DESIGN AND CONSTRUCTION OF A ROBOTIC ARM WITH ADAPTIVE BEHAVIOUR

BY

BONIFACE UMUNNA OGWUDIRE

REG NO:

20111786893

OPTION:

Electronic and Computer Engineering (ECE)

SUBMITTED TO:

THE DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

SCHOOL OF ENGINEERING AND ENGINEERING TECHNOLOGY

FEDERAL UNIVERSITY OF TECHNOLOGY, OWERRI (FUTO)

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE BACHELORS OF ENGINEERING DEGREE (B Eng) IN ELECTRICAL AND ELECTRONIC ENGINEERING

October, 2016

CERTIFICATION

This is to certify that this work, "Design and Construction of a Robotic Arm with Adaptive Behaviour", was carried out by BONIFACE UMUNNA, OGWUDIRE, in partial fulfillment of the requirements for the award of the Bachelor of Engineering (B. Eng) degree in Electrical and Electronic Engineering, Federal University of Technology, Owerri.

Approved By:

Dr. Ifeyinwa E. Achumba

……………………………… ………….....……………

Project Supervisor Date

Engr. Dr. D. O. Dike

……………………….……. ……………………………

Head of Department Date

……………………………... ……………………………

External Examiner Date

DEDICATION

This work is dedicated to Almighty God, who alone is the source of all I am and have achieved to date. And also; to all engineers laden with a burning desire to make the world a better place through advancements in technology.

ACKNOWLEDGEMENT

Great heights are never achieved alone. It is by the help of many that I have come this far in life. To this end, I wish to acknowledge my supervisor; Dr. Ifeyinwa. E. Achumba whose guidance and advice during the course of the project work proved to be much useful for the work done so far. Her encouragements were timely and always on point. Much thanks to my Course Adviser, Engr. I. F. Ezebili whose guidance throughout my undergraduate years as a student of EEE helped shaped my life as a student. My sincere gratitude goes also to the management and staff of FUTO library for their help in using the library resources.

Also to my parents, Crown prince and Lolo M. E. Ogwudire for their parental support, advice and guidance throughout the period of my studies. My siblings, Eze, Adamma, Ugochukwu, Chioma, Oluchi, and Akuforo have been supportive of me throughout my studies.

Finally, my friends, Uzor Uchenna, Chisom Ezeaku, Uzorue Chinedu, Chidimma Mberede and Ejike Brian for their numerous support in the course of this project.

ABSTRACT

This project work covers the design and construction of a robotic arm mechanically capable of 5 Degrees of Freedom. It solves the problem of automatically detecting and picking up objects placed within distances of 10-30cm round the robot base platform. It does this by using a simplified forward and inverse kinematic relation modeled in two dimensional robot workspace. The work does not cover the more general case, of an n-linked (n>2) robotic arm working within a three dimensional robot workspace. This later type produces system equations which are too complex to handle at this level of study. As part of building an adaptive behaviour into the robot, a thorough research material on the Adaptive Neuro-Fuzzy Inference System technique was presented and an attempt was made in implementing this on the project. –This technology gives the robot the ability to store angle location of the arm joints for various operations as it is manually controlled. This can then be used as feed data for autonomous repetitive operation. Ethical issues arising from using such automation technologies as robotic arm is discussed in chapter five together with recommendations and future works on the project.

CHAPTER ONE

INTRODUCTION

1.0 ROBOTS

The invention of programmable robots has created a paradigm shift in the way work is done both in nearby industries and in far away outer space exploration. More recently, robots have been used in the field of medicine for surgical operations. There have also been serious efforts especially by Japanese researchers to incorporate robots to our daily lives and even replace humans entirely in various routine tasks. Hence the creation of such advanced robots as ASIMO by Honda Inc.

The word robot was first used by a Czech science fiction writer Karel Capek in his 1921 play R.U.R (Rossum's Universal Robots) and is derived from the Czech word 'robota' meaning slave or forced labour **[1]**. This goes on to describe a robot as a machine which is adapted for untiring and repeated tasks. Subsequently, in 1942 the Russian born American science-fiction writer Isaac Asimov coined the word "robotics" where he portrayed robots as helpful servants of man in contrast to Capeks's idea of a rebellious set of mechanical beings **[1]**. Based on this concept, several definitions exist for robots; both behavioural and structural. However, in 1979 the Robot Institute of America (RIA), defined robot as "**a reprogrammable,**

multifunctional manipulator designed to move materials, parts, tools, or other specialized devices through various programmed motions for the performance of a variety of tasks". This became the working definition in many robotics research works and is the definition adopted in this project. This definition removes such manipulators which cannot exhibit intelligence through programmed instructions, information gathering through sensors that read environmental data. And also eliminating devices which lack mechanical systems for effecting intelligent movements from the set of machines referred to as robots.

1.0.1 ROBOTIC ARMS

Currently, there are many types of robots in existence, such as aerial drones (e.g. UAVs), ground reconnaissance systems (e.g. UGVs) and the more advanced humanoids with high artificial intelligence. A subset of the mechanical structures in humanoids is the robotic arm which closely models the human arm- The main focus of this project is the design, and construction of a Robotic Arm. Haven found widespread applications, and to better adapt these robotic arms to the problem area for which they are to operate, designers have adopted various structural modifications to achieve the same objectives of material handling, movement and manipulation as stated by the RIA. Thus robotic arms can be classified into eight (8) different types **[2]**:

1. Anthropomorphic Robots (articulated)
2. Cartesian Robots
3. Gantry Robots
4. Cylindrical Robots
5. Parallel Robots
6. SCARA Robots

7. Spherical/Polar Robots

The **figure (1.0a-f)** and **fig 1.1** below shows different types of robots often used for various industrial applications.

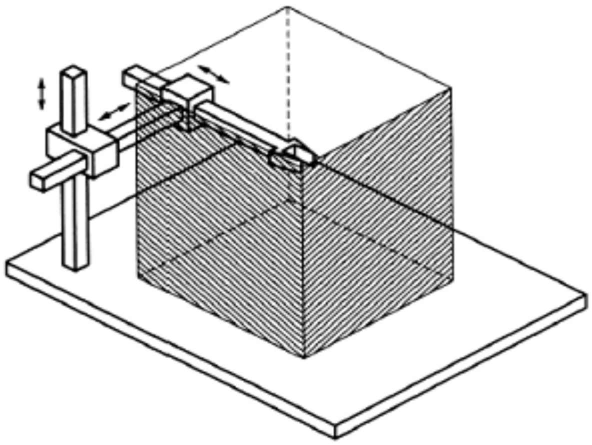


Fig1.0a: Cartesian Robotic Arm**[3]**

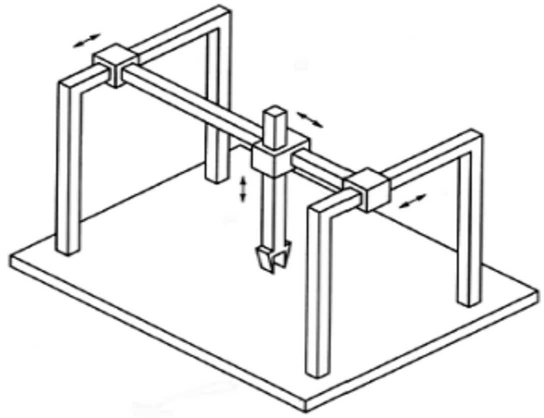


Fig1.0b: Gantry Robotic Arm**[3]**

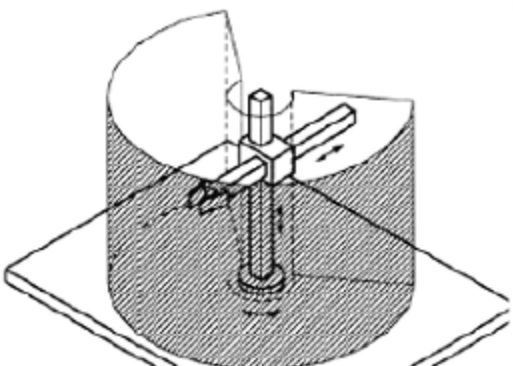


Fig1.0c: Cylindrical Robotic arm**[3]**

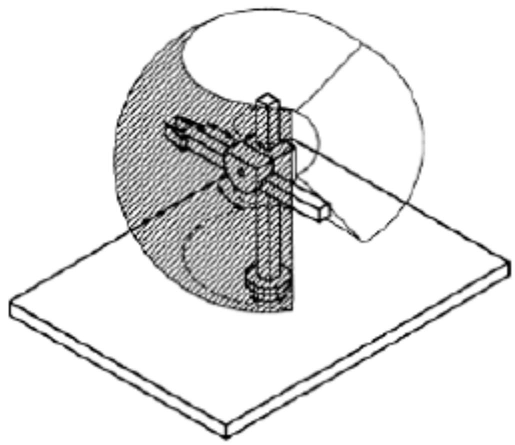
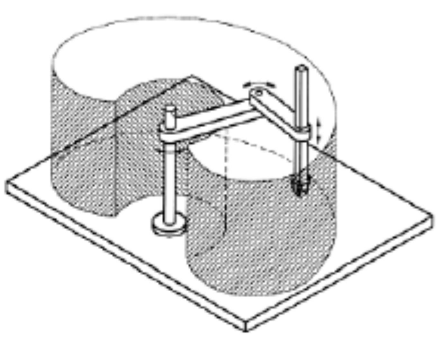


Fig1.0d: Spherical Robotic arm**[3]**



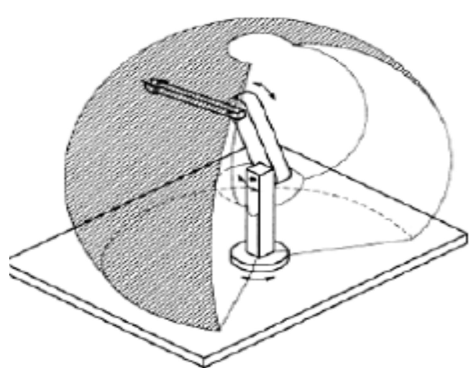


Fig1.0e: Scara Robotic arm**[3]**

Fig1.0f: **Anthropomorphic Robotic arm[3]**

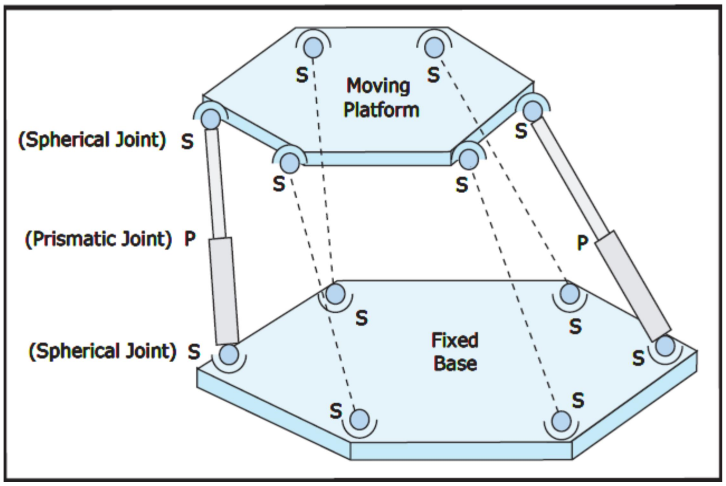


Fig1.1: Stewart's mechanism (parallel robotic arm)**[3]**

These robotic arms find applications in such fields as:

- Agriculture
- Defense
- Material Handling in Industries
- Medical (surgical) Operations
- Welding operation
- Vehicle Assembling
- Spray painting etc.

Of the available frameworks of the robotic arms available, the Anthropomorphic (or articulated) robotic arm is most favoured for several applications. This is due to the fact that it closely resembles the human arm. With a structural arrangement which enables it to mimic the dexterity of human arm. Also in the list of consideration is the possibility of programming this arm to perform different kinds of movements and tasks which ordinarily would require a different type of robot arm or in combination with another. It is this mechanical dexterity -the ability of the robot arm to perform several specialize motion- that has won the anthropomorphic model much attention over other robotic arm models. However, special cases exist such as in 3-D printers where models like the gantry robotic arm is most suitable for application than the anthropomorphic robotic arm.

The term robotic arm as used in this work is meant to describe a mechatronic device with parts similar to that of an inverted human arm. This arm mimics the human kinesiology; comprising parts equivalent to: Shoulder joint, humerus, elbow joint, radius/ulna and hand. **It is a mechanical assembly of appendages interlinked together by servo motor operated joints with limited degrees of rotation (usually 180 degree) under the control of a programmed microprocessor/microcontroller. A coordinated arrangement of the angles they make causes the necessary movements required for performing intended operations.** With proper programming and end of arm tooling, an industrial robot can repeat complex motions and activities with no compromise in accuracy. Even more, it's possible to mount multiple end of arm tooling on the same arm. However, this method is not common among industrial robots. More commonly, each robot focuses only on one single task **[4]**.

The complexity of motion obtainable by the robotic arm is determined by the following parameters:

i. ***Degree of Freedom (DoF)***: the total number of axial rotation at all joints of the robot as shown in **figure 1.2** below.

ii. ***Robot Workspace***: Three dimensional volume of space reachable by the robot arm respectively.

The motion of the robot arm while interacting with its environment is studied as the kinematics of the arm. This is further discussed in-depth in Chapter three.

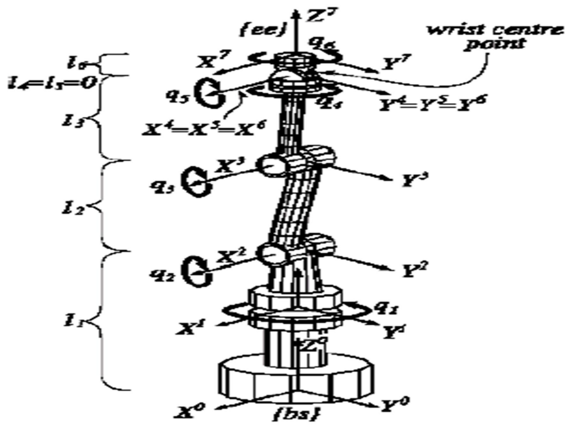


Fig 1.2: a robotic arm sketch showing 5 degrees of freedom.

1.1 BACKGROUND OF STUDY

Traditionally, many types of work can be done manually through a dexterous manipulation of the human arm. There is however the need to perform specialized operations in certain work environments with much effectiveness and pin point accuracy which dwarfs that obtainable by the human arm. Minimizing errors to the barest minimum, eliminating weariness and boredom associated with manual processes and speeding up production has been the driving force behind the automation of many industrial processes. Before recent times, industrial automation is mostly achieved entirely without the use of robots. This is achieved through a rich deployment of such electronic devices as PLCs, relays and various actuators. In such applications, industrial automation are only limited to processes with minimal mechanical requirements where translational movements of open solid material is almost absent or minimal.

This solution is inadequate in manufacturing industries such as car factories where materials, parts and heavy components or tools have to be handled in various orientations. Transferring components between locations and fixing parts in required positions with extremely high accuracy and precision are among tasks performed repeatedly in these industries. Often times, in dangerous work environments such as in arc welding it is in this special work conditions that robotic arms are employed for industrial automation. This novel solution eliminates the inconvenience encountered by workers when they have to repeat a task over and over again which makes a job boring over time no matter how interesting it may seem initially. It eliminates the possibilities of exposing workers to hazardous conditions in such environments as nuclear power plants, arc welding workshop and outer space exploration. Current systems installed in industries are mostly controlled by humans using an arm-like control stick e.g. outer space exploratory robots and nuclear reactor robotic assistive arms. In places where these arm-like control stick are absent, the arms are usually designed to perform just one task repeatedly (e.g. manufacturing industries) usually through a computer interface. However possibilities exist to integrate several functions into one arm- both automatic and controlled- with better means of control than is currently the case in industries.

1.2 PROBLEM STATEMENT

The current situation where most robotic arms are designed to perform just one operation in their places of application poses a high degree of limitation on these versatile manipulators. Deploying such systems for the many specialized industrial processes which needs to be automated with robots often proves to be too costly in the long run. Also, complete automation (without human intervention) in non critical applications is one goal which researchers are heavily engaged in. However, for processes which still have to be under human supervision and control for ethical reasons, devising ergonomically sound and highly interactive medium for controlling the robotic arm is one area that has also attracted serious attention. From the fore going, the need to reduce cost through designing a multifunctional (adaptable), automatic and also easy human controllable robotic arm are the core issues this project seeks to address.

1.3 AIMS AND OBJECTIVES

This project is driven with the purpose of designing and building a prototype robotic arm which is capable of:

1. Automatically (without human assistance) locating the position of objects placed within 10-30cm radius from its base, picking the object and placing at a predetermined spot.
2. The robot is to have mode selection buttons which will allow users to select a different mode of operation such as autonomous pick/place or receiving command through wireless joystick (PS2 gamepad) for human controlled operations.
3. Mechanically, the robot is to have 5 **degree-of-freedom** with a **robot workspace** encompassing a volume radius of 35cm
4. Interfacing a PS/2 game pad with the robot embedded controller for manually manipulating it to perform various tasks.
5. Finally, creating a system to enable the robot store joint angles for various operatations by utilizing the Adaptive Neuro-Fuzzy inference System (ANFIS), thus enabling the robot to perform same operation without human control.

In summary the project is aimed at developing a robotic arm with the following specification:

- Degree-of-Freedom: 5

- Payload Capacity(Fully Extended) : 150gm
- Maximum Reach(Fully Extended) : 35cm
- Computer interface : USB
- Human Control interface: PS/2 game pad
- Shoulder Base Swivel : 180°
- Shoulder Pitch : 90°
- Elbow Pitch : 180°
- Wrist Pitch : 180°
- Gripper Opening(Max) : 8cm

1.4 JUSTIFICATION

Because of the evolutionary nature of robotic systems and the technological complexity of designing and constructing a robotic arm, this project serves to contribute to the knowledge reserve of current research and developments in robotic arms technology. It tries to solve the problem of multi tasking by integrating different capabilities into one device. This will normally require separate systems. Being the first of its kind in the department (EEE, FUTO) , it sets the foundation for future final year students interested in the work to begin from in advancing this project. Also, it presents ample opportunity to the students engaged in the project in applying knowledge acquired in mathematics, dynamics and kinematics together with embedded systems programming in the design and construction of the robotic arm. Finally, it sets the pace for future work which will advance this system to be done by students in the nearest future.

1.5 SCOPE

This is project work is limited to building a prototype of the robotic arm (not a real deployable unit). In this work, mathematically model of the system is done for a two dimensional work space and a two link arm using common mathematical tools such as trigonometry and dynamics for describing both the forward kinematics and inverse kinematics. Matlab run code is done for the forward/inverse kinematics using the design parameters. This work does not seek to build a high capacity system with advanced artificial intelligence. Most important parts used include Atmega2560 processor based Arduino Mega embedded systems development board for the processing/ control and small sized servo motors for actuating movements. Programming of the processor is done only, using Arduino based C programming language. The mechanical structure is built using acrylic plastic glass.

CHAPTER TWO

LITERATURE REVIEW

2.1 Early Developments in Robotic Arm Technology

Serious efforts at developing robotic arms began around the 1930s. The Wrist "Position Controlling Apparatus" (PCA) was patented in 1938 by Willard Pollard . This was a spray finishing robotic asrm that had five degrees-of-freedom and an electrical control system. Although Pollard never built his arm, his design (**figure 2.1**) and interest in an industrial application for automated robotic arms would spur on the ingenuity of others. Harold A. Roselund, working for De Vilbiss, developed another sprayer that was indeed manufactured. Both arms were very sophisticated for their time, and each solved movement at the respective joints in unique ways; however, the electronic controller systems lacked the fidelity required to make them broadly utilizable **[5]**.

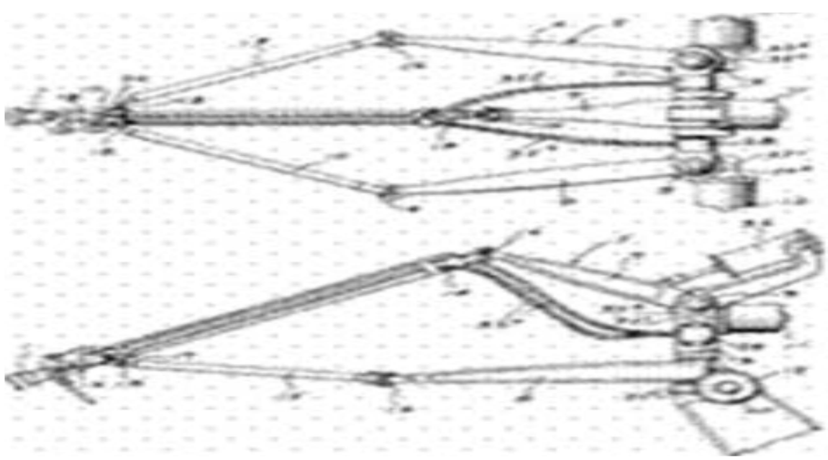


Fig2.1: Polard's painting arm**[5]**

The invention of integrated circuits technology in the early 1950s and the subsequent development of microprocessors which were integrated into microcomputers resulted in compressing electronic control systems into very small chip areas. This new technology possesses far more processing power than previous systems based on discrete components. The system consumes far less power than older generations of electronic computing devices. It was a combination of these new features in integrated circuits that made possible the development of VLSI’s and embedded systems with programmable memory thus ensuring intelligent control of devices like robots.

2.2 World’s First Programmable Robotic Arm

The first programmable robotic arm was designed in 1954 by George Devol in the USA which he named Universal Automation **[6]**. With its immediate application in industry, George Devol’s invention of the robotic arm has been the major driver of modern day production lines in automobile factories, speeding up product manufacturing throughout the world. His invention of the first robotic arm was immediately embraced by the Japanese. Today, over 50 years and running, George Devol’s invention has been speeding up production lines at manufacturing plants around the world. Robotic arms are now hard at work in production of everything from cars to pancakes. In 1961, Devol received patent for his invention (**figure2.2)** which was named Programmed Article Transfer **[7]**.

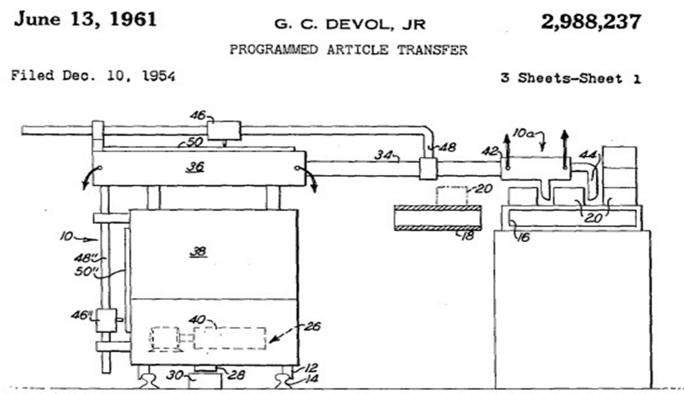


Fig2.2: Patent application sketch of the Programmed Article Transfer [7]

2.3 Early Advancements on the First Robotic Arm

“By 1956 Devol and Joseph Engelberger formed the world’s first robot company, Unimation. Unimate introduced its first robotic arm shown in **figure 2.3** in 1962. The arm was invented by George Devol and marketed by Joseph Engelberger. The Wrist industrial arm was installed at the General Motors plant in Ternstedt, New Jersey, for automated die casting. With this development, a host of academic centers became interested in the applications of microelectronics and the potential for these robotic arms.

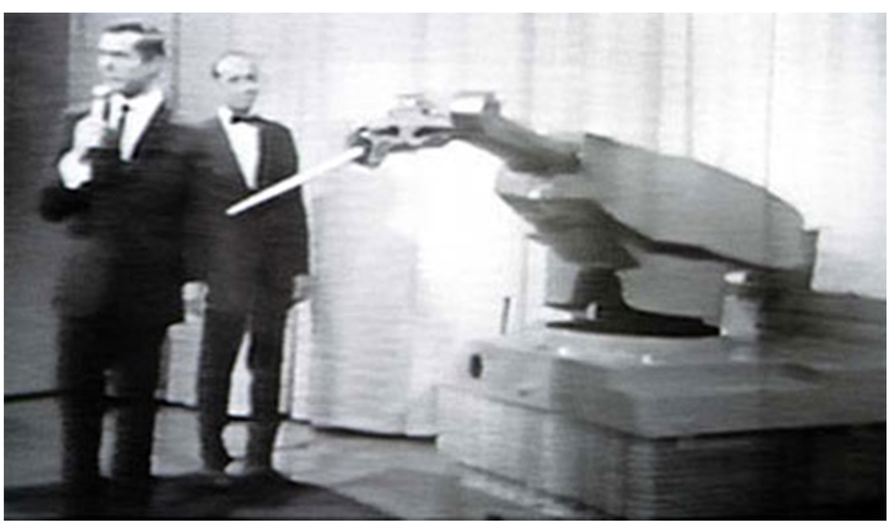


Fig2.3 An operational Unimate robot arm with George C. Devol and Joseph Engelberger inset [7]

A Stanford Research Institute investigator, Victor Scheinman, began working on electrically powered articulated arms that could move through six axes, which he called the Stanford arm.

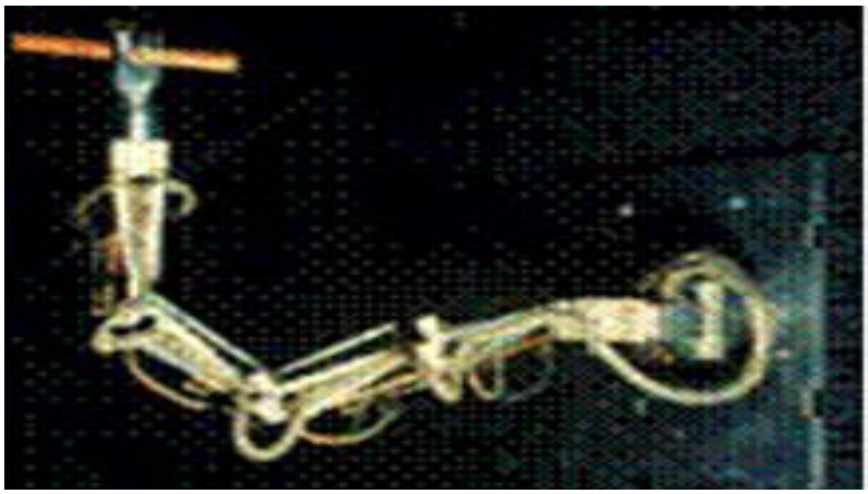


Fig2.4: Minsky's Tentacle Arm, 1968[5]

More complex tasks could now be given to the robotic arms. Marvin Minsky from MIT built the Minsky Tentacle Arm shown in **figure 2.4** above, for the office of Naval Research, for possible underwater exploration. Twelve single-degree-of-freedom joints were used to actuate this electro-hydraulic high-dexterity arm. Scheinman continued his work on robotic arms and, with backing from General Motors, Unimation developed Scheinman's technology into a Programmable Universal Machine for Assembly (PUMA)" **[5]**.

2.4 Time line of Industrial Robots

After Devol's invention, serious attention given to the development of more efficient robotic arms by both individuals and institutions led to further advancement industrial applications. Major activities in the development of robotic arms over the years are presented in the timeline below:

- **1954:** The first programmable robot is designed by George Devol. He coins the term Universal Automation.
- **1956:** Devol and engineer Joseph Engelberger form the world's first robot company, Unimation.
- **1960:** Unimation is purchased by Condec Corporation and development of Unimate Robot Systems begins. American Machine and Foundry, later known as AMF Corporation, markets a robot, called the Versatran, designed by Harry Johnson and Veljko Milenkovic.
- **1962:** The first industrial robot was online in a General Motors automobile factory in New Jersey. It was Devol and Engelberger's UNIMATE. It performed spot welding and extracted die castings.
- **1969:** Nachi starts its robotic business.
- **1973:** German robotics company, KUKA, creates the first industrial robot with six electromechanically-driven axes. It is called the Famulus.
- **1974:** A robotic arm (the Silver Arm) that performed small-parts assembly using feedback from touch and pressure sensors was designed. Professor Scheinman, the developer of the Stanford Arm, forms Vicarm Inc. to market a version of the arm for industrial applications. The new arm is controlled by a minicomputer.
- **1974:** Industrial robots were developed and installed in Fanuc factory. Dr. Inaba, President of FANUC was rewarded with "the 6th Annual Memorial Award of Joseph Marie Jacquard" by the American NC Society. The production and sale of DC servo motors were started under GETTYS MANUFACTURING CO., INC license.

- **1977:** The Motoman L10 was introduced. It featured five axes and a maximum workload of 10 kg, which included the gripper. It weighed 470kg. The Motoman L10 was the first robot that Yaskawa introduced on the market.

- **1977:** ASEA, a European robot company, offers two sizes of electric powered industrial robots. Both robots use a microcomputer controller for programming and operation. Unimation purchases Vicarm Inc. during this year.

- **1978:** Vicarm, Unimation creates the PUMA (Programmable Universal Machine for Assembly) robot with support from General Motors. Many research labs still use this assembly robot.

- **1979:** Nachi developed the first motor-driven robots for spot welding.

- **1979:** OTC DAIHEN was known as OTC America. OTC was an acronym for the Osaka Transformer Company. Located in Charlotte, NC, OTC was originally a supplier of welding equipment for other transplant companies. They expanded to become a provider to the Japanese auto market of GMAW supplies. In these early years, OTC Japan introduced its first generation of dedicated arc welding robots.

- **1980:** The industrial robot industry starts its rapid growth, with a new robot or company entering the market every month.

- **1981:** Takeo Kanade builds the direct drive arm. It is the first to have motors installed directly into the joints of the arm. This change makes it faster and much more accurate than previous robotic arms.

- **1983:** The Remote Reconnaissance Vehicle became the first vehicle to enter the basement of Three Mile Island after a meltdown in March 1979. This vehicle worked for four years to survey and cleans up the flooded basement.
- **1984:** The Terregator pioneered exploration, road following and mine mapping. It was the world's first rugged, capable, autonous outdorr
- **1985:** OTC DAIHEN became the official OEM supplier of robots to the Miller Electric Company. Miller chose to assign different model numbers to the robots sold in the North American market. The prefixed the letters in the model with "MR," for Miller Robot. Miller no longer supports the robots that were manufactured in this era. The Japanese models featured their own number and name.
- **1987:** ASEA of Vasteras, Sweden (founded 1883) and BBC Brown Boveri Ltd of Baden, Switzerland, (founded 1891) announce plans to form ABB Asea Brown Boveri Ltd., headquartered in Zurich, Switzerland. Each parent will hold 50 percent of the new company.
- **1988:** The Motoman ERC control system was introduced with the ability to control up to 12 axes, more than any other controller at the time.
- **1989:** Nachi Technology Inc., U.S.A. is established.
- **1992:** FANUC Robot School was established. GM Fanuc Robotics Corporation was restructured to FANUC's wholly owned share holding company, FANUC Robotics Corporation, together with its subsidiaries, FANUC Robotics North America, Inc. and FANUC Robotics Europe GmbH. A Prototype of the intelligent robot was built.

- **1994:** The Motoman MRC control system was introduced with the ability to control up to 21 axes. It could also synchronize the motions of two robots.

- **1995:** Miller departed from the robotic business. OTC launched the Dynamic Robotic Division and moved the headquarters to Ohio to focus on selling robots to new users.

- **1996:** Nachi expands robotics business, cutting tool, and bearing product ranges.

- **1998:** The introduction of the XRC controller allowed the control of up to 27 axes and the synchronized control of three to four robots. The Motoman UP series introduced a simpler robot arm that was more readily accessible for maintenance and repair. Honda was instrumental in driving the development of both the UP series of arms and the XRC arm control.

- **2003:** OTC DAIHEN introduced the Almega AX series, a line of arc welding and handling robots. The AX series robots integrate seamlessly with the OTC D series welding power supplies for advanced control capabilities. **[6]**

2.5 Technology behind Today's Era of Industrial Robots

"Devol's industrial robots have their origins in two preceding technologies: *numerical control* for machine tools, and *remote manipulation.* Numerical control is a scheme to generate control actions based on stored data. Stored data may include coordinate data of points to which the machine is to be moved, clock signals to start and stop operations, and logical statements for branching control sequences. The whole sequence of operations and its variations are prescribed and stored in a form of memory, so that different tasks can be performed without requiring major hardware changes. Modern manufacturing systems must produce a variety of products in small batches, rather than a large number of the same products for an extended period of time, and frequent changes of product models and production schedules require *flexibility* in the manufacturing system. The transfer line approach, which is most effective for mass production, is not appropriate when such flexibility is needed **(Figure 2.5)**.

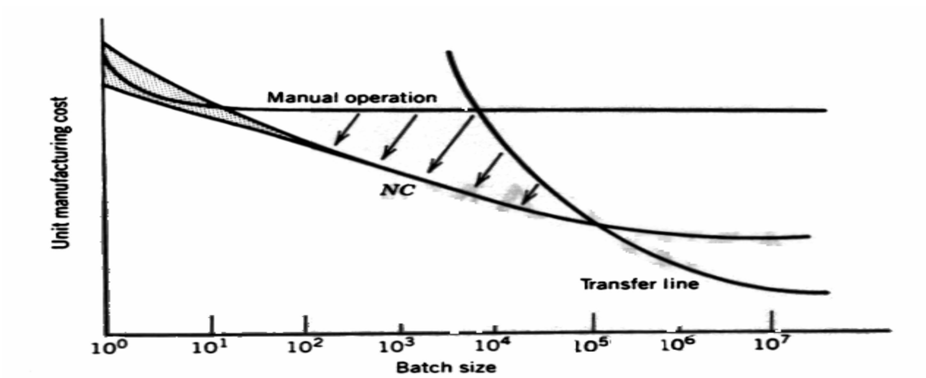


Figure 2.5: General trend of manufacturing cost vs. batch size[8]

When a major product change is required, a special-purpose production line becomes useless and often ends up being abandoned, despite the large capital investment it originally involved. Flexible automation has been a central issue in manufacturing innovation for a few decades, and numerical control has played a central role in increasing system flexibility. Contemporary industrial robots are programmable machines that can perform different operations by simply modifying stored data, a feature that has evolved from the application of numerical control.

Another origin of today's industrial robots can be found in remote manipulators. A remote manipulator is a device that performs a task at a distance. It can be used in environments that human workers cannot easily or safely access, e.g. for handling radio-active materials, or in some deep sea and space applications.

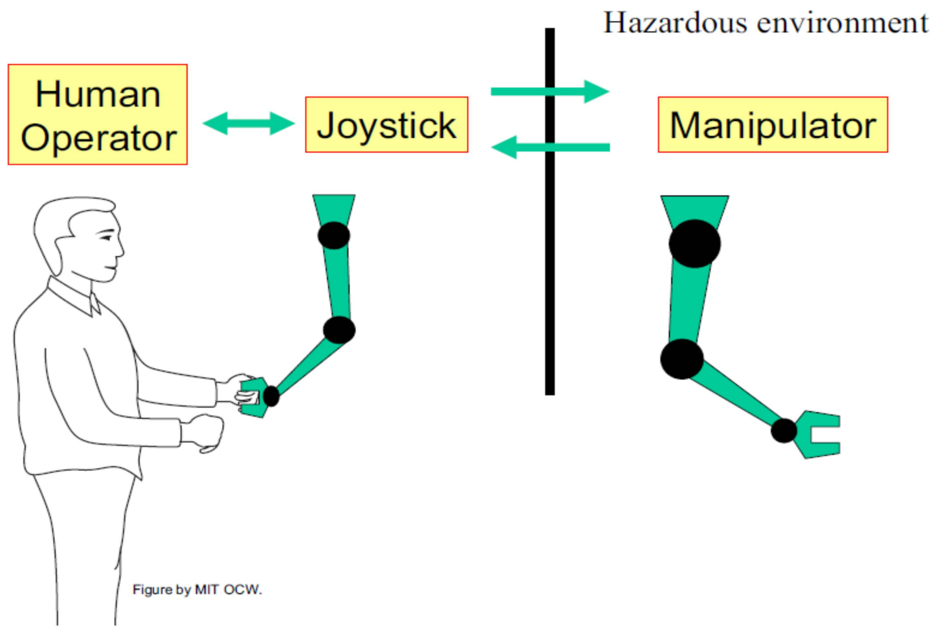


Fig2.5: Remote manipulation of robotic arm [8]

The first *master-slave manipulator* system was developed by 1948. The concept involves an electrically powered mechanical arm installed at the operation site, and a control joystick of geometry similar to that of the mechanical arm (**figure 2.6**). The joystick has position transducers at individual joints that measure the motion of the human operator as he moves the tip of the joystick. Thus the operator's motion is transformed into electrical signals, which are transmitted to the mechanical arm and cause the same motion as the one that the human operator performed. The joystick that the operator handles is called the *master* manipulator, while the mechanical arm is called the *slave* manipulator, since its motion is ideally the replica of the operator's commanded motion. A master-slave manipulator has typically six degrees of freedom to allow the gripper to locate an object at an arbitrary position and orientation. Most joints are revolute, and the whole mechanical construction is similar to that of the human arm. This analogy with the human arm results from the need of replicating human motions. Further, this structure allows dexterous motions in a wide range of workspaces, which is desirable for operations in modern manufacturing systems. Contemporary industrial robots retain some similarity in geometry with both the human arm and remote manipulators. Further, their basic concepts have evolved from those of numerical control and remote manipulation. Thus a widely accepted definition of today's industrial robot is that of a numerically controlled manipulator, where the human operator and the master manipulator in the figure are replaced by a numerical controller" **[8]**.

2.6 Current Trends in Robotic Arms Applied in Surgery

The progress made so far in robotic arm technology and its ubiquitous application in virtually every field of human endeavour is tremendous. Today, aside the manufacturing industries, surgical operations have been successfully automated using advanced robots. The world's first surgical robot was the "Arthrobot" **(figure 2.7)**, which was developed and used for the first time in Vancouver, BC, Canada in 1983 **[9]**.

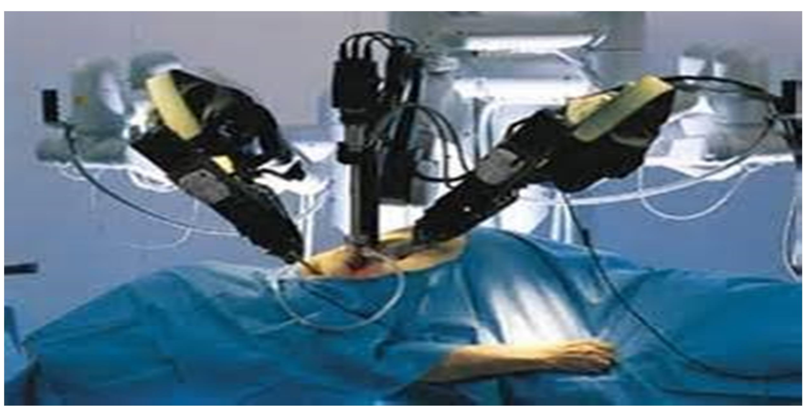


Fig2.7: Arthrobot performing an operation on a patient [9]

The robot was developed by a team led by Dr. James McEwen and Geof Auchinlek, in collaboration with orthopaedic surgeon, Dr. Brian Day. In related projects at that time, other medical robots were developed, including a robotic arm that performed eye surgery and another that acted as an operating assistant, and handed the surgeon instruments in response to voice commands. Further development of robotic systems was carried out by Intuitive Surgical with the introduction of the da Vinci Surgical System and Computer Motion with the AESOP and the ZEUS robotic surgical systems. The da Vinci System shown in **figure 2.8** was approved by the United States Food and Drug Administration in the year 2000. It was used for about 48000 procedures by the year 2006 and sells for $1.2 million [9].

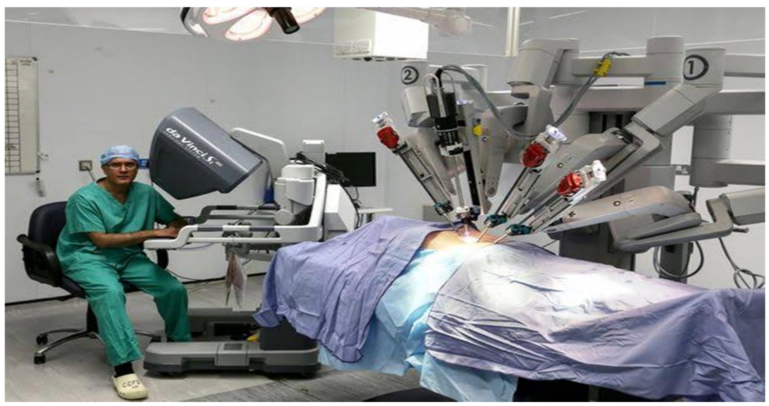


Figure2.8: Da Vinci robot performing an operation [7]

Similar units developed are outlined in the timeline below:

- In 1985 a robot, the PUMA 560 was used to place a needle for a brain biopsy using CT guidance.
- In 1988, the PROBOT, developed at Imperial College London, was used to perform prostatic surgery.
- In 1992, the ROBODOC form Integrated Surgical Systems was introduced to mill out precise fittings in the femur for hip replacement.
- In 1997 a reconnection of the fallopian tubes operation was performed successfully in Cleveland using ZEUS.

- In May 1998, Dr. Friedrich-Wilhelm Mohr using the Da Vinci surgical robot performed the first robotically assisted heart bypass at the Leipzig Heart Centre in Germany.
- On September 2nd 1999, Dr. Randall Wolf and Dr. Robert Michler performed the first robotically assisted heart bypass in the USA at The Ohio State University.
- In October 1999 the world's first surgical robotics beating heart coronary artery bypass graft (CABG) was performed in Canada by Dr. Douglas Boyd and Dr. Reiza Rayman using The ZEUS surgical robot.
- In June 2008 the German Aerospace Center (DLR) presented the first robotic system for minimally invasive surgery with force-feedback in 7 DOF in the tip of the instrument, distal of the 2-DOF hand wrist (Mirosurge).

Development of the robotic arm, its applications whether industrial, Extraterrestrial (space) or Surgical has a very rich history with diverse topics to be covered. It is one technology which although tremendous progress has been made on but is still on the course of technological improvements. This is hinge on the quest to achieve a completely autonomous system that can be integrated into larger robotic systems for non human operations.

2.7 Robot Arm parameters and Terminology

In designing and building the robot arm, certain technical terms and concepts are needed to fully describe and understand the intricacies of the work. Terms, tools and materials which will continually feature in the rest of this document are presented here for full understanding by the reader.

2.7.1 Robot Workspace: The robot workspace (or reachable space) is all points on a 2 dimensional area or three dimensional volume that the robot end effector can reach. It can be defined as the work volume in a three dimensional spatial consideration or the total number of points the mechanism of the robot allows it to reach. The workspace is dependent on the degree of freedom (DOF), angle/translation limitations, the arm link lengths, the angle at which something must be picked up at, etc. The workspace is highly dependent on the robot configuration whether cylindrical, Cartesian, Gantry, SCARA or Anthropomorphic (articulated) as in this project.

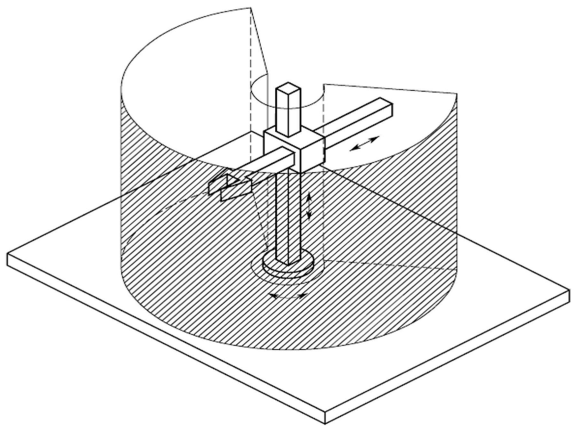


Fig2.9a: Workspace of a cylindrical robot arm [a]

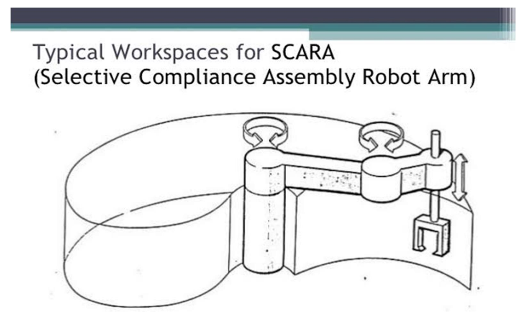


Fig2.9b: Workspace of a SCARA robot arm[b]

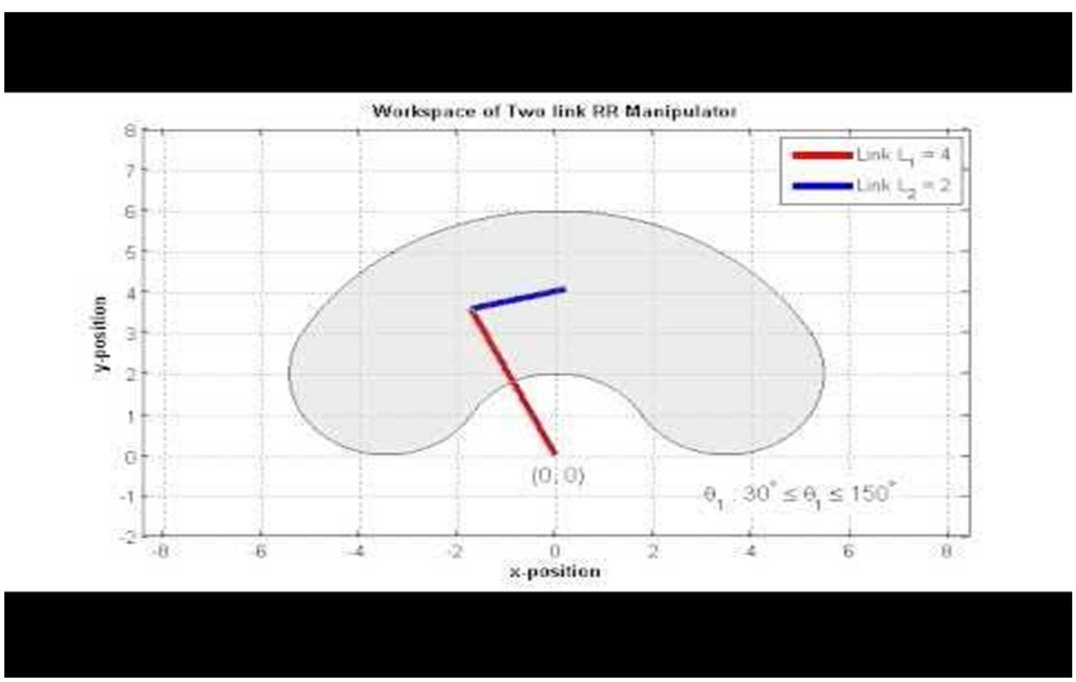


Fig2.9c: 2-D workspace of a Two Link robot arm (This is the work space of the robot designed in this project) [c]

2.7.2 Degree-Of-Freedom: this is used to describe a robot's freedom of motion in three dimensional space—specifically, the ability to move forward and backward, up and down, and to the left and to the right. For each degree of freedom, a joint is required. Each degree of freedom is a place where it can bend or rotate or translate. You can typically identify the number of degrees of freedom by the number of actuators on the robot arm. **Figure 3.1** is a comparison of the human arm and the robotic arm degree of freedom.

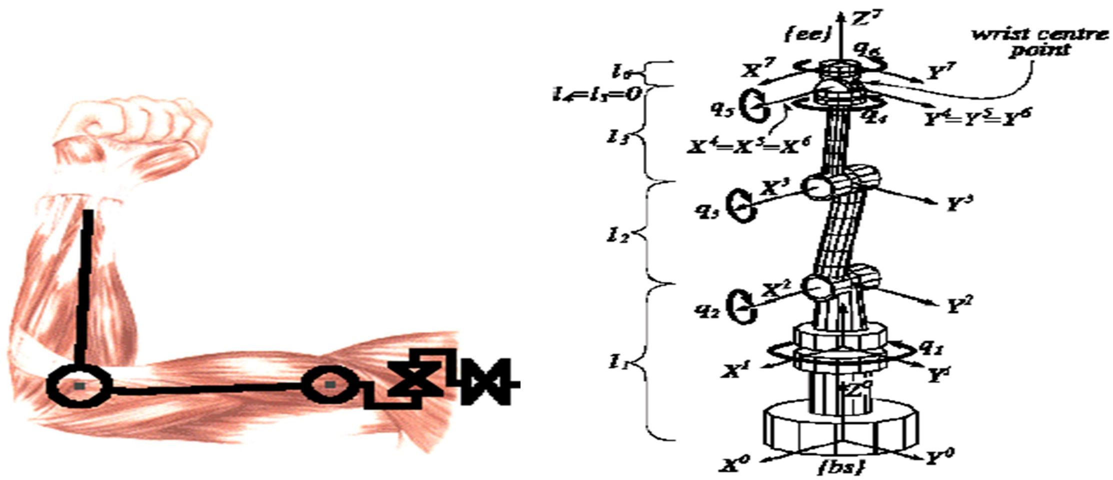


Fig2-10: A comparative sketch of the human arm and a robotic arm showing different degrees of freedom [d]

2.7.3 End Effector: This is the mechanism, tool or device which is attached to the end of the robot arm. It is the part of the robot through which it interacts with the environment. It handling and manipulating things and performing specific operations. The end effector can be as simple as a gripper for picking objects or as complex as a set of surgical apparatus for performing specialized automated operations.

2.7.4 Forward and Inverse Kinematics

"Kinematics is the science of motion. In a two-joint robotic arm, given the angles of the joints, the kinematics equations give the location of the tip of the arm. Inverse kinematics refers to the reverse process. Given a desired location for the tip of the robotic arm, what should the angles of the joints be so as to locate the tip of the arm at the desired location? For an n>2 arm linkages, there are usually more than one solution and can at times be a difficult problem to solve. This is a typical problem in robotics that needs to be solved to control a robotic arm to perform tasks it is designated to do. In a 2-dimensional input space, with a two-joint robotic arm and given the desired coordinate, the problem reduces to finding the two angles involved. The first angle is between the first arm and the ground (base) the second angle is between the first arm and the second arm [10]."

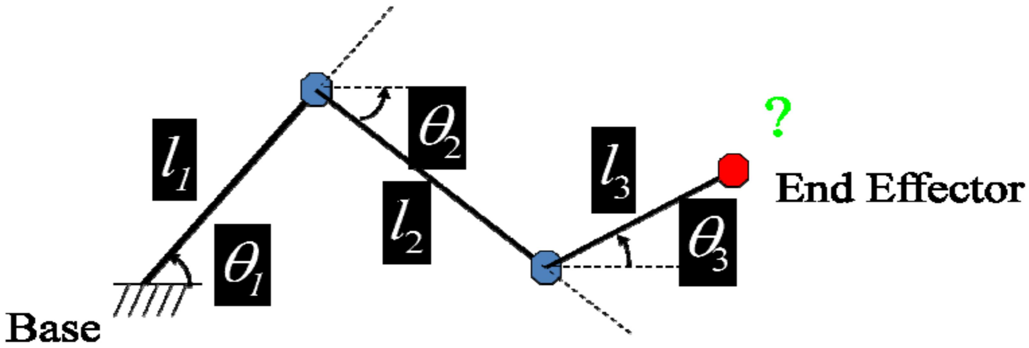


Fig2.11: A two-link robot arm with end effector showing forward kinematic [11]

From the above discussion, robot kinematics is mainly of the following two types: forward kinematics and inverse kinematics **[11]**. The set of points which a particular arm configuration can reach is called the **forward kinematics**. It is more of controlling the robot arm to reach various positions for different arm orientations that is accurately known. In forward kinematics, the length of each link and the angle of each joint are given and we have to calculate the position of any point in the work volume of the robot. While in **inverse kinematics**, the position of the specific points in the workspace is given and we have to calculate the angle of each joint to reach such points.

The following methods can be used to solve kinematics problems (forward and inverse).

- **Straight forward geometrical deductions:** This is the simplest method and is often used where the robot workspace is a 2-D planar area. The possible geometrical arrangement of the arm is visualized and drawn on paper. Equations modeling arm-joint angles with respect to possible object positions are derived. **This is the particular method adopted in this work.**
- **ANFIS (adaptive neuro-fuzzy inference system):** An extension of the straight forward geometrical deduction method above is the ANFIS. This method is based on fuzzy logic and can give learning capabilities to the robot. **Part of the work on this project is based on this method.**

- **Transformational Matrices:** This is a more complex system used for n-joint robot arm with a 3-D workspace (correctly referred to as work volume). It uses advanced mathematical tools such as the Jacobian transformations. This method is beyond the scope of this work.

2.8 A Fuzzy Solution of the Inverse Kinematics

"For simple structures like the two-joint robotic arm, it is possible to mathematically deduce the angles at the joints given the desired location of the tip of the arm. However with more complex structures (e.g.: n-joint robotic arms operating in a 3-dimensional input space) deducing a mathematical solution for the inverse kinematics may prove challenging. Using fuzzy logic, we can construct a Fuzzy Inference System that deduces the inverse kinematics if the forward kinematics of the problem is known, hence sidestepping the need to develop an analytical solution. Also, the fuzzy solution is easily understandable and does not require special background knowledge to comprehend and evaluate it. In the following section, a broad outline for developing such a solution is described, and later, the detailed steps are elaborated.

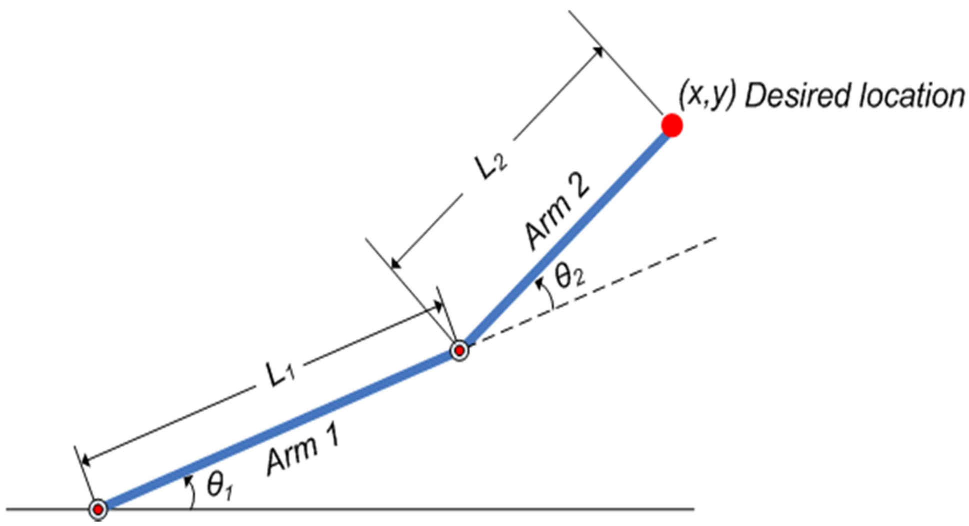


Fig2.12: Illustration showing the two-joint robotic arm with the two angles, theta1 and theta2 [10]

Since the forward kinematics formulae for the two-joint robotic arm are known, x and y co-ordinates of the tip of the arm are deduced for the entire range of angles of rotation of the two joints. The co-ordinates and the angles are saved to be used as training data to train ANFIS (Adaptive Neuro-Fuzzy Inference System) network. During training the ANFIS network learns to map the coordinates (x,y) to the angles (theta1, theta2). The trained ANFIS network is then used as a part of a larger control system to control the robotic arm. Knowing the desired location of the robotic arm, the control system uses the trained ANFIS network to deduce the angular positions of the joints and applies force to the joints of the robotic arm accordingly to move it to the desired location.

2.9. ANFIS

ANFIS stands for Adaptive Neuro-Fuzzy Inference System. It is a hybrid neuro-fuzzy technique that brings learning capabilities of neural networks to fuzzy inference systems. The learning algorithm tunes the membership functions of a Sugeno-type Fuzzy Inference System using the training input-output data. In this case, the input-output data refers to the "coordinates-angles" dataset. The coordinates act as input to the ANFIS and the angles act as the output. The learning algorithm "teaches" the ANFIS to map the co-ordinates to the angles through a process called training. At the end of training, the trained ANFIS network would have learned the input-output map and be ready to be deployed into the larger control system solution."[10]

2.10 Structural Description of the Robot Arm

In designing the robot arm, a brief structural description of the physical frame-work is first given with reference to **figure 2.13** below.

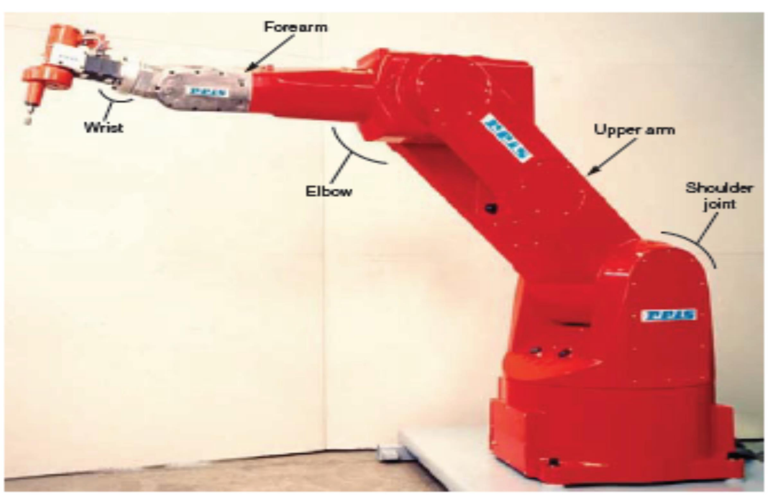


Fig2.13: A robotic arm showing different parts [e]

The arm is structurally divided into the following sections:

Base: This is the platform on which the whole structure rests. It can either be mobile (locomotive as in search robots e.g. Mars Rover built by NASA) or stationary like industrial robots used in assembly lines. **The base of the arm built in this project is of the stationary type. However locomotion can be added students working on the project in a future version.**

Upper of Hind arm: This is the appendage linked with the base through a "shoulder" joint. It is equivalent to the humerus of the human arm. The forward part of the hind arm makes an "elbow" joint with the forearm.

Forearm: This is the second and final linkage of a two link robot arm. It connects with the hind arm to form an "elbow joint". It is equivalent to the radius/ulna of the human arm. The forward part of the forearm forms the "wrist" joint with the end effector.

End Effector: As described above in section …. It is the end tool of the arm which interacts with objects in the environment. The end effector used here is a gripper for picking and holding objects.

Actuators: These are force producing mechanisms which are incorporated to the joints of the robot arm. Usually, they are electromechanical devices like servo motors (used here), stepper motors or hydraulic systems. It is the actuators that give "mechanical live" to the robot arm.

CHAPTER 3

MATERIALS AND METHODS

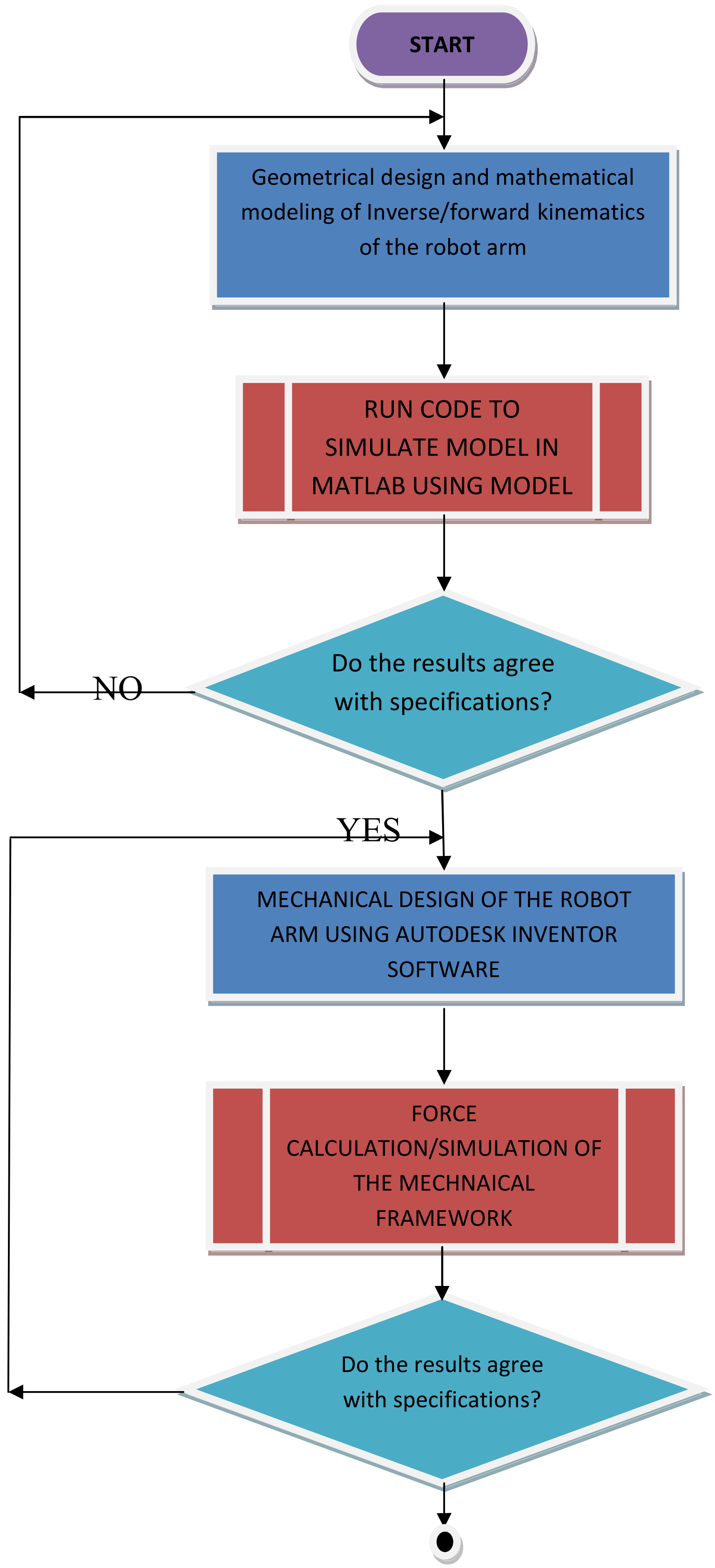
3.1 Methodology-overview

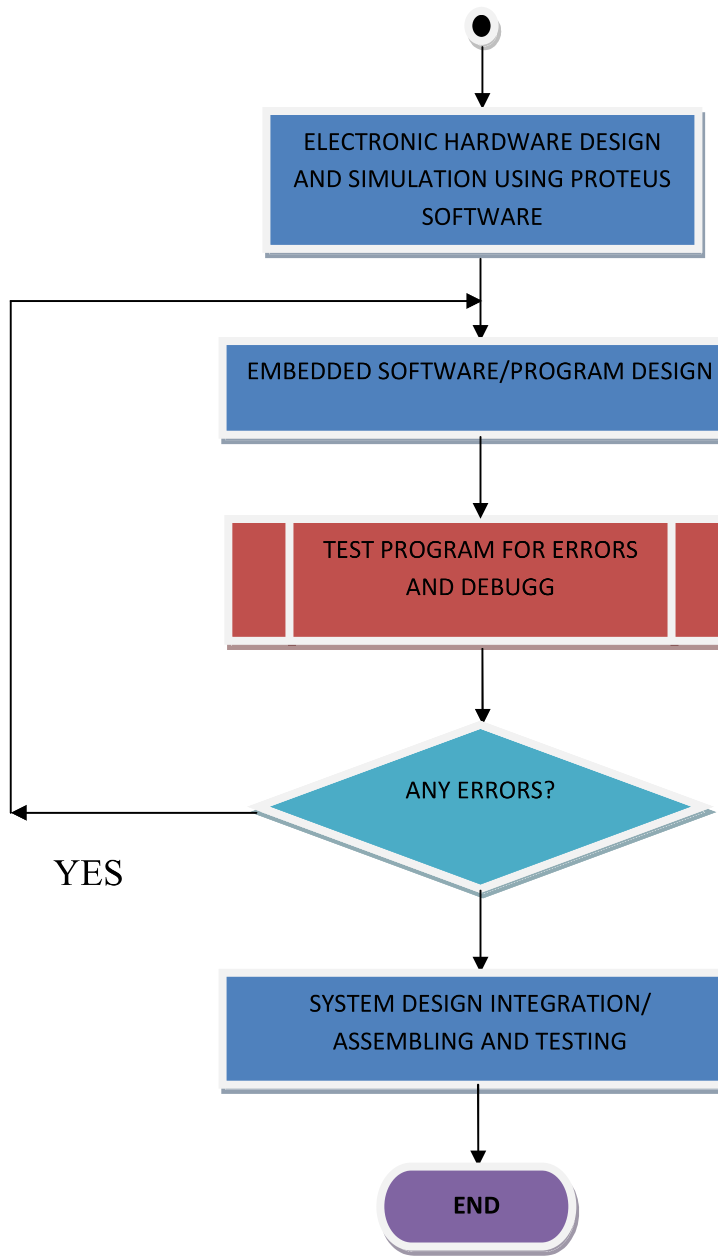
With the goal of achieving the aims and objectives stated in section 1.3; the procedures employed in the course of the development of the robotic arm are outlined in the flow diagram of **figure 3.1** below. The project involves both hardware and software design activities. The hardware is further subdivided into mechanical hardware and electronic hardware (circuits and boards). Ideas for the mechanical hardware are developed on a mathematical (theoretical) framework. The variables developed mathematically are taken as entrant data for a Matlab software simulation. Upon successful Matlab simulation, a three dimensional (3-D) image of the robot arm is created using Autodesk Inventor software. Simulation results are collated and the mechanical hardware built using specified materials.

Secondly, relevant electronic circuits/boards such as motor drivers, and power circuits which will integrate with the mechanical hardware are built. Electronic hardware modules like the popular Arduino board; HC-506 Arduino compatible Bluetooth shield, 16x2 LCD screen, distance sensors, USB camera and wireless PS2 gamepad are also employed as part of the electronic hardware.

The final step is the design and development of the embedded software which gives intelligence to, and makes the previously ‘dead’ hardware to come alive. The embedded program is written with the Arduino language (which is based on C++) in the Arduino IDE. The approach used in developing the software is modular (i.e. divide and conquer) where the whole software system is divided into key components which are further divided into subunits. The subunits are coded and integrated to form the main software system.

SYSTEM DESIGN FLOW CHART




ELECTRONIC HARDWARE DESIGN AND SIMULATION USING PROTEUS SOFTWARE
EMBEDDED SOFTWARE/PROGRAM DESIGN
TEST PROGRAM FOR ERRORS AND DEBUGG
ANY ERRORS?
YES
SYSTEM DESIGN INTEGRATION/ ASSEMBLING AND TESTING
END

3.2 Geometrical Design/Mathematical modeling of the Robot arm

The figure below shows a geometrical layout of the planer view of the robot arm structure. From here trigonometric equations are derived which models the systems inverse kinematic equations. The main variables of the system are the object's distance x_o from the base, the arm's joint angles $\theta_1,\ \theta_2\ and\ \theta_3$. These variables are used as inputs to model both the forward and inverse kinematics of the system. L_1 and L_2 are the arm lengths for the hind and fore arms respectively. H is the height of the shoulder base structure on which the hind arm pivots.

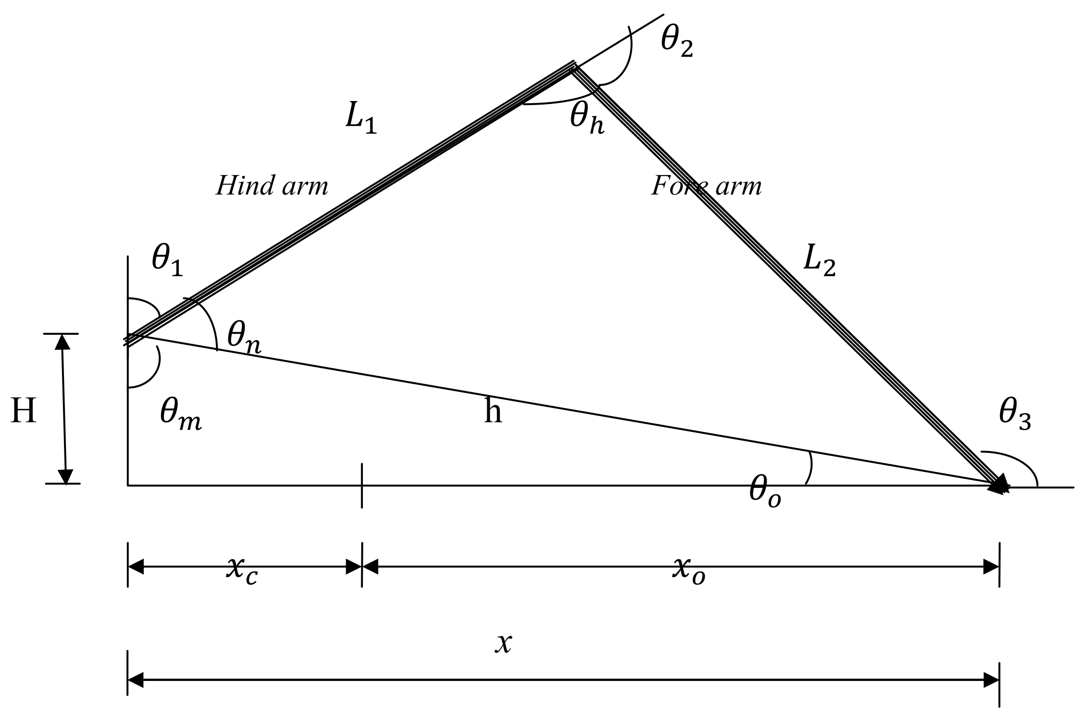


Fig 3.7: Schematic of the robot arm showing a planar view.

From figure 3.3 above, the following equations can be derived as follows

θ_1 = angle made by hind arm with respect to the vertical axes

θ_2 = angle made by for arm with respect to hind arm

θ_3 = angle made by gripper with respect to the fore arm

x_c = 6cm –Constant distance from base axes to edge of the base.

x_o = object distance detected by distance sensor

x_c= fixed distance of ultrasonic sensor from base axis

H = 8cm default value height of the shoulder base

Given the object distance obtained through an ultrasonic distance sensor we have

$$x_h = x_c + x_o \quad (3.1)$$

$$\theta_m = \tan^{-1}(\frac{x}{H}) \quad (3.2)$$

$$\theta_0 = 90 - \theta_m \quad (3.3)$$

We solve for θ_2 as follows:

$x_h{}^2 + H^2 = h^2$ ……Pythagoras theorem

$$h = \sqrt{(H^2 + x_h{}^2)} \quad (3.4)$$

$$h^2 = L_1{}^2 + L_2{}^2 - 2L_1L_2Cos\theta_h \quad (3.5)$$

$$L_1{}^2 + L_2{}^2 - h^2 = 2L_1L_2Cos\theta_h \quad (3.6)$$

$$Cos\theta_h = (L_1{}^2 + L_2{}^2 - h^2)\frac{1}{2L_1L_2} \quad (3.7)$$

$$\theta_h = Cos^{-1}[\frac{L_1{}^2+L_2{}^2-h^2}{2L1_2L_2}] \quad (3.8)$$

$$\theta_2 = 180 - \theta_h \quad (3.9)$$

We solve for θ_n as follows:

$$L_2{}^2 = L_1{}^2 + h^2 - 2L_1hCos\theta_n \quad (3.10)$$

$$Cos\theta_n = \left(L_1{}^2 + h^2 - L_2{}^2\right)/2L_1h \quad (3.11)$$

$$\theta_n = Cos^{-1}\left[\left(L_1{}^2 + h^2 - L_2{}^2\right)/(2L_1h)\right] \quad (3.12)$$

Finally,

$$\theta_1 = 180 - \theta_m - \theta_n \quad (3.13)$$

$$\theta_3 = \theta_n + \theta_h - \theta_o \quad (3.14)$$

With input data of x_o, x_c and H a table of results (table 4.1) for individual values of θ_1, θ_2 and θ_3 are generated for specific values of object position x_o (see chapter four).

3.3 Matlab program to test the mathematical model

Code 1: generates table of values for joint angles

```
%%%%AUTHOR: OGWUDIRE BONIFACE UMUNNA 20111786893%%%%%%%%
%%%%DEPARTMENT OF ELECTRICAL ELECTRONIC ENGINEERING%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%FUTO%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%CODE DATE: SEPTEMBER, 2016%%%%%%%%%%%%%%%%%
%=============================================================%
%This program will calculate the values of theta1, theta2 and
%theta3 given the object position x0.

%Variable initializing
H = 8;
xc = 6;
L1 = 11;
L2 = 10.5;
%INITIALISE JOINT ANGLES THETA1, THETA2 AND THETA3
theta1 =0.0;
theta_h =0.0;
theta3=0.0;
thetaN=0.0;
thetaM=0.0;
%CALCULATE JOINT ANGLES FOR OBJECT PLACED WITHIN 10cm to 20cm
for xo=4:1:14;
x = xc + xo;
h = sqrt(x.^2 + H.^2);

%Begin calculations for joint angles using imaginary
%angle m as start point

thetaM = atand(x/H);

theta_o = 90 -thetaM;

q= (L1.^2 + L2.^2-h.^2)/(2*L1*L2); %Cosine formula

theta_h = acosd(q); %Solve for theta_h

theta2 = 180-theta_h; %Solve for theta2

r= (L1.^2 + h.^2 - L2.^2)/(2*L1*h); %Cosine formular

thetaN = acosd(r);

theta1 = (180 - thetaM - thetaN); %Solve for theta1

theta3 = thetaN + theta_h - theta_o; %Solve for theta3
```

```
%Generate table of values after computation
Table_Angles = table(xo,xc,x,thetaM,thetaN,theta_h,theta1,theta2,theta3)
End
```

Code 2 (Modified): Generates a figure of the workspace for theta angles from 0-90 degrees

The following codes were run on matlab (version 2014a). The original codes were obtained from the official website of Matlab (http://www.mathworks.com). The source codes were modified to suit the system parameters designed here. The run codes generated the 2-D view of the robot workspace shown in **figures 4.1 and 4.2**. The Matlab command is: **edit('traininv')**. This code when keyed into the command line generates the following code (which has been edited in this case with modifications in L_1 *and* L_2 and the angular limits of θ_1 *and* θ_2).

```
%TRAININV
% Data generation script for the inverse kinematics demo
% - Data generation through direct kinematics
% - Data generation through inverse kinematics
%
% Code is written in unvectorized form for understandability. Refer the
% demo for the vectorized version of the code.
%
%   J.-S. Roger Jang, 6-28-94.
%   Madan Bharadwaj, 6-20-05
%   Copyright 1994-2005 The MathWorks, Inc.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   EDITED BY OGWUDIRE, BONIFACE UMUNNA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DIRECT KINEMATICS
%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Deducing x and y coordinates using direct kinematics formulae
% x = f(theta1, theta2)
% y = g(theta1, theta2)

l1 = 11; % CHANGED TO LENGTH OF FIRST ARM
l2 = 10.5; % CHANGED TO LENGTH OF SECOND ARM

theta1 = 0:0.1:pi/2; % some first angle
theta2 = 0:0.1:pi; % some second angle
[THETA1, THETA2] = meshgrid(theta1, theta2);% generate a grid of theta1 and
theta2 values
X = 11*cos(THETA1) + 12 * cos(THETA1 + THETA2); %compute x coordinates
Y = 11*sin(THETA1) + 12 * sin(THETA1 + THETA2); %compute y coordnates

data1 = [X(:) Y(:) THETA1(:)]; %create x-y-theta1 dataset
```

```
data2 = [X(:) Y(:) THETA2(:)]; %create x-y-theta2 dataset

for i=1:1:length(theta1)
    for j=1:1:length(theta2)

        x = l1 * cos(theta1(i)) + l2 * cos(theta1(i)+theta2(j)); % x
coordinate
        y = l1 * sin(theta1(i)) + l2 * sin(theta1(i)+theta2(j)); % y
coordinate

        data2 = [data1; x y theta1(i)];
        data2 = [data2; x y theta2(j)];
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%
% INVERSE KINEMATICS
%%%%%%%%%%%%%%%%%%%%%%%%%%
% Deducing theta1 and theta2 from x and y coordinates using inverse
% kinematics formulae
% theta1 = f(x, y)
% theta2 = g(x, y)
l1 = 11; % length of first arm
l2 = 10.5; % length of second arm
X = 0:0.1:8; % x coordinates for validation
Y = 8:0.1:16; % y coordinates for validation
theta1D = [];
theta2D = [];
xy = [];

for i = 1:1:length(X)
    for j = 1:1:length(Y)

        x = X(i);
        y = Y(j);
        c2 = (x^2 + y^2 - l1^2 - l2^2)/(2*l1*l2);
        s2 = sqrt(1 - c2^2);
        theta2 = atan2(s2, c2); % theta2 is deduced

        k1 = l1 + l2*c2;
        k2 = l2*s2;
        theta1 = atan2(y, x) - atan2(k2, k1); % theta1 is deduced

        theta1D = [theta1D; theta1]; % save theta1
        theta2D = [theta2D; theta2]; % save theta2

        xy = [xy; x y]; % save x-y coordinates
    end
end

plot(X(:), Y(:), 'r.');
axis equal;
xlabel('X','fontsize',10)
title('X-Y co-ordinates generated for all theta1 and theta2 combinations
using forward kinematics formula','fontsize',10)
```

3.4 Mechanical Hardware Specifications:

3.4.1 Mechanical Framework

Gripper length = 20cm

Weigth of gripper =113.40g

Maximum gripper opening width = 6.0 cm

Length of hind arm L_1= 11.00 cm

Length of forearm L_2 = 10.5cm

Weight of forearm =112.47g

Weight of hind arm = 12.47g

Height of swivel base *H*= 8.0cm

Height of base platform = 5.0cm

Width of hind and for arms = 5.0-5.5cm

3.4.2 MG995 (Base) Servo Motor Specifications

- Weight: 55 g
- Dimension: 40.7 x 19.7 x 42.9 mm approx.
- Stall torque: 8.5 kgf·cm (4.8 V), 10 kgf·cm (6 V)
- Operating speed: 0.2 s/60º (4.8 V), 0.16 s/60º (6 V)
- Operating voltage: 4.8 V a 7.2 V
- Dead band width: 5 µs
- Stable and shock proof double ball bearing design
- Temperature range: 0 ºC – 55 ºC

3.4.3 MG996r (Joints) Servo motor Specification

- Operating speed: 0.17sec / 60Ã‚Â° (4.8V no load), 0.14sec / 60Ã‚Â° (6.0V no load).
- Stall torque: 13 kg / cm (180.5 oz-in) at 4.8V, 15 kg / cm (208.3 oz-in) at 6.0V.

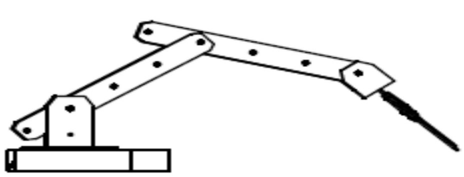
- Operation voltage: 4.8 - 7.2V.
- Temperature range: 0Ã‚Â°C -- 55Ã‚Â°C.
- Dead band width: 5usec.
- Dimension: 40mm x 19mm x 43mm.
- Weight: 55g.
- Gear type: metal gears.
- Connector wire length: 300mm.

3.4.4 SG90 Tower Pro (Gripper) Micro Servo motor specification

- Operating speed: **4.8v:** 0.12sec/60^o
- Stall torque: **4.8v:** 1.8 kg-cm
- Operation voltage: 4.8v
- Weight: 9.0g
- Dimension: 23mmx12.2mmx29.0mm
- Pulse Width: 500-2400us
- Connector type: JR
- Gear type: plastic
- Motor type: 3-pol

3.5 Hardware Design of Mechanical Framework

This task was carried out using AutoDesk Inventor CAD software. The framework of the robot arm was drawn in 3-D view using this CAD tool. The design diagrams are shown in figures 3.10-3.17 below showing separate structural components.



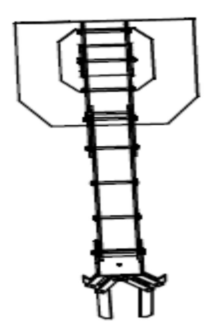


Fig3.10: Side and Plan view of the robotic arm.

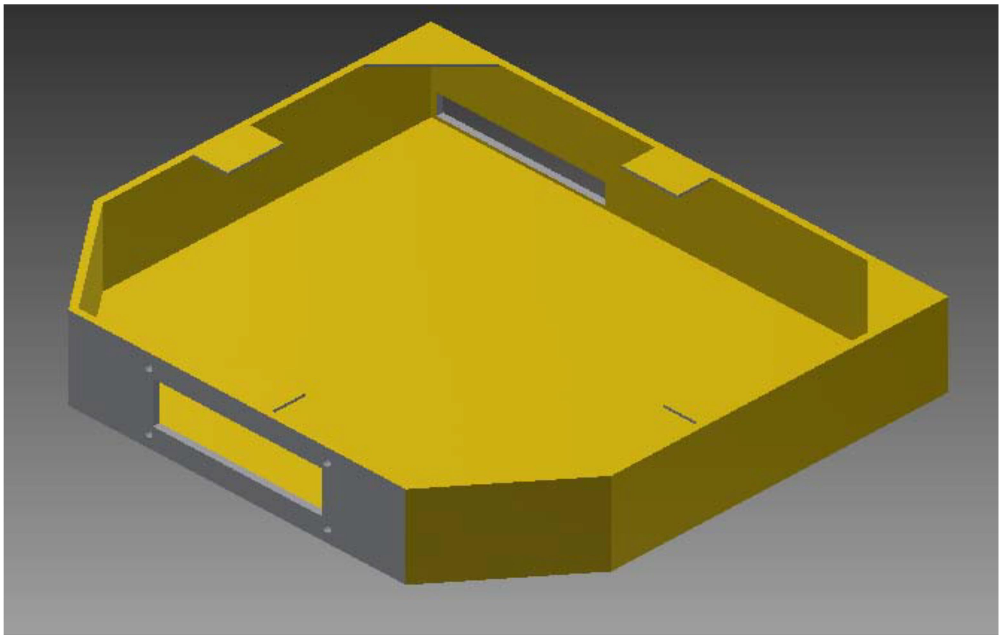


Fig3.11: CAD of the base structure drawn with Autodesk Inventor.

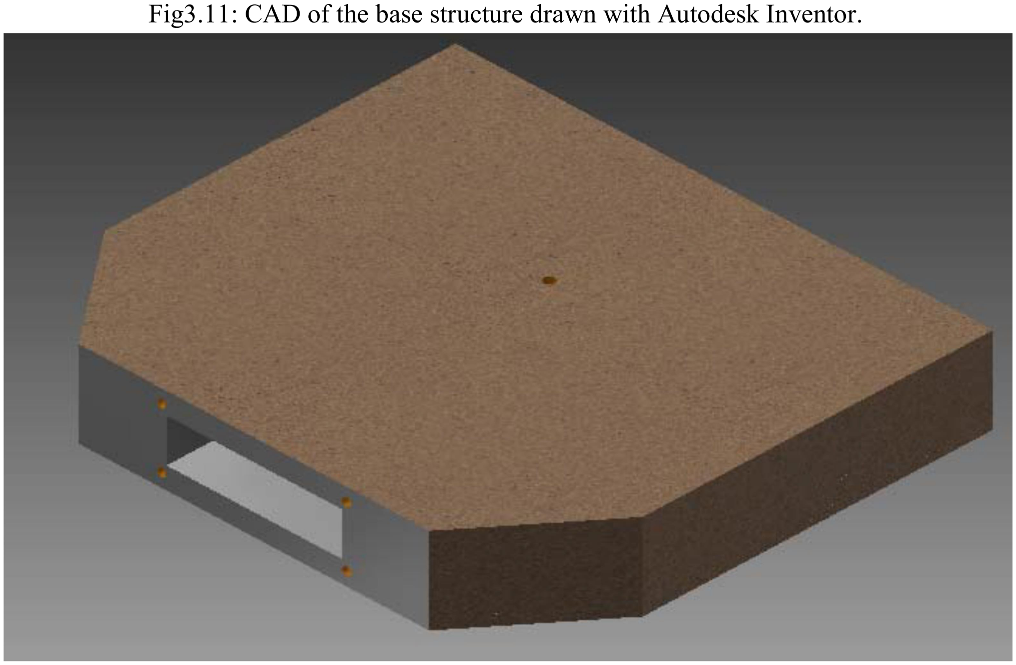


Fig3.12: CAD of base with base cover drawn in Autodesk Inventor

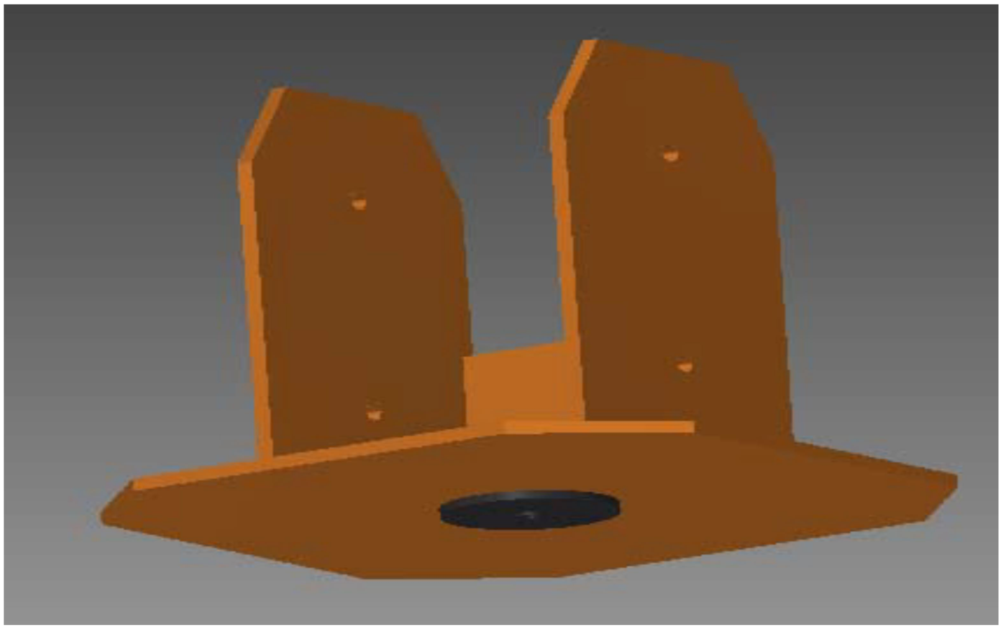


Fig3.13: CAD of Shoulder/Base swivel part.

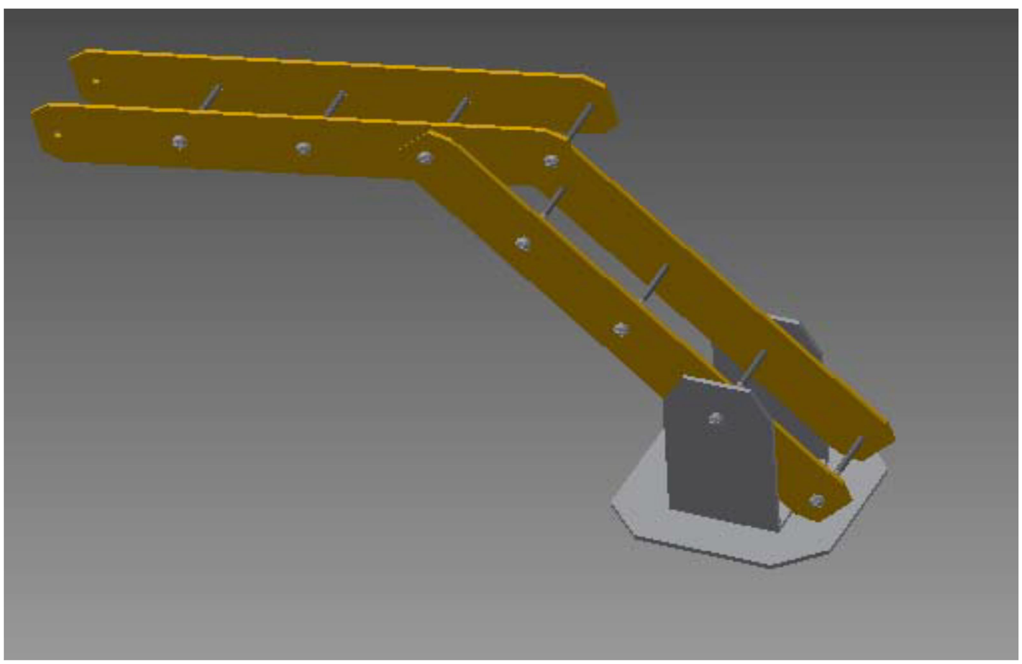


Fig3.14: CAD of the hind and fore arm linked together

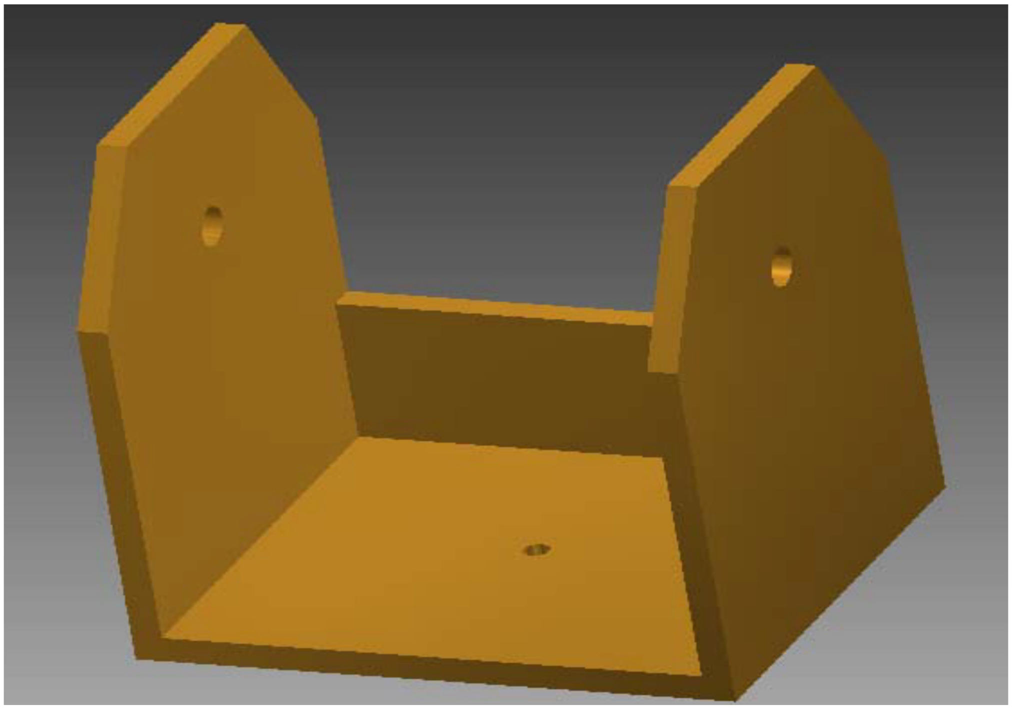


Fig3.15: CAD of gripper base structure drawn in Autodesk Inventor. Diagram by Uzor Uchenna.

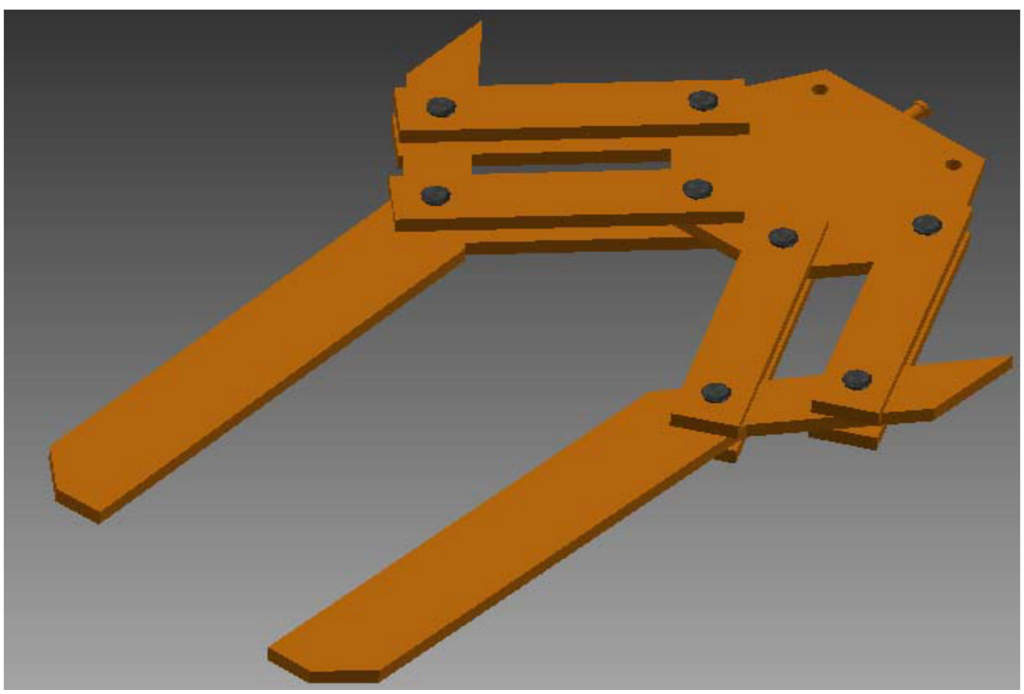


Fig3.: CAD of the gripper drawn in Autodesk Inventor.

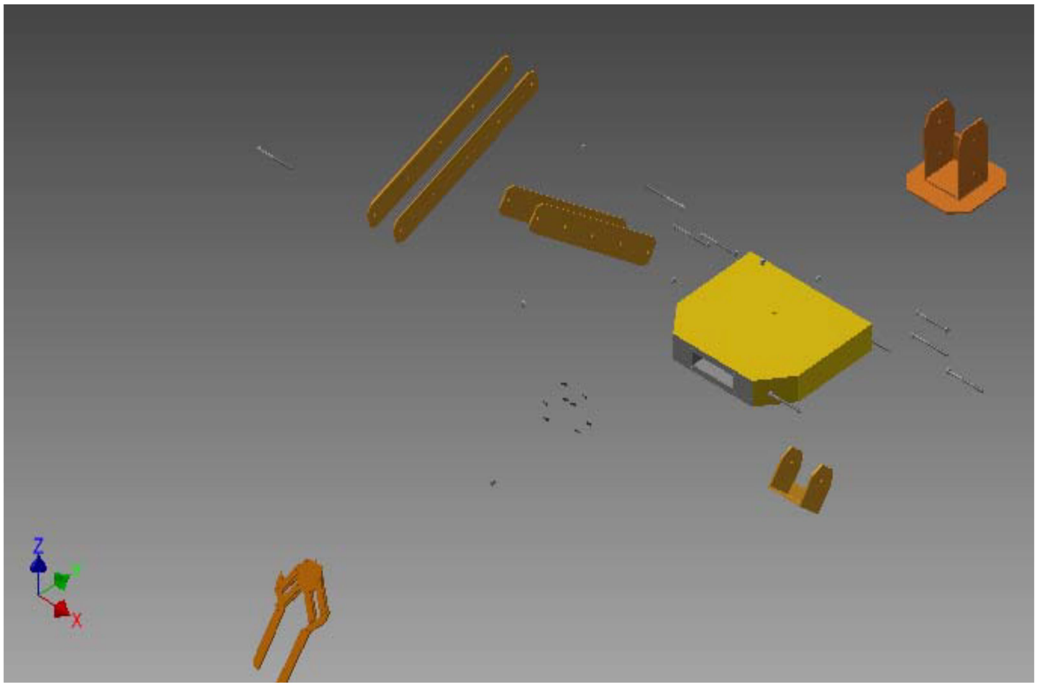


Fig3.16: CAD of exploded view of component structure of the robotic arm drawn in Autodesk Inventor.

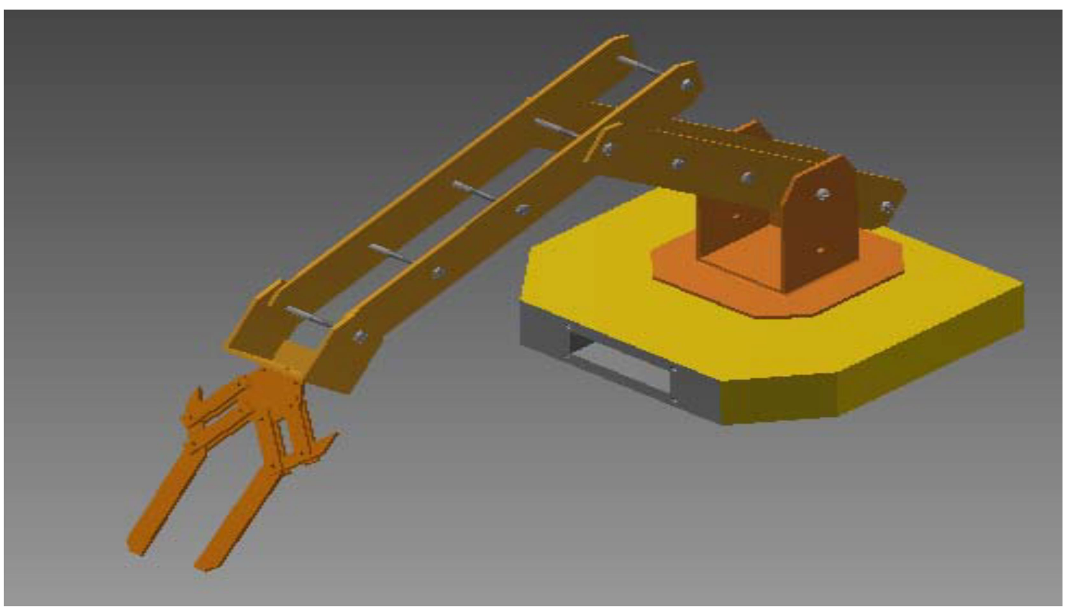


Fig3.17: CAD of complete mechanical structure of the robotic arm drawn in Autodesk Inventor.

3.6 Force Calculations for the Robot Arm

The major parameters of interest in the operation of the robot arm are the maximum carrying load at each joint, maximum carrying capacity (weight) of the entire arm and the maximum gripping force.

Note: it is assumed here that the weight of individual component part lies exactly at their geometrical centers of gravity (i.e. middle points).

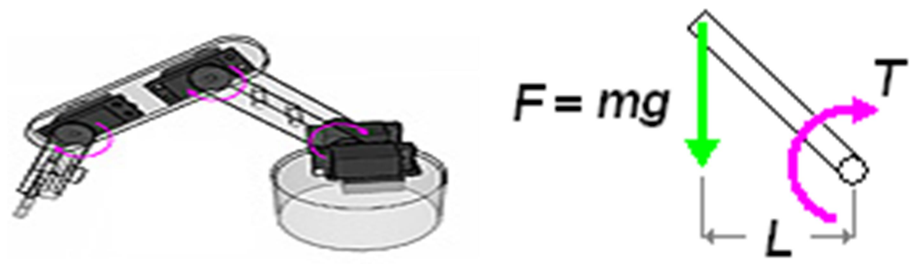


Fig3.8: Force relation in a robot arm

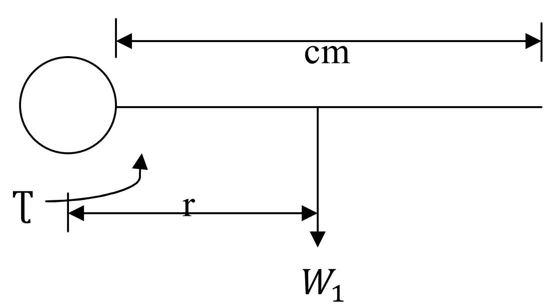
Maximum carrying load of the wrist joint (at no load)

Stall torque of wrist servo motor = 11kg-cm (1.078Nm)

Weight of the gripper (no load) =

Length of gripper = 20cm (0.6m)

r= 10cm (0.1m) assuming C.G is at the middle.



We start with the resolution of forces at the wrist noting that the sum of forces at a point is zero.

$$\sum F = 0 \quad (3.12)$$

The torque generated by the servo motor is given as

$\tau = rFsin\theta$ (3.13)

From the principle of moments

$F_1r_1 + F_2r_2 + \cdots + F_nr_n = F_mr_m$ (3.14)

i.e. $\tau = W_1 * r$ (3.15)

$W_1 = \frac{\tau}{r}$ (kg) (3.16)

Thus $W_1 = \frac{11}{0.6}$ = 18.33 (kg) (3.17)

Maximum carrying load of the shoulder joint (no load)

Weight of forearm =

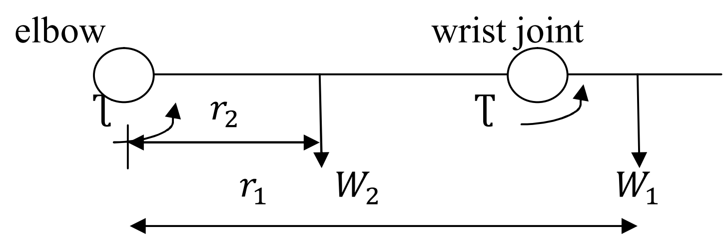
Stall torque of elbow servo 11kg-cm

Weight of servo at wrist joint = 0.055kg

Weight of gripper =

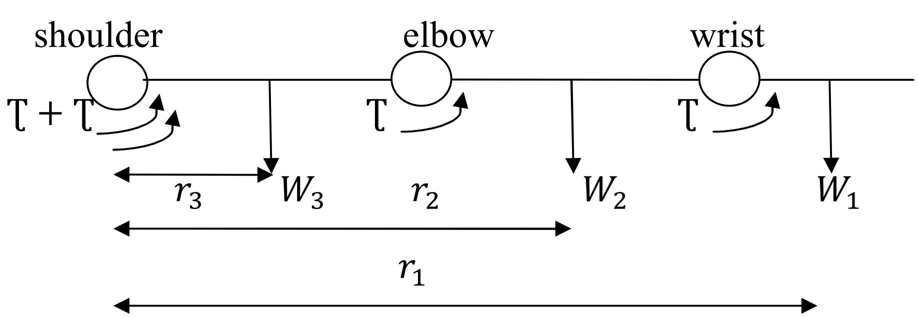
We again use the principle of moments:

$F_1r_1 + F_2r_2 + \cdots + F_nr_n = F_mr_m$ (3.18)



$\tau = W_1 * r_1 + W_2 * r_2$ (3.19)

Maximum Carrying Capacity of the entire arm



Note: The shoulder joint contains two MG996r servo motors, generating twice the stall torque normally produced at the elbow and wrist joints.

$$2Ţ = W_1 * r_1 + W_2 * r_2 + W_3 * r_3 \qquad (3.18)$$

3.7 Electronic System Design.

The electronic system powering the robot arm is comprised of the following:

1. Arduino mega2560 development board –This houses the Atmega2560 microcontroller which provides the computing power of the system.
2. Servo motor driver board –This board provides separate power to drive the six servo motors used in the arm joints.
3. 5 volts DC power board and the ultrasound and proximity sensors.

These are interconnected together as shown in the **figure 3.9** below:

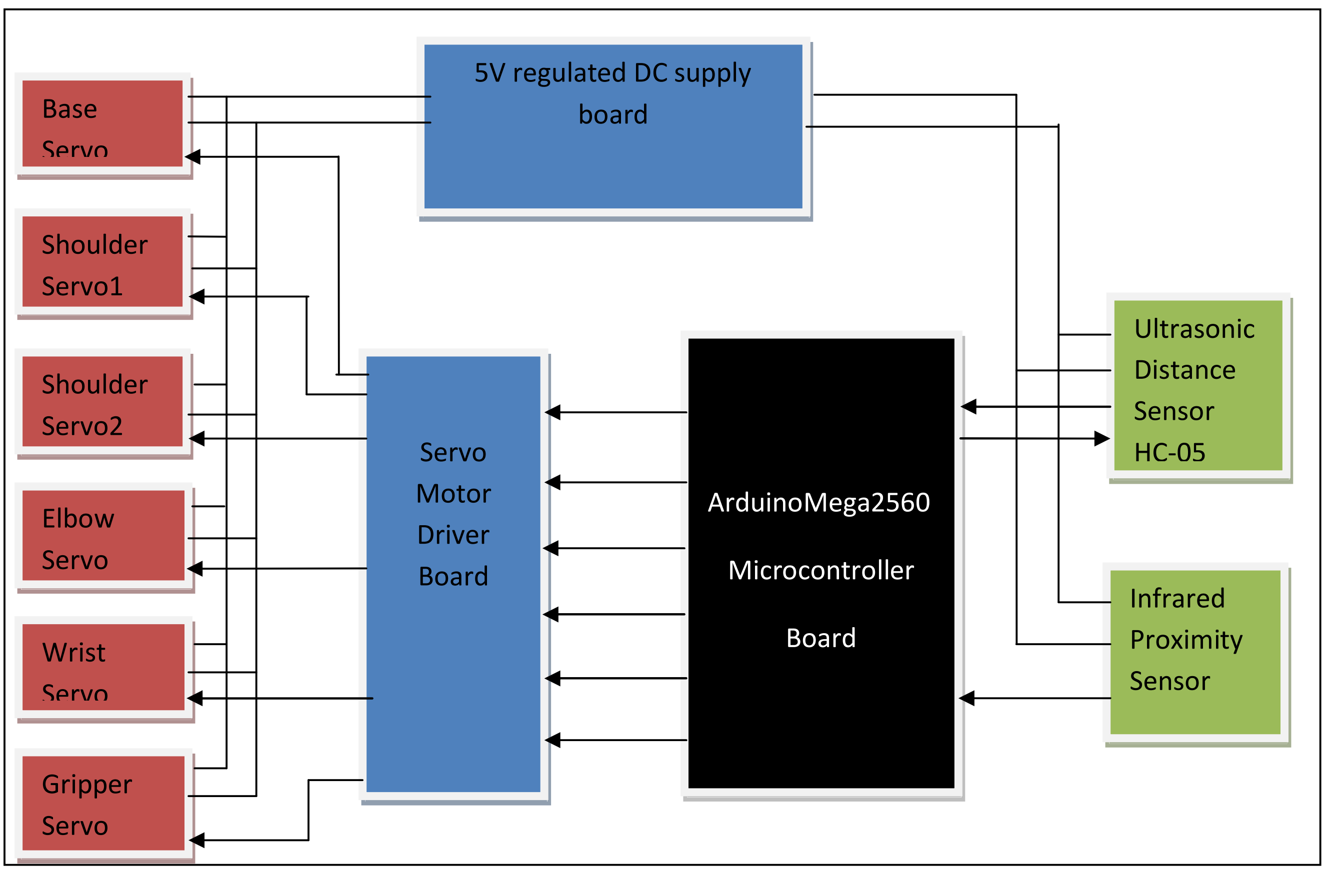
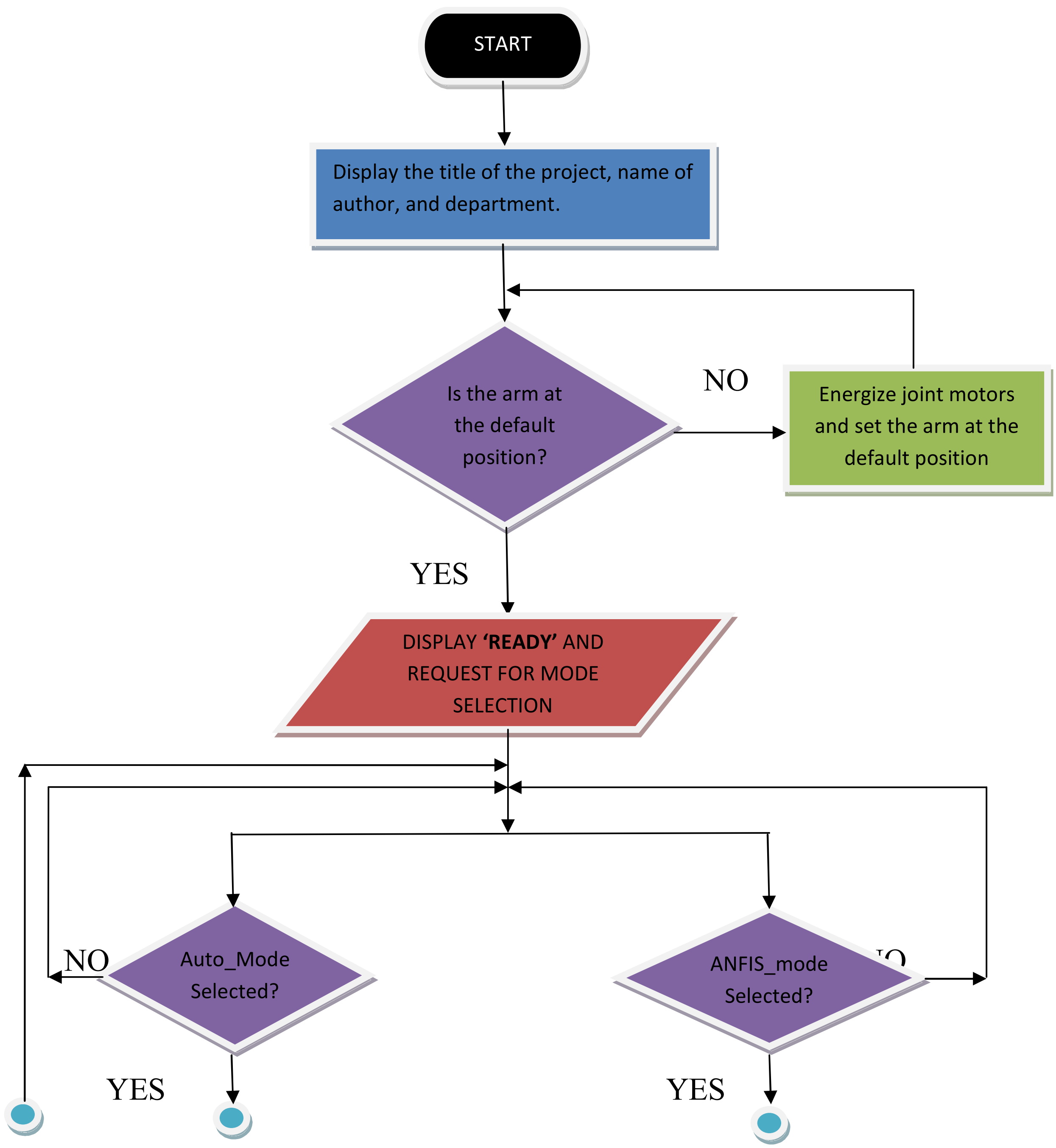
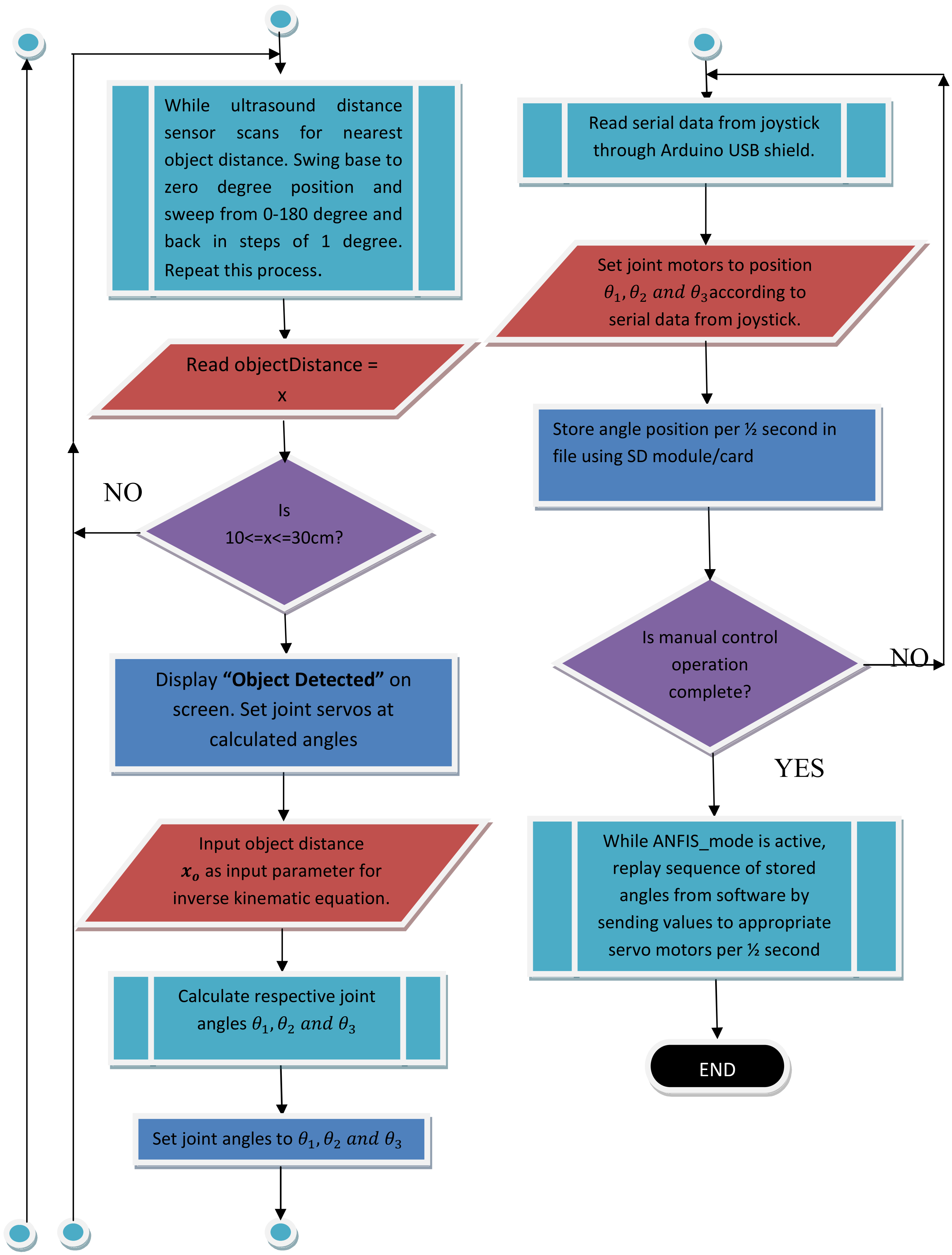


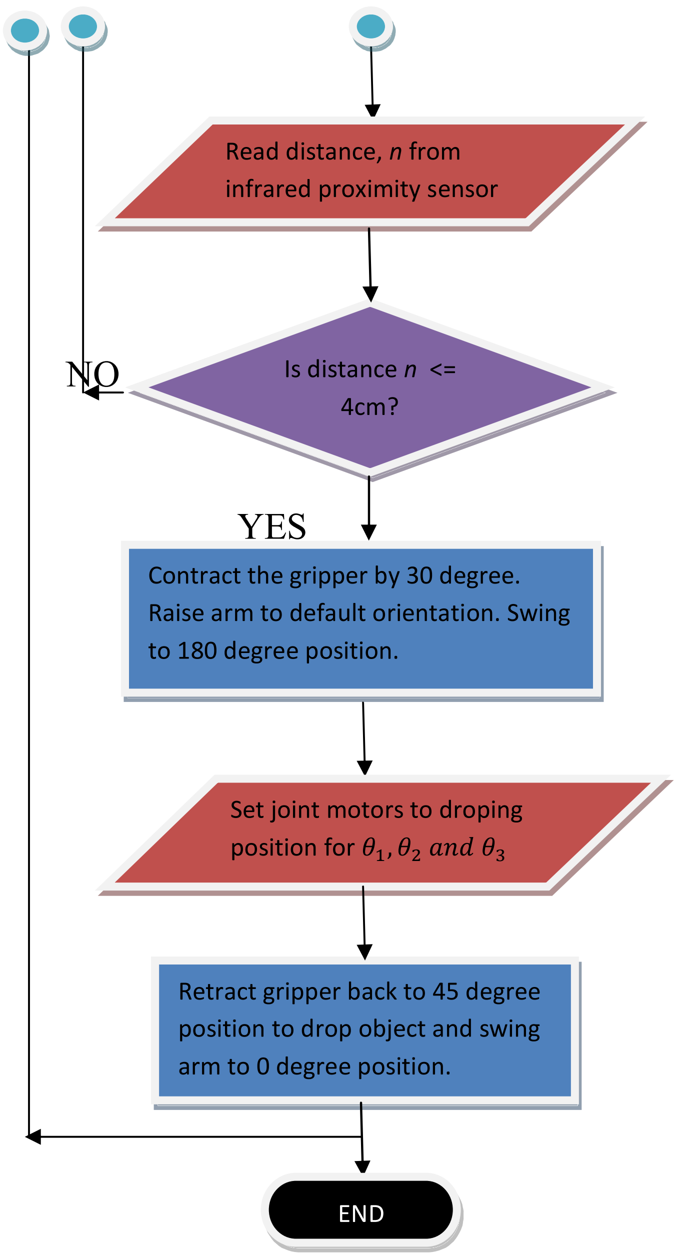
Fig3.18: Electronic System Design block diagram.

3.8 Embedded Software Design

Both Flow chart and algorithms (for detailed programming) were used in the design of the embedded software. The sequence of actions, inputs and outputs for various operations necessary to achieve design objectives were clearly spelt out in the flow chart and algorithms.




While ultrasound distance sensor scans for nearest object distance. Swing base to zero degree position and sweep from 0-180 degree and back in steps of 1 degree. Repeat this process.
Read objectDistance = x
NO
Is 10<=x<=30cm?
Display **"Object Detected"** on screen. Set joint servos at calculated angles
Input object distance x_o as input parameter for inverse kinematic equation.
Calculate respective joint angles θ_1, θ_2 and θ_3
Set joint angles to θ_1, θ_2 and θ_3
Read serial data from joystick through Arduino USB shield.
Set joint motors to position θ_1, θ_2 and θ_3 according to serial data from joystick.
Store angle position per ½ second in file using SD module/card
Is manual control operation complete?
NO
YES
While ANFIS_mode is active, replay sequence of stored angles from software by sending values to appropriate servo motors per ½ second
END



Note: Most of the steps in the flow chart stated above are further broken down into micro steps during actual programming. The flow chart was implemented using the Arduino programming language which is based on C++.

3.9 Materials Employed

The following materials were used in building the robot arm. Choices of the materials below are based on cost, mechanical strength, light weight, availability and technical simplicity for use.

3.9.1 Hardware materials

The following hardware materials were employed in building the arm.

1. Acrylic glass sheet (3mm thick) - yellow and transparent white colour:

This is a type of plastic sheet. It was chosen for its light weight and relative mechanical strength.

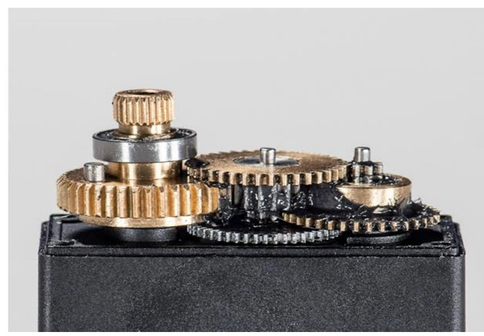
2. Bolts and nuts:

bolts and nuts of various sizes were used as mechanical fastener to hold moveable joints together and also the base cover lead.

3. Plastic glue (UHU Alplast):

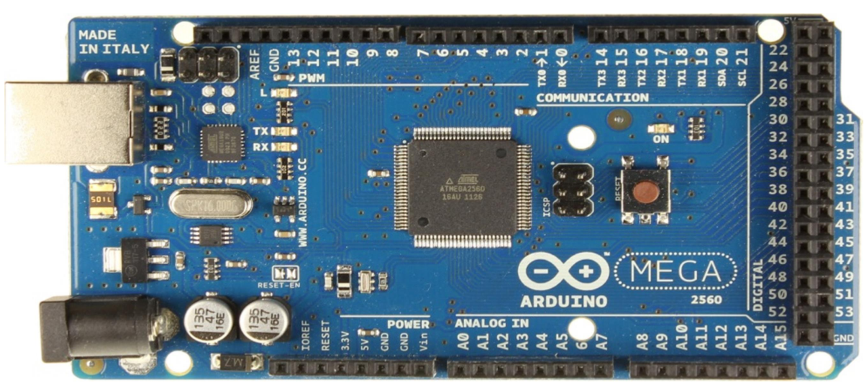
This glues is specially made to hold plastics. I used it for holding permanent joints.

4. Servo motors (6X MG996r, 1X MG995, 2X SG900 micro servos):



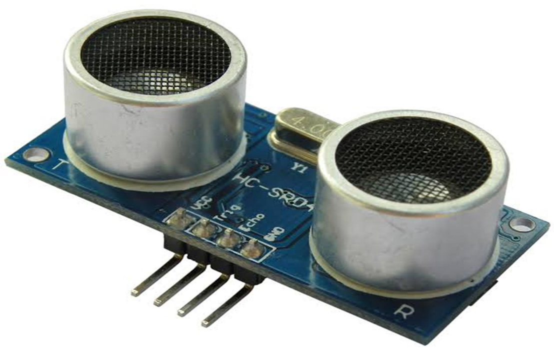
Servo motors unlike normal free running dc motors have feedback control circuitry for accurately positioning the axel to specific angles. It can move clockwise and anticlockwise. It is controlled by a PWM signal from a microcontroller (in this case, the Atmega2560).

5. Arduino Mega2560 development board



The Arduino mega board is based on the Atmega2560 microcontroller. The board is programmed using the Arduino language. It has a rich supply of I/O pin outs and this is the main reason behind the choice of a mega. The specification of the board forms the core computing specification of this robot arm system. The chip onboard operates at 16Mhz, it takes 4.5-5V dc, has a reset button and a programmable memory of 256KB, 8KB SRAM, 4KB EEPROM, 86 general purpose I/O lines.

6. Ultrasonic distance sensor module:

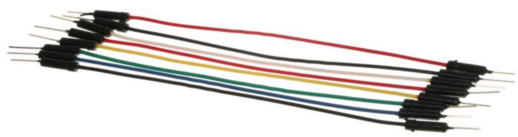


Specially built for the Arduino development boards, this device uses ultra sound echo to measure distance for a range of 2-60cm.

7. Infrared Proximity sensor (SHARP)

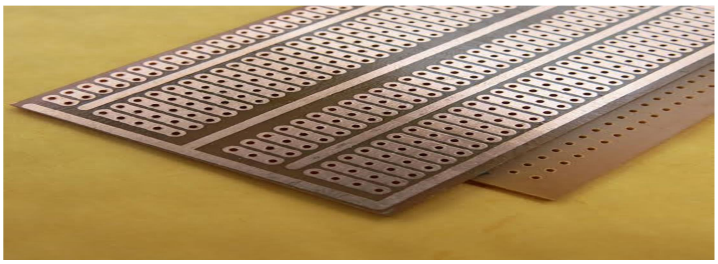
This device uses infrared rays to measure distance. The accuracy and range is far lesser than the ultrasound type. However, it is cheaper.

8. Jumper wires



connections among system components were made using jumper wires.

9. Vero board



Circuits are built using the stripped copper (vero) board.

3.9.2 Software Tools Employed

The following software products were used in simulating the hardware framework, designing the electronic circuits and coding the embedded software for the robot arm.

1. Matlab Software (version 2014a) –for modeling forward/inverse kinematics of the robot arm.
2. AutoDesk Inventor –for designing the mechanical frame work.
3. Circuit Wizard software –for designing and simulating the servo driver board.
4. Arduino IDE for programming the Arduino Mega2560 development board.

3.10 The finished work

Fig3.19: The robot arm scanning for nearest object.

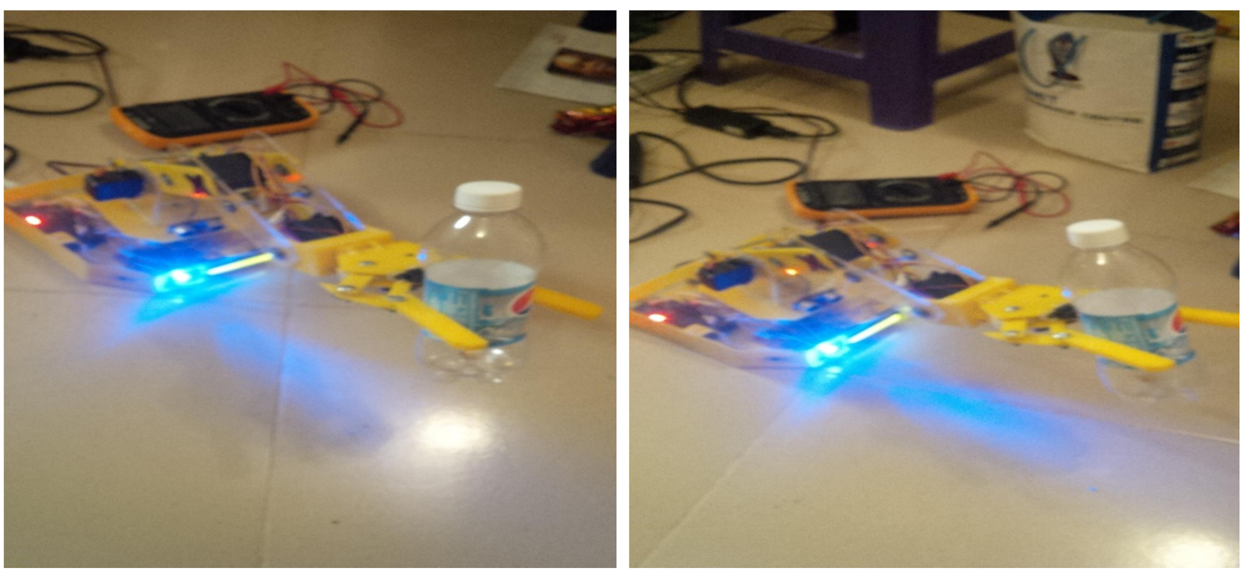


Fig3.20: Robot arm under test

4.10.1 Operation Manual and System Documentation

WARNING!!! This section should be studied very carefully before any attempt is made to operate, disassemble or study the hardware of this project to avoid permanent damage to key components.

The system is described in detail highlighting how to operate it and how the various components used in the work are interconnected. This should serve as a guide to anyone willing to improve on the work.

Physical features description:

Operational buttons:- The system contains 4 operational buttons

1. **Power button** (x1): This is a push-to-make button at the front of the base just by the left of the LCD screen. This button will supply electric power to the system and thus energize it once depressed and **only if the slider button at the right hand side of the base is pushed down**. Else, only the servo motors will be energized and remain at stall torque until control panel (Arduino board and motor driver circuit) are energized by pushing the slider down!
2. **Mode Selection buttons** (x2): The mode selection buttons are located to the right hand side of the base front panel LCD. There are two mode selection buttons arrange vertically. Request to select a mode is made once the robot arm is ready to receive command. To select a mode, press a button; to unselect a mode or to select another mode, repress the current mode button before selection another.

   2.1 Auto_mode: This button is connected to the Arduino digital port pin 42 through a pull down resistor (i.e. it registers a logical HIGH signal when pressed and LOW if not). **Note:** this pin connection (pin 42) is used in the programming for the function of the button. If the Auto mode is selected, the robot arm begins an automatic cycle of scanning for objects. This is achieved by sending control signal to the base servo telling it to sweep through an angle of 0-180 degree and back in steps of 1 degree per step. This allows the ultrasound distance sensor attached to the moveable platform to be able to scan for the nearest object. The base stops its swivel motion at the particular angle from zero degree at which an object is detected. With object distance as input variable, the processor calculates the necessary joint angles and sets the arm to the position of the detected object for pick up.

2.2 ANFIS_mode: This button is connected to the Arduino digital port pin 41through a pull down resistor (i.e. it registers a logical HIGH signal when pressed and LOW if not). This pin connection (pin 41) is used in the programming for the function of the button. If the Manual mode is selected, the system becomes ready to receive serial data input from the manual controller (this can be implemented either with use of game pad, joystick, potentiometers or PC keyboard based on choice). Otherwise, pressing any button or turning any nub from external control has no effect on the system. (**Note:** an application can be developed which allows a system keyboard to control the arm. This could be implemented easily using Matlab or Python programming language).

3. **Slider Bar** (x1): This is a white slider located at the right hand side of the base. Its normal position is down selection. At this position, the Arduino board is supplied DC power once the system is supplied from AC mains.
   However, if the user whishes to connect the Arduino board using USB cable to a computer either for loading new code or to power the Arduino then the SLIDER BAR MUST BE PUSH UP.
   WARNING!!! Never plug a USB cable from a computer port to the Arduino board when the slider bar is in the downward position and the system connected to AC power. Check for this condition before using USB.
4. **Reset Button** (x1): This is a small push to make button located at the left side of the base. Pressing this button RESESTS the system program to start running from the start position. The reset button is connected directly (without a pull-up or pull-down resistor) to the Arduino reset pin (close to the Power-in) and GND- There are four (4) GND connections in an Arduino Mega.
5. **LCD display**: This is a 16 by 2 character LCD screen used to output information about the system. The LCD needs 6 wire leads for its operation aside the power, GND and Contrast connections. **These are:**

RS, E, D4, D5, D6, D7 connection leads and are all connected to digital pins 22, 23, 24, 25, 26, 27 respectively.

6. **Ultra sound distance sensor**: This is component uses ultrasound and echo technique to scan for the nearest object. It functions more like the eye of the robot. The sensor has four connections viz: power, GND, Trigger and Echo. The power and GND are connected to the Arduino power and GND while **the Trigger and Echo are connected to digital pins 8 and 9 respectively.**
7. **Infrared Proximity Sensor**: This sensor also measures distance but functions to measure how close the gripper is to the object to be picked. It is an analog sensor with three connection terminal Power, GND and signal line. **The signal line is connected to Analog pin A0 of the Arduino board.**
8. **Servo Motors**: The robot arm uses a total of 6 servo motors. All of which are from the same manufacturer. Five of these servos are big standard sized high torque MG996r model used for the various joints (base swivel, shoulder; elbow and wrist joints). The sixth servo which is a much smaller MG90 micro servo is used to operate the gripper. Each servo has three connection wires: Power (red), Ground (brown) and Control (orange).

   The servo control lines are connected to the Arduino board through a servo driver board as follows:

   Base Servo: Digital pin 2 of Arduino board
   Shoulder Servo1: Digital pin 3 of Arduino board
   Shoulder Servo2: Digital pin 4 of Arduino board
   Elbow Servo: Digital pin 5 of Arduino board
   Wrist Servo: Digital pin 6 of Arduino board
   Gripper Servo: Digital pin 7 of Arduino board

   Noted that the names of the servos and the digital pins to which they are connected are as used in variable names in the program. Shoulder Servos 1&2, are used together as the shoulder servo to provide more torque to carry the entire arm. They are controlled simultaneously in the programming with no delay time apart.
9. **Calibration of the Servo Motors:** Before the motors can be used in the robot arm, they must first be aligned at zero degree position. Then

the motors are fitted appropriately with the connecting appendages set to position where they should be interpreted as the zero degree position. To calibrate the motors, connect each motors individually and from the Arduino programming environment ‘write’ a zero degree to the motors. This can also be done by connecting all of the motors to the Arduino board and ‘writing’ the zero degree position. To each of them individually.

Default Arm Position:

Base Swivel: The base is set at the zero degree position by default.

Shoulder Joint: The shoulder joint is aligned to the 10 degree position during the calibration. This angle is measured from the vertical base stand facing up.

Elbow Joint: The elbow joint at zero degree is aligned such that the fore arm and hind arm make a straight framework.

Wrist Joint: The wrist joint is aligned at zero degree position such that the gripper end makes a 90 degree angle with the fore arm.

Gripper: The gripper is set closed at the zero degree position.

10. **Fitting the Parts Together:** When fitting the component parts together, it is advisable to start from the base. The motors can either be energized or not during the assembling process. The joints should be set according to the default angle setting of the servo motors.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Matlab Simulation of Mathematical Model

Table4.1: results generated for object distance ranging from 10cm to 20cm from the shoulder base. (Test data).

Table 1: Test_result showing values of system variables (joint angles) generated using Matlab.

$\boldsymbol{x_o}$	$\boldsymbol{x_c}$	$\boldsymbol{x_h}$	θ_m	θ_n	θ_h	$\boldsymbol{\theta_1}$	$\boldsymbol{\theta_2}$	$\boldsymbol{\theta_3}$
4	6	10	51.34	51.665	73.075	76.995	106.93	86.08
5	6	11	53.973	49.143	78.45	76.884	101.55	91.566
6	6	12	56.31	46.415	84.223	77.276	95.777	96.948
7	6	13	58.392	43.461	90.434	78.147	89.566	102.29
8	6	14	60.255	40.25	97.15	79.495	82.85	107.65
9	6	15	61.928	36.729	104.48	81.343	75.522	113.13
10	6	16	63.435	32.814	112.59	83.751	67.406	118.84
11	6	17	64.799	28.355	121.81	86.846	58.193	124.96
12	6	18	66.038	23.051	132.73	90.912	47.268	131.82
13	6	19	67.166	16.102	147.01	96.732	32.992	140.28
14	6	20	68.199	0+3.4422i	180-7.0482i	111.8-3.4422i	0+7.0482i	158.2-3.6059i

>>

4.2 Work Space Data Generation

The total area of separate points reachable by the robot arm is referred to as the work space. The **figure 4.1** below is a Matlab generated figure of the workspace of the robot arm. The original source code was obtained from http://www.mathworks.com **[11]** with modifications in arm lengths L_1 *and* L_2 and angle limits of θ_1 *and* θ_2 to suit the system for which it is employed for simulation.

Let θ_1 be the angle between the first arm and the vertical axis of the shoulder. Let θ_2 be the angle between the second arm and the first arm (see **figure 4.1** for illustration). Now the length of the first arm is 11cm and that of the second arm be 10.5cm; let us assume that the first joint has limited freedom to rotate and it can rotate between 0 and 90 degrees. Similarly, assume that the second joint has limited freedom to rotate and can rotate between 0 and 180 degrees. Hence, 0<=θ_1<=90 and 0<=θ_2<=180 **[11]**.

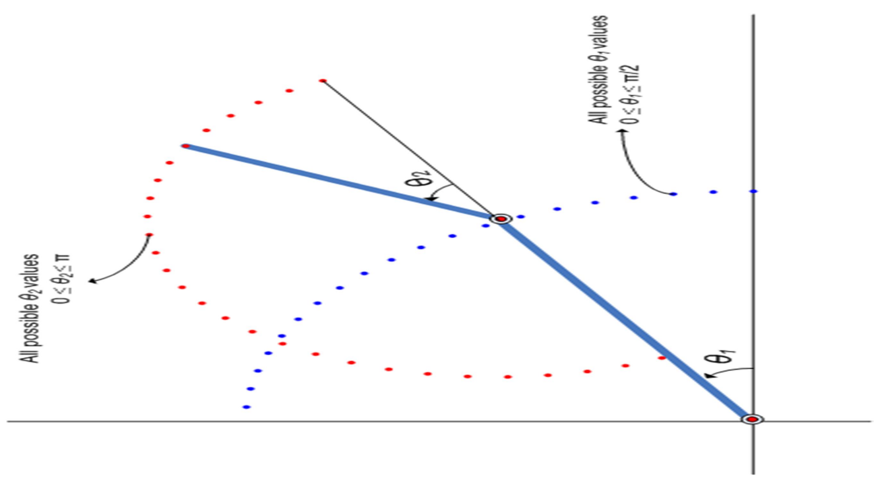


Fig 4.1: Illustration showing all possible θ_1 and θ_2 values.

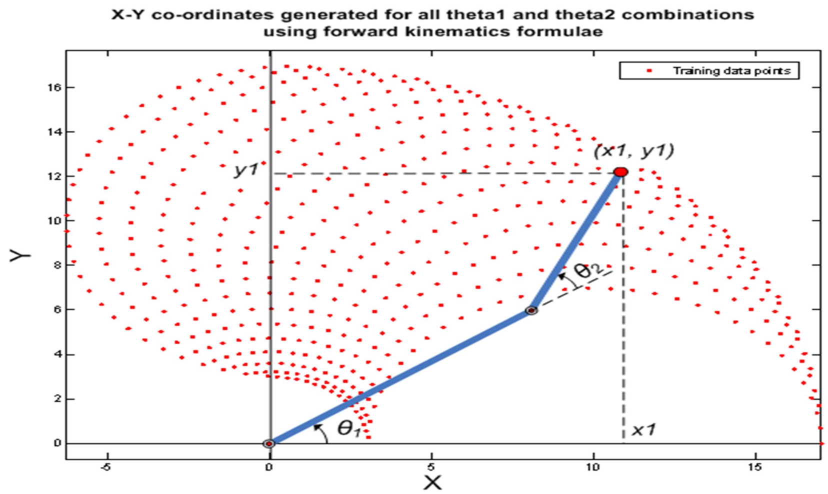


Fig 4.2: X-Y co-ordinates generated for all θ_1 and θ_2 combinations using forward kinematics formulae [11]

4.3 Discussion on Results

The most important parameters of the robot arm are the joint angles i.e. θ_1, θ_2 *and* θ_3 respectively. These parameters accurately position the robot arm for various object distances, x_o thus enabling it to reach the object for pick-up. The modeling/calculations were done for a two 2-D workspace as against a more realistic 3-D workspace. This is in effort to reduce the complexity of calculations necessary for 3-D modeling thereby reducing the system equations to normal trigonometric equations which are easily solved. The test input data (object distance) was taken from a distance of 4cm to 14cm spanning a range of 10cm gap. As observed from Table 1, the various joint angle values θ_1, θ_2 *and* θ_3 generated for each object distance x_o are real values in degree until $x_o = 14cm$ and beyond which gives complex values. Thus the critical value of object distance x_o for which the robot arm can accurately reach is 13cm from the ultrasonic distance sensor and together with the offset position of 6cm from the shoulder base axis, the total distance is 19cm or 20cm approximately from the base axis.

The workspace generated gives an ideal case for the robot arm lengths $L_1 \; and \; L_2$. However, all points are not covered because of physical limitation of complete rotation of the second arm over the stated range of 180^o due to the structural arrangement of component parts. The whole points displayed graphically are not reached especially for points closer to the base of the robot arm.

From the results above it can be seen that given the position of object location in an X-Y planar work space, the corresponding angle position can be determined as shown in the Matlab Code. Also, given angle positions, the possible points reachable by the arm in a 2-D workspace can be plotted graphically. Hence given forward kinematics, the inverse kinematics of a robot arm can be accurately determined.

4.4 Project Test Results

Under test, the device was found to work normally by detecting objects (using the ultrasound distance sensor) with approximate flat solid surface. However, there was no means for determining the right gripping force to be applied with the gripper claws. To overcome this limitation, the gripper servo was set to contract by 15 degrees to enable gripping. Hence for objects smaller than this range, the robot fails to pick them up even after detection.

4.5 Implementing Autonomous Operation using ANFIS Method

The data obtained in Table 1 is typical of angular positions $\theta_1, \theta_2 \; and \; \theta_3$ with respect to object distance x_o in implementing project. With necessary electronic hardware component such as SD card module, Arduino USB Shield

Wireless/Bluetooth module USB joystick and programming, it is possible to store up joint angles in a file located in the memory module which are necessary for reaching an object on an X-Y plane, picking it and placing it at a desired location. This process is referred to as "training". Such data (angle values) obtained for the process can be replayed/fed-in to the various servo motors operating the robot arm joint, thus repeating the process autonomously.

Thus autonomous action of the robot is achieved through either system equations which models the forward/inverse kinematics or through 'learned behavior' using the Adaptive Neuro-Fuzzy Inference System (ANFIS) technique.

4.6 Limitations and Challenges

Serious efforts were made to complete the project and achieve the design aims and objectives within the short time duration given to present and defend the work. However, the progress made was not without a fair dose of limitations in the work in itself and challenges faced while executing the project.

- Object detection by the system uses ultrasound distance sensor for detecting the closest object which falls within design range 10-20cm. There is no specialized camera installed for doing this. The ultrasonic sensor is spaced over 6cm thus it can effectively detect objects with width within this range. Anything less may be skipped. For objects which are wider than this, the gripper with a maximum opening aperture of 8cm cannot grip the object in such cases.
- Objects with height below or above the line of sight of the Ultrasonic sensor are obviously out of range and cannot be detected.
- During test, the robot arm was found to be able to pick only light objects. A small size empty plastic water can was used as a test specimen and was

successfully detected and picked. The motors used for the joint are only small and micro size (for the gripper) servos whose stall torque have already been exhausted carrying the weight of the arm. Thus small torque is left for lifting objects.

- The Adaptive Neuro-Fuzzy Inference System technique of 'learned' autonomous behaviour was not implemented due to non arrival of some of the materials (Arduino USB shield, Bluetooth module, and wireless joystick and Arduino SD card module) purchased online –AliExpress.com.

Major challenges encountered while carrying out the project was non availability of the component parts in local markets. Therefore, I had to resort to online purchase from China through an online store –Aliexpress.com. This has its own risks which I suffered –loss of goods and money. Some of the servo motors and sensors which arrived were not functioning well as there was no means for testing them before purchasing.

The burden of doing everything from research and design to financing and purchasing of parts and then to actual construction and typing of the paper work proved to be too much of a burden for a single person to carry.

Mitigation

In view of the challenges encountered, it is therefore advisable that purchase of materials be done through local retailers which can bear the online purchasing risks instead of the students. Goods should be paid for only when they deliver them in working condition. However this is usually at an added cost. Also the project should be advanced only by a team of minimum two members. This will ensure division of tasks and financing. Finally, to any student interest in furthering this work, time is a critical factor especially early purchasing of materials to avoid delays and meet up with given deadline.

CHAPTER FIVE

5.0 Conclusion

The project work on the design and construction of a robotic arm presented so far has touched several areas of technology both directly and indirectly. With serious effort and resources invested by researchers in automating several processes normally manned by human labour, the quest for speed, higher efficiency and pinpoint accuracy has necessitated the creation and deployment of robotic systems. Robotic arm is one such system that has attracted so much attention. It has also proven over time to be a promising technology for completely replacing the human hand in key operations where precision, safety and quick repetition are primary factors for consideration.

With the early robotic arms controlled mechanically and or electronically through manual levers or arm-like control sticks, the drive to make these systems fully autonomous has been the golden pursuit of researchers. Autonomously performing varieties of tasks with minimum human supervision yet maintaining acceptable standards has always been the main goal in developing robotic arm systems. To achieve this, a variety of simple to complex mathematical formulations are often derived for modeling the robot arm operations in its intended work environment and predetermined behaviour. Be it SCARA, gantry or Anthropomorphic (articulated) robotic arms. One basic mathematical formulation necessary for all robotic arms is the inverse/forward kinematic relations. A good forward and inverse kinematic mathematical relation will give accurate information on the total workspace reachable by the robot arm end effector and the various joint configurations possible with the mechanical structure to enable it reach such points. Complexity of such relations comes with increasing consideration in the dimensional reach in space of the robot arm end effector whether 2-D or 3-D.

The use of the Adaptive Neuro-Fuzzy Inference System technique, a stored data concept is one way by which robotic arms are given autonomous capability that mimics human learning. The ability to store up joint angle in a file during a human controlled operation and with such angle data fed into the system later is a process called ‘adaptive learning’. Currently, many robotic arm systems used in industrial manufacturing use this method which is an extension of the computer numerical control (CNC) technique.

The technology of robotic arms has found widespread applications in industrial manufacturing processes such as car assembling, material handling and autonomous spray painting. It has also been used in radiation prone areas such as in space exploration for extra vehicular activities (EVA) and in radioactive material handling in nuclear facilities. In recent times, robotic arms have found its way into the medical field as highly advanced and effective surgical systems. And have recorded great success since they were first used. The medical application of such robotic arm systems as Arthrobot, ZEUS and Da Vinci are pointers to what is possible with the deployment of robotic arms in human endeavours.

This work has solved the simple task of autonomous detection of objects and pick and place of same in a predefined location. This is what is normally done manually in various everyday tasks. Whether for personal use or as part of manufacturing activities, use of robotic arms proves to be a better alternative to the human arm which is easily weary after hours of work. Robots are faithful slaves that can give us exactly what we want every time without tiredness or complaint –as is often the case with humans –once the programming and physical parts are in order.

5.1 Ethical Consideration

The use of robotic arms as replacement for the human arm is not without some ethical questions and arguments. In a society where unemployment is high, technology such as this which in essence replaces manual labour is normally seen as worsening the case of unemployment. A good example is the case of a manufacturing industry where workers are hired to assemble and package goods for shipments; bringing in robotic arm as a replacement for manual labour will be seen by workers as a threat to their lively hood. Thus they perceive it as a disadvantage to them.

The above being the case, it can be argued that the advantages of the use of robotic arms far outweigh any perceived disadvantages. On the side of the manufacturer, speeding up production in a more accurate and efficient manner is something worth investing on. Since this will cut cost and enable the production of more goods in record time, it proves to be a better solution. As against human labour, robotic arms never get tired of working for as long as their hardware and the accompanying embedded software are in order. Robotic systems can continue working for several hours that will normally leave human hands sobbing of stress.

For considerations of job losses due to replacement of human hands by robots, it can be argued that the process of creation of robots, programming them, installing and maintaining them in industries have provided new jobs for people. Technological innovation is a continuous process which will continue growing. While technological innovation will definitely render some types of jobs obsolete, it will definitely usher in new fields of work which will provide more interesting jobs as a replacement. The net effect being that no job is actually lost rather, the creation of cutting edge technological disciplines. It is then the responsibility of people who would want to be relevant in the work force to stay acquainted and be up to date with current technologies as they evolve yearly.

5.2 Recommendations and Future Work

As with every technical venture, much excellent performance is hardly recorded in one stroke. Rather, it is normally through several modifications and improvements that perfection is reached. To this end, this work needs serious attention from students/researchers willing to undertake the challenge involved in furthering this project. Areas of improvements where more work needs to be done and recommendations are therefore stated below:

- The Adaptive Neuro-Fuzzy Inference System where joint angles are stored in a file in an SD card module as a means of implementing adaptive/'learned' behaviour in the robot is yet to be implemented. This was due to non availability of the necessary hardware as at time of building the project. Careful following of the embedded software design flow chart in chapter 3 and the discussion on ANFIS in chapter 2 will guide the students in its implementation. It is also recommended that a separate desktop application be created for this purpose. Such that data is stored in a file located in the PC and means of control can either be a USB game pad or PC keyboard. This can be easily implemented with a Python application. Matlab gives a reasonable success from my experience but Python has better resources for USB communication and file handling.
- The gripper of the robot arm designed here was not incorporated with a touch/force sensor. As such the sensing of object touch and gripping force

could not be accurately determined. This should be added in future work to enable calculation of the gripping force for appropriate picking of different types of object.

- Students interested in this project should work on integrating internet capabilities to the arm to enable remote control over the internet.
- Effort should also be made to interface a USB camera working with an object detection and image recognition software application (e.g. in Matlab or Python application). This will enhance object detection and autonomous operation of the robot.

REFERENCES

[1] Origins of “robot” and “robotics”. (n.d). Robotics: A Brief History.[Online]. Available:https://cs.stanford.edu/people/eroberts/courses/soco/projects/1998-99/robotics/history.html . Accessed: June. 6, 2016.

[2] TECHNOLOGY INSIGHT REPORTS. (n.d.). Patent Insight Pro. [Online]. Available: http://patentinsightpro.com/techreports.html. Accessed: Jun. 6, 2016.

[3] Coskun Yetim, “Kinematic analysis for robot arm,” MSc. Thesis, Dept. of Computer Eng. Yildiz Technical University. Instabul, Turkey, (2009). [Online].Available:https://www.scribd.com/mobile/document/291550852/cc

[4] Mohamad Alblaihess, William Farrar, Fernando Gonzalez et.al. “Designing a Robotic Arm for Moving and Sorting Scraps at Pacific Can, Beijing, China”. B.Sc. Project, Dept. Comp. Science. Worcester Institute of Technology. UK (n.d).

[5] Michael E. Moran. (2007, May 1). “Evolution of robotic arms”. *Journal of Robotic Surgery*. DOI 10.1007/s11701-006-0002-x. [Online]. Available: https://www.researchgate.net/publication/2251458_Evolution_of_robotic_arms. Accessed: June 9, 2016.

[6] History of industrial robots (n.d). RobotWorx. [Online]. Available: https://www.robtos.com/education/industrial-history. Accessed: July 4, 2016.

[7] Rebecca J. Rosen. (2011, Aug. 16). Unimate: The story of George Devol and the first robotic arm. *The Atlantic* [Online]. Available: http://www.theatlantic.com/technology/archive/2011/08/unimate-the-story-of-george-devol-and-the-first-robotic-arm/243716/. Accessed: July 4, 2016.

[8] H. Harry Asada. (2004). 2.12 Introduction to Robotics. DSpace@MIT. [Online]. Available: http://dspace.mit.edu/disseminate-package/1721.1/34967/334967.zip. Accessed: July 8, 2016.

[9] Background and History of Surgical Robotics (2014). *All About Robotic Surgery.* [Online]. Available: http://allaboutroboticsurgery.com/roboticsurgeryhistory.html. Accessed: July 4, 2016.

[10] Modeling Inverse Kinematics in a Robotic Arm (n.d). *MathWorks.* [Online]. Available: https://www.mathworks.com/help/examples/moldelling-inverse-kinematics-in-a-robotic-arm.html. Accessed: August 6, 2016.

[11] Coskun Yetim, "Kinematic analysis for robot arm," M.Sc thesis, Dept. of Computer Eng. Yildiz Technical University. Instanbul, Turkey, 2009. [Online]. Available: https://www.scribd.com/mobile/document/291550852/cc. Accessed: August 6, 2016.