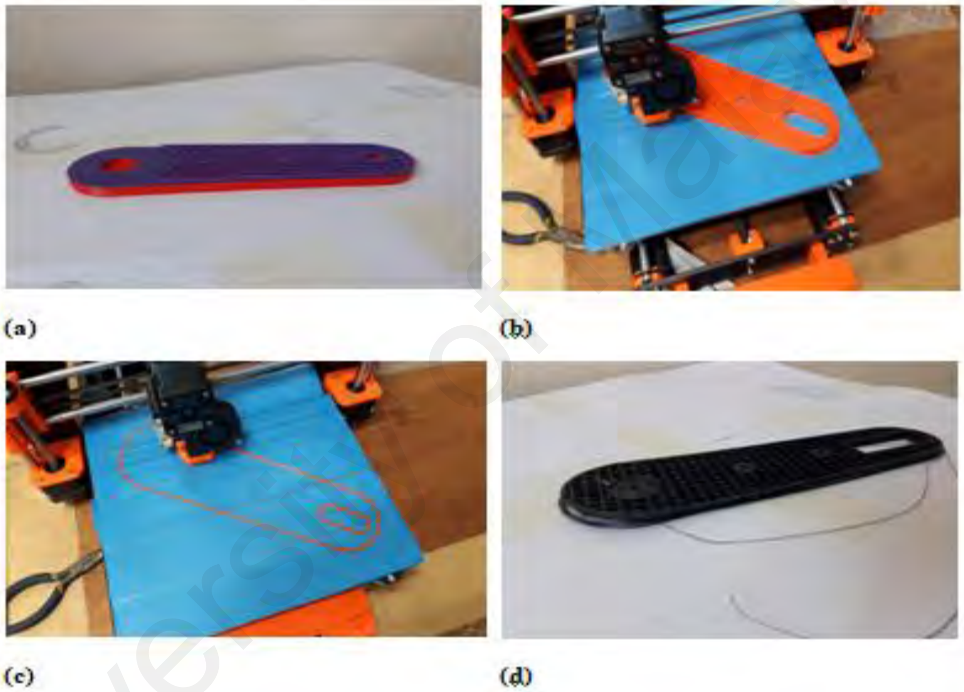


Figure 4. 8 Warping and Exhaustion of filament

CHAPTER 5: CONCLUSION

5.1 Summary

In this research project, a robotic arm has been successfully developed and tested. The robot arm was built using three different 3D printers; Prusa I3 Mk3, Flashforge creator Pro, and Cr8 3D. The forward kinematics (FK) of the robot arm was derived using the DH convention. The inverse kinematics (IK) was derived using the geometrical approach. In controlling the robot arm, Arduino mega 2560 was used. The program is written in the Arduino IDE which is suited for c++, then this program is sent to the board which in turns control the motors using PWM signals to driving the robot arm. The joint accuracies for three major joints were calculated and it was found that lower and centre arms have very little discrepancies while the upper arm was fully accurate. A simple pick and place experiment is performed to implement the project. Two different objects with different shapes were used in the experiment to showcase the versatility of the end-effector.

It is hoped that this robot arm will serve as an educational tool for teaching and learning robotics and additive manufacturing. Also it will expose the students to some common industrial based applications such as machine tending, pick and place in packaging.

5.2 Future Work

The robotic arm printed was heavy for the RC servos that were used. The design of the arm can be optimised in order to reduce the weight of the robotic arm. Also the design can be modified to accommodate other better motors in the joints rather than the RC servos used.

The end effector is meant for only pick and place purpose. This can also be upgraded by replacing it with tools such as drill, paint brush, grinding wheel, among others.

In the area of programming, the arduino IDE is tedious for the control of the motors as the there are several tunings before a required joint angle is obtained. This can be improved by implementing the program on ROS. Although ROS has a steep learning curve, but it has been successfully used to control varieties of robot arms.

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