POSITION CONTROL OF TWO LINK ROBOT SYSTEM BY PD & FUZZY CONTROLLER

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

CONTROL & INSTRUMENTATION

(Electrical Engineering)

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DECLARATION

I, Ajit Kumar Sharma hereby declare that the work, which is being presented in the project report entitled, **"POSITION CONTROL OF TWO LINK ROBOT SYSTEM BY PD & FUZZY CONTROLLER"** submitted for partial fulfillment of the requirements for the award of the degree of Mater of Technology (CONTROL & INSTRUMENTATION) is an authentic record of my own work carried out under the able guidance of DR. BHARAT BHUSHAN, Associate Professor, EED, DTU. The matter embodied in the report has not been submitted for the award of any other degree or diploma.

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CERTIFICATE

I, Ajit Kumar Sharma, Roll No. 2K11/C&I/17 student of M. Tech. (Control & Instrumentation), hereby declare that the project titled "**POSITION CONTROL OF TWO LINK ROBOT SYSTEM BY PD & FUZZY CONTROLLER**" under the supervision of Dr. Bharat Bhushan, Associate Professor of Electrical Engineering Department Delhi Technological University in partial fulfillment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

Place: Delhi **(AJIT KUMAR SHARMA)**

Date: 28.06.2014

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ABSTRACT

This work is carried out to study the simulation of two link robot system using brushless DC motor drive. The main motivation is to perform kinematics, and position control of the robot in real - time. The graphical user interfaces (GUI) has been developed in Matlab. The GUI has been designed such that the user can feel forward kinematics of the 6-axis articulated robot. The system was developed for demonstrating the basic trajectory planning method for the position control of robot. Further the trajectory planning platform was tested for a particular experiment and was found to be accurate enough for experimental purposes.

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List of Symbol & Abbreviation

1. BLDC	Brushless dc motor
2. PMSM	Permanent magnet synchronous machine
3. PD	Proportional derivative
4. θ	Angular position
5. ω	Angular velocity
6. α	Acceleration
7. β	Axis angle
8. γ	Axis angle
9. φ_m	Magnetic flux
10. T	Torque
11. J	Ineria
12. C	Coriolis force
13. G	Gravitational force
14. N	Speed

CHAPTER 1
INTRODUCTION

1. Introduction:

Nowadays, with increase in complexities and simultaneously need for efficient system, automation is of high concern. Robots have been emerged to overcome such complexities, which cannot be performed by manual labor. Further enhancing the efficiency, and performing repetitive work with accuracy, robot and its operation are of high importance. Robotics is a very young and modern technology which crosses all boundaries. For understanding the robotics applications knowledge of electrical engineering, mechanical engineering, systems and industrial engineering, computer science, economics, and mathematics will be required. For good and desired operation of robots, control mechanism has drawn a great attention by several researchers. Position control is very interesting domain in field of robotics, and it can be steering up by limits the static and dynamics property of robots.

1.1 Robot Axis Control:

Robot axis control constitutes main role of in various part of robot. Since robot is a complex mechanical system, where many electrical drives are used to control the movement of robots. Robot has six axis in which three is used for arm positioning ($\theta1$, $\theta2$, $\theta3$) and the other three is used for orientation of end effector (α, β, γ). End effector is mostly used for gripping and tooling purpose. Robot joints are connected through brushless dc motor which is fed by PWM inverter. Robot axis control is basically to control the position of robot manipulator. Since

1.2 Brushless DC Motor:

Brushless dc (BLDC) motors are preferred for small horsepower control motors due to their high efficiency, reliability and low maintenance. However the problems are encountered in these motor for variable speed operation over last decades continuing technology development in power semiconductors, microprocessors, adjustable speed drives control schemes and permanent-magnet brushless electric motor production have been combined to enable reliable, cost effective solution for a broad range of adjustable speed applications. BLDC is mostly used for position control scheme. In these applications, the dynamic response of speed and torque are important. These systems are mostly closed loop, and could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop and Position Control Loop. Optical sensors or synchronous resolvers are used for measuring the actual speed of the motor. In some cases, the same sensors are used to get relative position information. Otherwise, separate position sensors may be used to get absolute positions.

1.3 Scope of Present Work:

A simulation model for the control of robot axes has been developed in the present work. Focusing on the reliable and effective operation of robot through different trajectories and varying positions, a two link robot manipulator has been considered in this regard.

The position controls have been performed over two joint axes, using brushless DC motor. A brushless DC motor drive included in the present model comprises two position control loop, i.e. speed and torque control, for studying and analyzing the movement of robot over different axes.

In order, to monitor positional changes minutely in detail, five different ranges of angular position has been set for the present study. Further, analyses of the robot movement, with varying values of parameters in brushless DC motor has been made in the present work.

To explore, best optimal position of a robot movement through the varying operating characteristics of a brushless DC motor, two types of control system has been implemented and developed here. This has been achieved by application by two types of control system, i.e. conventional proportional derivative controller and non-conventional fuzzy logic controller. The fuzzy logic controller has been developed for the purpose, using sigmoid function with 81 logical rules, and simulated by the technical software @ MATLAB.

1.4 Contribution of Present Work:

The automation with emerging robotics technology has received intense attention in the recent literature, one of their most important aspects *i.e.* the effective operation of robot needs further attention. The current work has emphasized on improving the operational features of robot through various controlling technique. The positional control of two link robot has been achieved by controlling the speed, acceleration and torque as a function of angular position. Further, the torque applied to attain the specific position according to a given reference trajectory, is controlled through brushless DC motor.

The electrical parameters of a brushless DC drives have been varied within a given constraining range of Voltage. These electrical parameters, *viz* current, speed and torque are controlled by the implementation of proportional derivative controller, and fuzzy logic controller.

Applications of fuzzy logic controller have resulted in a better operation in both robot and drives, with respect to that of the proportional derivative controller.

The values of angular position, speed and subsequently the torque, relating to the two axes robotic motion have been obtained more towards the given reference value, by the employment of fuzzy logic controller. Moreover fewer variations in moment of inertia have been obtained, through fuzzy logic controller; while controlling the angular position of a two-link-robot over a given range.

Smooth operations have been obtained for DC drives, when sigmoidal function based fuzzy logic controller have been used instead of conventional proportional derivative controller. The operational value of current, speed, and torque also ranged within the given rated value over a specific simulated time.

However, it can be inferred that fuzzy logic controller can be adapted as a better option for robot axes control through DC drives, with respect to the conventional proportional derivative controller.

1.5 Overview of Thesis:

This thesis contains six chapters, described all part of project in detail. Chapter 1 gives an overview on the motive behind the present work and the contributions. Chapter 2 describes the literature review on the robotics and brushless dc motor.

Chapter 3 describes the detailed knowledge about robots, type of robots. It also gives the idea about that on which basis we classified the robots i.e according to their shape, size etc. It describes the function of robots, specifications of robot and applications of robotics.

Chapter 4 describes about the drive system, brushless dc motor their construction operation and applications of bldc motor. Chapter 5 describes the modeling and simulation of two link robot, modeling of drive system and position control of two link robot system by both conventional and intelligence controller method.

Chapter 6 gives the result of two link robotic systems and their drive system at different angle positions for PD and fuzzy logic controller, and its conclusion

CHAPTER 2
LITERATURE REVIEW

The demand for automatic technology has grown up substantially over last few epochs. The automatic technology using robots are achieving fast recognition for providing various beneficial features in society viz. reliability, accuracy, productivity. In focus to provide efficient and effective processes in today's life, robot technology has gained high importance. Several researchers have dealt with different aspects of the operational portion of robot [1].

The manufacturing industry is undergoing era of robotic revolution. Manufacturing cost reduction, increased productivity, higher product quality and possibility to substitute human operator from unsafe and hazardous working environment are some of the boons of robotics in manufacturing sector [1]. Not only manufacturing industry, robotics is playing prominent role wherever opportunity present itself to introduce automation. Major application of robotics can be seen in : space mission for planetary surface exploration, in space operation like component assembly, inspection and maintenance[2-3], underwater exploration for environmental and biological study of deep sea and in collection of geological samples from deep sea surface [4-5][7], search and rescue operations to save life in collapsed buildings, diffusing of bomb, rescuing people trapped in radioactive and hazardous environment [6] , aerospace for aircraft production and unmanned aerial vehicles [8] medical field for robot assisted surgeries[9] and finally prostheses such as artificial limbs[10].

In most industrial applications, robot executes a specific motion, dictated by manipulator's end effectors for completion of task. This motion can be constrained or unconstrained depending upon physical interaction/non interaction of between end effectors and environment [1]. A control system is indispensable for correct execution of end effectors motion in consistency with desired trajectory [11-14]. Achievement of accurate operational space sensing and motion control of robot arms have been driving force of researchers. First-order lag filter as a perturbation-observer has been investigated by Komada et al [15]. Similarly, time delay method is studied by Hsia *et al.* [16] and Youcef-Toumi and Fuhlbrigge [17] have been proposed for the estimation of the unknown dynamics terms used for linearization. Robust controllers have been investigated to nullify the effect of some of the unknown dynamics terms. Lu and Meng [18] proposed impedance controller while Liu and Goldenberg [19] improved robustness of impedance controller by an integral term. In order to achieve the operational space motion control accurate acceleration is needed. Sensor fusion is applied for measurements obtained with various sensors. Kalman filter has been investigated for enhanced sensor fusion between end-effectors accelerometers and joint position sensors [20-21]. Model predictive controller has also been tested for estimation of unknown dynamics [22].

Mechanical manipulator either places a work piece at prescribed position or move along trajectory [23]. In general ,unhindered motion of manipulator in a workplace, six independently driven axes come into play ,three axes are needed to position robot hand and three hand axes are needed to orient hand axes in specific direction [24-25]. In order to activate various axes, different drive principles exist in literature, namely: electric, hydraulic and pneumatic [26].

In most general cases, a hydraulic actuator is composed of two oil compartments separated by a movable part. In rotary vane actuator this movable part is vane joined with output shaft. The role of actuating element is performed by a valve which is in control of oil flow, moving in and out of compartments[27].Rotation of constant speed is obtained by constant oil flow which in turn obtained by keeping pressure drop over valve constant. Compressibility of oil in two compartments makes these two oil columns to work as two springs. This explains integrating and the second order behavior of a hydraulic actuator. Hydraulic actuator display many desired features: precision in motion control in varying speed, heavy load handling, workability in explosive environments,[28] However, they demand high cost of purchasing and maintenance, they are inferior in energy efficiency. Moreover Hydraulic actuator drivers are noisy in operation and always have danger of hydraulic fluid leakage. Air-driven actuators are used in Pneumatic drives**.** Since air can also be considered as fluid, therefore operating mechanism of both of these drive system are similar in many respects. Since pneumatic drives use air as working fluid they are economical and less noisy than hydraulic drives [29]. However precise control is very difficult to obtain in pneumatic drives because of compressibility of air [30]. Electrical servo drive system has emerged as a preferred solution for driving action in field of robotics. Because of their superior controllability, low cost, easy maintenance they continue to replace hydraulic and pneumatic drive systems [31]. Servo motors, dc servo motors, and stepper motors are mostly used for electric actuator drives. In order to control exact position both ac and dc servomotors have inherently built in methods .Nowadays most robots of new generation employ servo motors rather than hydraulic or pneumatic ones. Dc servo motors are usually preferred in and medium-size robots while for robots, handling larger and heavy loads Ac servo motor are preferred as they have large torque handling capability. A stepper motor is preferred mostly in education robots rather than in industry [32].

For every technical operation, a control system has always been the most essential part. Further different methods or processes are often implemented for controlling various functions. Numerous drives and motors have found their applications in doing so. Depending on the requirement of the robots' job the drives are chosen accordingly**.**

Brushless DC (BLDC) motors are widely used in most servo applications in robotics, dynamic actuation, machine tools and positioning devices, due to their favourable electrical and mechanical characteristics, high torque to volume ratio, high efficiency and low moment of inertia [33]. Problems like irregular commutation, noisy operation and wear and tear , are absent in DC brushless motors . In BLDC motors, an electronic controller [34] is used in place of the brushes .Commutation is achieved electronically rather than mechanically resulting higher efficiency, longer life, quieter operation and wide range of operating region. In order to move the rotor, current coils which are kept stationary are energized sequentially. Electric controller determines which coil has to energised next, to generate torque. Both sensor less and with sensor design exist in literature for giving positional information of rotor to electronic controller [35].

Brooks, Rodney analyzed a Layered control system which is made up of asynchronous module to let the robot to operate at increasing levels of competence[38].Similarly hemati et al shows the high-performance of BLDCM which needs the effects of reluctance variations and magnetic saturation as well as control law to drive, using transformation theory[36]. With the help of single-link direct-drive arm in BLDC motor the efficiency if overall control law is analyzed[37-38]. Hirzinger, Gerd, et al designed a mechatronic approach which enables the implementation of effective vibration damping and advanced control strategies for compliant manipulation [39].

However, the controls of different axes of a robotics technology through brushless DC motors are rare in literature. Again the output responses fluctuate frequently with the characteristic features of the applied drives. To overcome such problems, implementation of a suitable controller is much needed. Different new methods are emerging to adjust and improve various factors in order to achieve the desired function by the robot.

A non-linear autoregressive-moving average L2 controller has been used in [40] for the speed control of separately excited DC motor. The authors modeled a system and found a it as a superior method over other conventional techniques like hysteresis current controller and PI controller. An ac-dc buck booster converter has been developed [41] using PWM uniform techniques for the better operation of DC motor. Stephan. et.al. have implemented a cascade scheme for thyristor driven DC motor. The scheme resulted as a robust and efficient method for the speed control of DC motor [42]. Authors in [43] have studied the performance of DC motors through current control. A switched LQ controller has been used and analysed for the speed control by Chevral.et.al. The operations of sensor-less electric drive have been studied by kukolj.et.al. Several analyses have also been performed by the authors [44] regarding the operation of DC motor using AI technique. Here, the authors have focussed on the usage of both classical and modern optimization techniques in the operation of dc drives.

In order to provide robust solutions within a wide range the authors [45] have recommended an intuitive method for the operation of linear brushless dc motors having modeling uncertainties. The method considered every specifications of different mixed sensitivity function, to offer a good tracking control method. Lin et.al. developed two-parameters such as proportional, integral, and derivative control framework through a genetic searching approach in order to ensure more stability, excessive control and robustness in its performance**.** Cerruto. et.al have dealt with the operational performance of a PM motor drive for the application in robotics. An adaptive controller has been developed [46] in this regard, and resulted in good response while controlling robot actions. Speed controls of BLDCM servo motor have been performed by Xia. et.al. through the implementation of two techniques. Enhancement of the dynamic performance of the system has been found [47] by the application of GA based fuzzy controller with respect to the conventional PID controller. Increase in robustness has also been obtained when fuzzy logic is used instead of PID controller. Authors in [48] have also dealt with operating characteristic linear brushless dc motor by the application of conventional controller viz. PID. Non-conventional techniques, viz fuzzy controller have been used [49] for the application of induction motor drives. The velocity of DC motors is controlled [50] considering the settling time for the responses by implementing two techniques. The first technique is based on genetic algorithm based PID controller; while the other method has been developed by combining integral controller with optimal state feedback control. Sharifian et.al. analyzed the results with the application of 20% noise. A better result has been obtained by using integral controller combined with state feedback problem. Authors have also proposed [51] a PID control technique for optimal speed control of brushless DC motor through LQR approach. Gao.et.al. developed an adaptive controller for the control of robot manipulator. Here, a better performance has been obtained using neural fuzzy technique as the control scheme [52].

It has been noticed that different computational intelligent tools are gaining more popularity in dealing with the operation of drives and robots. However, implementation of non-conventional methods for the control of brushless DC motor subsequently governing the actions of robot is spare in literature.

CHAPTER 3
ROBOT

3.1 Overview of Robot:

In the last three decades, robotics has shifted from wild imagination of film makers and science fiction writers to real world of industry and seemingly diverse applications in space exploration, medical field, military, search and rescue operations, nuclear facilities, agriculture. The possibilities of robotics appear to be endless. Robot manipulators can be seen at assembly lines at factory floor for welding, painting car bodies, inserting IC components into PCB with sophistication, doing maintenance and inspection of structures in nuclear, under sea environments, and even plucking apples in agriculture [13]. Although, we are still far way from our fascination to have electromechanical replica of ourselves we have achieved fair degree of progress in making up simpler robots with end effectors that work in wide range of circumstances. Looking at amount of activity and energy being put in research of robotic field, it is fair to say robot is on verge of new explosion to touch every possible aspect of our life.

The word robot was first given by Czech novelist Karel Capek. It comes from the Czech word **"robota"** which means forced laborer or slave laborer. In the picture of Capek robot is represented by machine which has leg, arm and lots of other similarities like human being. However, in reality there is very few similarities between an industrial robot and human [11]. Although Capek gives the word *robot* but the term *robotics* was coined by Isaac Asimov in his story *Runaround*. Further it also gives *three rules of Robotics*-

1. A robot may not injure a human being through action or, through inaction, allow one to come to harm.
2. A robot must obey the orders given to it by human being, except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such its protection does not conflict with the First or Second Laws.

The early designs of robots were basically of the master-slave type [13]. The master and slave unit were joined by mechanical linkages. Later on, electric or hydraulic mechanism occupied place of these linkages. While development of these teleoperators was done, work on Computer Numerically Controlled (CNC) machine tool was also being carried out for milling operation in aircraft manufacture. master manipulator was replaced by programmability of the CNC machine tool controller by George Devol in 1954.This innovation of "programmability" of the machine allowed its retooling and reprogramming to perform various task at low cost. It was found that robot performance can be enhanced by use of sensory feedback. Ernst in 1962 developed a robot to stack blocks with ability to sense force. Robots handling voice and visual signals came in during the period between1965-1975. The first computer controlled manipulator was introduced by Cincinnati Milacron, Inc, in 1974. This design had ability to lift a 100 pound load and could track objects moving on assembly line[11]. Robots were builts to perform component assembly and part injection for assembly lines. The focus of research during period of eighties was on formulating new control algorithm for manipulator control, planning of trajectory and amalgamation of sensor technology with robotics. Lagrangian and computational schemes, computing torque method were developed during this period. During nineties, trend was to build modifiable robots that can handle different assembly operations. It was shown that different end effectors can be attached to same robot unit to cater various demand of industry. Recent trend in robotics is toward integration of robotic field with technological advances of sensor and actuator technology, microprocessor inventions and advances of computation and control. There are lots of applications of robotics where possibility for use of human operator is either nonexistent or unsafe like undersea and planetary exploration, satellite retrieval and repair, the defusing of explosive devices, and work in radioactive environments [13].

One of the robots which are so popular in modern industry is robotic arm. Robotic arms can serve as prosthetics, work in an assembly line and even perform repairing work at the International Space Station. The main reason of its popularity is precision in movement.

3.2 Classifications of Robots:

Robots can be classified in various ways, on the basis their components, configuration, and use. Robots are generally classified according to the types of control system used bring employed, actuator drive, and on the basis of shape of the working envelope [11]**.**

3.2.1 **Robotic like devices:**

Robotic like devices are not exact robots in true sense .however they are called robots because they employ some traces of robotic technology and often known as robot .few of them are listed here:

3.2.1.1 **Prostheses**:

It is referred as robotic arm or robotic leg which is built of either hydraulic or servomotor actuators and have mechanical linkages. They are not programmable and don't have any thinking prowess .the command signal generates from human brain which are processed by a special purpose computer to control the motion of limb. Prosthesis has served immensely to work as artificial limb for handicapped people .However there are still many difficulties in solving and processing of the low level nerve impulse signals which are indispensable for prosthesis to truly work as human limb [6].

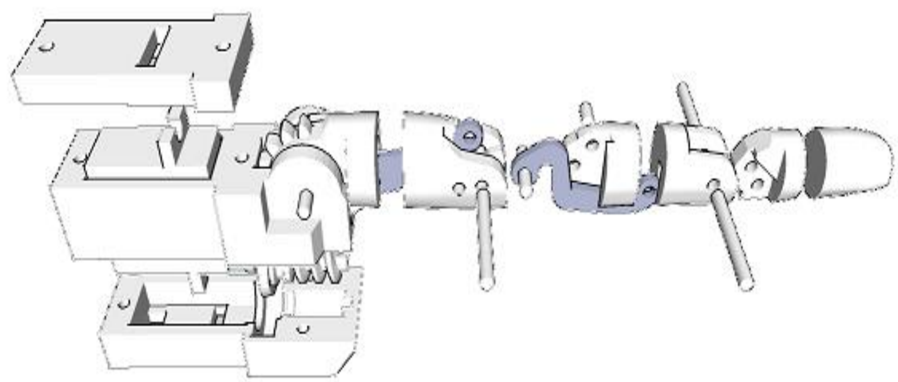


Fig 3.1 Prostheses of robot

3.2.1.2 Exoskeletons:

It is a collection of mechanical linkages which are made to surround either human limbs or the entire human body frame. Exoskeletons have ability to amplify the power. They cannot act independently and therefore can't be called robot. In fact when exoskeleton is used, extreme caution is required by wearer due to increase in forces/speed [27]. An example of exoskeleton device is General Electric Hardeman which utilizes hydraulically actuated servos .once worker wears this equipment he can lift a weight of 1500 lb.

3.2.1.3 Telecherics:

Telecherics is used for manipulation or movement of materials which are located away from an operator. This device uses either hydraulic or servo motor actuators which utilizes closed loop control system. These devices are not exactly robots as they need human being to close the loop and make decision regarding position and speed. Such devices are used in dealing with hazardous condition such as radioactive waste; an example of application of telecheric mechanism can be seen in the arm that is installed on the NASA space shuttle.

3.2.1.4 Locomotive mechanism:

Locomotive mechanism is the collection of highly sophisticated linkages that are hydraulically or electrically actuated under closed loop control, to execute the locomotive process. Even after having sophistication, these devices can't be termed as robot as they need human intervention for their execution.

3.2.2 Classification by Coordinate System:

The mechanism of robot axis must allow robot to move a part from one point to another in a space. The major axes of the robot normally consist of joints or degree of freedom which are mostly mechanically robust in nature and used for the dynamics [27]. According to the coordinate, robots are classified in four categories which are discussed in this thesis briefly.

3.2.2.1 Cylindrical coordinate robots:

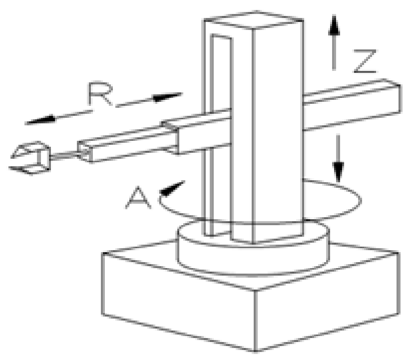


Fig 3.2: Cylindrical coordinate of robot

In this coordinate system, horizontal arm is mounted on a vertical column and this column is mounted on a rotating base. The arm can be moved in and out (in the r direction) carriage can be moved up and down on the column (in the z direction) and the assembly (both arm and carriage) rotate as a unit on the base (in the θ direction).due to constraints imposes by actuators complete 360 degree rotation is not possible in θ direction. The working envelope looks like some part of cylinder; hence they are referred as cylindrical coordinate robots. Typical applications for Cartesian robots include the following:

• Assembly

• Machining operations

• Adhesive application

• Surface finishing
• Inspection
• Water jet cutting
• Automated CNC lathe loading and operation
• Remotely operated decontamination
• Advanced munitions handling

3.2.2.2 Spherical Coordinate Robot:

Spherical coordinate device is classified as when its axis bears a resemblance to a tank turret. Because of limitation (due to mechanical and actuator) the work envelope of such a robot is a portion of a sphere.

Die casting
• Injection moulding
• Forging
• Machine tool loading
• Heat treating
• Dip coating
• Press loading
• Stacking and unshackling

3.2.2.3 Jointed Arm Robots:

There are three types of jointed arm robot.

3.2.2.3.1 Pure Spherical:

This is the most common joint in which all the links of robot are pivoted and so that they can move in a rotary manner. In this joint, the upper portion of the arm is connected to lower portion and forearm is free to rotate (in the direction). The upper arm is connected to a base. Motion of plane is perpendicular to base; base is free to rotate which allows moving the whole assembly in parallel to plane.

Typical applications of spherical configurations include the following:
• Die casting
• Injection moulding
• Forging
• Machine tool loading
• Heat treating

• Glass handling
• Parts cleaning
• Material transfer
• Stacking and unshackling

3.2.2.3.2 Parallelogram Jointed:

In this joint the upper arm is replaced by a multiple closed linkage manner, forming parallelogram like shape. The main advantage of this arrangement is that the joint actuators are closely placed with the base of robot, which reduces the arm inertia and weight resulting in larger load capacity compared to the same size of other type of actuators.

3.2.2.3.3 Cylindrical Jointed:

In this joint single axis is replaced by multiple linked open kinematic chains. These devices are quite cheap and are used where rapid and smooth motions are required. Typical applications for cylindrical configurations include the following:

• Machine loading and unloading
• Investment casting
• Conveyor pallet transfers
• Foundry and forging applications
• General material handling and special payload handling and manipulation
• Meat packing
• Coating applications

3.2.2.4 Cartesian coordinate robot:

This is the simplest configuration where links of the manipulator are bounded to rotate in a linear manner. Linear motion allows simpler Control mechanical rigidity, accuracy, and repeatability.

Typical applications for Cartesian robots include the following:

• Assembly
• Machining operations
• Adhesive application
• Nuclear material handling
• Robotic X-ray and neutron radiography
• Automated CNC lathe loading and operation
• Remotely operated decontamination

• Advanced munitions handling

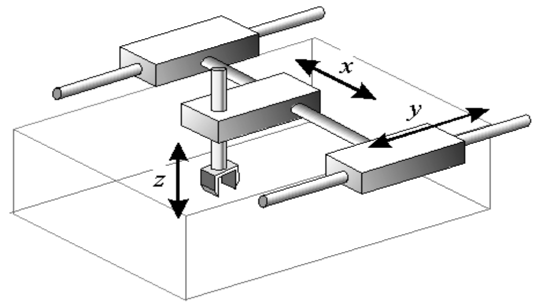


Fig 3.3 Cartesian coordinate robot

These devices behave in a prismatic manner. There are two types of Cartesian robot.

a. Cantilevered Cartesian
b. Gantry-Style Cartesian

3.2.3 Classification by control method:

There are two types of control system employed in robotic manipulator as follows-

3.2.3.1 Non Servo controlled robots:

The non-servo controlling method is the simplest technique, in which manipulators are known as an *end point robot*, *pick and place robot*, or *bang bang robot*. In this technique, device axes remain always in motion until the limits are arrived; regardless any mechanical configuration is used. There will be no monitoring unit at the midpoint of motions. That's why such a robot is controlled in open loop manner. The movement of non servo robots is generally limited by mechanical stops[14].

3.2.3.2 Servo controlled robots:

The ***servo robot*** is a closed-loop system because it employs feedback. In a ***closed-loop system***, the **servo amplifier** handles feedback and transforms signals into current and voltage. Servo amplifiers are used in those applications where great deal of accuracy is required in position or velocity during motion control [12]. Characteristics of servo motor can be listed as:

• Relatively expensive to purchase, operate, and maintain.

• Use a sophisticated, closed-loop controller.

• Wide range of capabilities.

• Can transfer objects from one point to another, as well as along a controlled, continuous path.

• Respond to very sophisticated programming.

• Use a manipulator arm that can be programmed to avoid obstructions

Within the work envelope

Servo controlled robots are subdivided into two groups-

a. Continuous path
b. Point to point devices

In both the cases information regarding position and velocity is monitored every time by feedback mechanism to the associated joints of the robot. With this closed loop controlling, manipulator can move or stop anywhere within travel limit for individual axes. Servo controlled robots are able to store many positions, so that movement becomes smoother.

3.3 Basic component of robot:

Robot is a combination of various structures like mechanical, electrical, and computational. Few of its major components are discussed here briefly.

3.3.1 The Manipulator:

Manipulator is basically a mechanical unit which consists of open kinematic chain, gears, coupling devices. It is a movable part of robot which is used to move in various directions. The manipulator is distinguished by controlling algorithm, power source, joints actuation, and other features [11]. These features help us to select the suitable robot for required task. For example, an electric robot can't be used in combustible environment. The manipulator consists of series of segments and joints. Two segments are connected by joints and they can move relative to one another. The joints can have either linear or rotational motion with help of actuators. Few of the units of robotic manipulator are discussed here:

3.3.1.1 Links:

Links is basically a rigid body or bar which is used to movement in manipulator.

3.3.1.2 Joints:

Joints are used to connect two links. There are two basic types of joints majorly used in industrial robot.

a. Revolute (R) and
b. Prismatic (P)

The movement of links are depend on type of joints, i.e either rotary on linear.

Revolute Joint: In this joint two links are joined by a pin about the axis, and the motion is of rotary nature.

Prismatic Joint: In this joint two links are joined by screw and nut, and the motion is of linear nature about the axis.

Moreover, there are also other types of joints are used like planar (in this, one surface slide over other surface), cylindrical (link can rotate by 90^0 angle) and spherical (in this, one link can rotate in three dimensions with respect to another link).

When the two links are joined and extended by connecting them with more links, they are known as a kinematic chain. In any manipulator, if one end of chain is connected with base/ground by chain, it is called open kinematic chain while in closed kinematic chain structure; last chain of any manipulator is connected to end effectors.

3.3.1.3 Degree of freedom (DOF):

Robot's freedom to move in three dimension space is described by term *Degrees of freedom (DOF)* to move forward and backward, up and down, and to the left and to the right. a joint is needed for every degree of motion[27]. For example, to move along three axes: X, Y, and Z, three joints, or three degrees of freedom are needed. These degrees of freedom are known as, rotational transverse the radial traverse, and the vertical traverse. Vertical axis movement is rotational transverse .The *radial traverse* in-and-out motion relative to the base is known as radial traverse while up and down motion is vertical traverse. Additional degree of freedom is obtained from wrist. The degrees of freedom of wrist are referred as: pitch, yaw and roll. Roll is rotatory motion of wrist; yaw is side to side movement while pitch is up and down movement of wrist.

Six independent movement of a rigid body is shown in above figure.

- Three translations (X, Y, and Z) represent linear motion along to three axes.
- Three rotations (θx, θy, and θz) show angular motions about three axes.

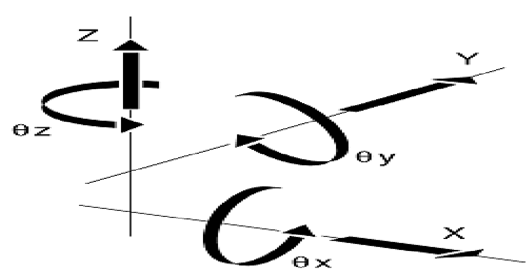


Fig 3.4: Degree of freedom

3.3.1.4 Wrist Configuration:

The wrist configuration is used to enable the manipulator to orient the end effector for performing the task. Wrist only requires rotary joint because it's only purpose to orient the end effector. For the wrist rotation three perpendicular axes are provided –

- roll (motion in a plane perpendicular to the arm)
- pitch (motion in vertical plane of arm)
- yaw (motion in horizontal plane of arm)
- Wrist configuration is also referred as roll-pitch-yaw (RPY) wrist.

3.3.1.5 End Effector:

The ***end effectors*** are the robot's hand, or the end-of-arm tooling on the robot. There are different types of end effectors being used for attachment with wrist. These effectors are categorized in two groups-

- Grippers
- Tools

Grippers are used to hold the work piece during an operation, for expert materials handling, machine loading and unloading etc. Tools are used for operations like cutting, drilling etc.

3.3.2 Sensor Devices:

The sensor devices are used to send the information of the manipulator to the robot controller about status of manipulator positions. Sending of information can be done in two ways either continuously or at the end of motion [11].

Sensors in industrial robot can be classified in two groups-

- Nonvisual
- Visual

Non visual sensors included switches, positions sensors, velocity sensors, and force sensors etc. And visual sensors included vidicon, charge coupled devices, charge injection devices etc.

3.3.3 The Controller:

The controller provides intelligence to manipulator to perform three functions:

- It initiates or terminates the movement of manipulator in desired sequence at any points.

- It store position and sequence data in its memory.
- It permits the robot to interface with external sensors, where robots have to performed works.

To carry above tasks controller must take necessary actions like arithmetic computations for calculating path, speed, and position of manipulator.

Robot controller usually categorized in following category:

- Simple step sequencer
- Pneumatic logic system
- Electronic sequencer

3.3.4 Power Conversion Unit:

The power conversion unit is to provide the necessary energy to the manipulator's actuators. It can also be be used as a power amplifier in case of servomotor actuated system, or a remote compressor, when pneumatic or hydraulic devices are used.

3.4 Function of a Robot System:

Robot system has to facilitate dual work: first, training of robot and second, working with ancillary equipment. In particular robot has following capabilities which are desirable:

- Ability to define points in space
- Ability to move from points to points in various ways
- To control the program (execute the instructions without any delay)
- Controlling for end effector
- Interface with ancillary equipment
- To control external robots and communicate with them properly
- Program debug and simulation
- System parameters (reliable etc.)
- Serviceability

From above observation, it is clear that robot system is quite complicated and at the same time it has to be sophisticated enough to able to change in its program sequence or performance in real time environment. It means robot should be capable of interfacing with world.

3.5 Specifications of Robot System:

Robot is identified by its performance and its features. Specifications of few industrial robots are given by manufacturer, but there is no standard in robot industry. Manufacture specifications vary according to particular industrial requirement. For example while measuring tool tip location of robot , non-contact sensor measurement and contact sensor measurement will yield different results .Because contact sensor damps the oscillations and forces on robot to overcome, on the other hand non-contact sensor never touch any arm dynamics[16].

The load carrying capacity or payload specifications never guarantee the weight that manipulator can carry. In addition, the specification does not define shape of the gripper. Two grippers of same weight may have different inertia, so it is important to know about the inertia of each axis of particular robots. Because inertia affects the torque at the time of acceleration, and if large inertial load is applied, acceleration will reduced.

Apart from above mentioned points, specifications are also affected by may parameters, like: repeatability of robot, maximum tip speed, maximum movement of robot, types of drives used, which control method is used, memory devices, programming method, memory capacity etc. And the most important thing that one should be aware of is that, which type of robot is most suitable for particular applications e.g, spray printing robot is not suitable in small part assembly or machine loading. Some manufacturers design their robot to fulfill market task like electronics and semiconductor industries, where high degree of accuracy and low particle emissions are required.

3.6 Recent and future applications of robotics:

The field of robotics is on verge of explosion to enter new area of applications. robotic manipulators are currently handling simpler operations like welding, spray painting, grinding, part handling and transfer, assembly, operation ,part sorting and part inspection[23]. A number of studies have been done which anticipate new areas where there is possibility of robotic application. The days of deaf, dumb, blind and tactless robot are numbered. Development of sophisticated, low cost, dependable sensors, technological advancement of material science and ascent of control algorithm will ultimately usher a robotic revolution. Few of application area of robotic field which are undergoing major technological breakthrough are mentioned here:

1. Robots in Hazardous Environments: One of the major applications of robots for future (and current) is usability of robots in hazardous environments. A brief description of the some of these environments in which robots is presented here.

a) **Space:** Most suitable example of a robot in space would be remote manipulator system of 20 metre length installed on space shuttle. This mechanism has six degrees of freedom and works under command of astronaut with teleoperation. Nowadays robot can moved in Cartesian coordinates in under computer controlled environment. There are plans to build two cooperating robot arms by Japanese for repairing satellites. Mars rover is a successful example of planet exploring robot with moving base and arms to collect soil samples. However still lot has to be done to to remove time delays for command signals in order to achieve remote feedback actions and control this robot from remote location thoroughly [2-3].

b) **Underwater:** In the last twenty years, several vehicles have been designed for underwater oil exploration and to study see life and surface. The motivation behind their development is to safeguard life of deep see divers. There are two designs of robots in these type of vehicles, one have fully independent mobile platform while in other design mobile platform remain attached with line from mother ship. Hydraulic actuators are used to make it more robust against undercurrent forces in these robots [4-5].Future trend is toward building fully autonomous robust robots that can explore of the deep ocean surfaces, collect and analyze geological samples where it is too risky and cumbersome to have human physical presence.

c) **Nuclear, toxic waste disposal and mining:** It was requirement to handle nuclear waste and radioactive material that initiated ground breaking work in field of robotics [1]. Now days in nuclear industry it is routine to see mobile robots having on board robotic arms inspecting, maintaining, and even taking care of spent fuel rods. With the advent of nuclear energy, there is rise in the of radioactive nuclear waste worldwide, robots having ability to handle and dispose toxic materials are need of hour is mining environment is Similarly hazardous ,where specialized robots can save both human labour and life.

d) **Fire fighting, construction and agriculture:** Robotics in fire fighting operation is still in infant stage. Such robots should have on board heat and smoke detectors, ability to carry and spray fire containing chemicals and to relay video signals to remote locations. Moreover such robots should have ability to go through staircase as well as corridor. In underground and underwater construction robots can ensure economical, safer accurate constructions. Multi fingered robot hands, armed with vision systems are now doing harvesting and picking up oranges in agriculture. University of West Australia have developed a fantastic robot for sheep shearing.

2. Medical Applications for Multi fingered Hands:

Minimally invasive surgery is talk of town in medical field. The motivation behind minimal invasive surgery is to reduce risk to life, hospital stay time and recovery time by discarding the need to cut muscles and other tissue. This is done by accessing affected internal organ by small incisions or offices in body. Several instruments have been developed to help doctors to have a vision inside the body. The endoscope is used for gastro-intestinal tract, the laparoscope in abdominal cavity, the thoracoscope in thoracic cavity and the arthroscope for the joints. At mecical operation theatre, Several procedures like cholecsystectomy (removing gall bladder using the laparoscope), repairing hernias in the lung cavity using the thoracoscope to repair hernias in at lungs, removing scarred tissue at knee joint with the help of arthroscopic, are now done in routine manner. Future belongs to, minimally invasive techniques rather than traditional open surgeries. Advanced manipulators having many degrees of freedom and precision control mechanism will increase safety, application range and efficiency of these methods [9].

3. Robots on a Small Scale: Micro robotics

Some operations require handling at micro or nano scale, like dealing with livings cells, some part of semiconductor material. Two approaches are being investigated to meet these sorts of micro and nano level material handling and manipulation [9]. In first approach a very precise control system is used conventional manipulator is used, while in second approach manipulator is itself is scaled down in size for these micro level material handling. Reducing size or miniaturization of robotic manipulator allow application of delicate forces and thus improves precision.

As vision and other tactile sensors are introduced, controllers become smarter, applications which were not originally thoughts of or only imagined will become reality. Robots will not only replace human workers but they will do jobs that human worker can’t do. Fully automated factory floor, automobile repairing and maintenances, trash collection, a robot handling household chores, robot soldiers in army , they all seem to be not far from present. However as already mentioned improvement in sensor technology that's exceeds human sense capability, technological advancement in AI to make robots smarter to take intelligent decisions, groundbreaking inventions in dynamics to increase degrees of freedom of manipulator andcontrol mechanism to achieve precision of manipulator at nano scale are perquisite to make robot fully capable of handling such futuristic applications.

CHAPTER 4
DRIVE SYSTEM

4.1 Introduction:

Drive system is used for variable speed over a fixed speed of any motor, due to certain reasons.

- Energy saving
- Position and velocity control
- Amelioration of transient

The electric motors and drives mostly run at integral-horsepower at their rated speed. If this rated speed of a motor is used to run a flow process, where the flow is control by throttling or by recirculation. In above mentioned cases the motor runs rated speed in spite of flow requirement, and hence losses are excessive.

So in these types of applications it is necessary to energy using adjustable-speed drives, which reduces excessive losses. Since these variable-speed drives are also less efficient than the original rated -speed motor, but with drive system overall efficiency will improved. In other words, the additional energy losses in the power electronic converter are small compared to the overall savings achieved by converting to adjustable speed.

Velocity and position controls are needed for speed control of electric train, portable hand tools, and domestic washing-machine drives. Elevators and lifts are also required not only position and velocity control, but also acceleration control. ***Robot is an example where three different independent drives are used to control the moment of each axis.***

Suppressions of transient (electrical and mechanical stresses) can be done by using adjustable-speed drives with controlled acceleration. A adjustable-speed drive is used where very large motors are used or where the start-stop cycles are so frequent. For that series SCRs (or triacs with smaller motors) are used which reduced the starting current to a controlled value, and are bypassed the mechanical switch when the motor reaches full speed.

4.2 Structure of Drive System:

The general structure of drive system is shown in fig. which is divided in four major groups.

a. The load
b. The motor

c. Power electronics converter;
d. The control

Loads are defined in very wide range and according to its application it have different requirement also. The common requirements are speed control, with precision and accuracy. Position control, in any automated plants and processes. Hence in few cases steady-state operation are more important, like in air-conditioning and pump drives. And in few cases, like in robots, tape drives, and actuators, dynamic performance is more important, to minimize the time taken to perform operations or effect of control changes.

To fulfill above load requirement it is quite tough to select particular motor drive which satisfy all criterion. We have different types of motor with their advantages and disadvantage both. Since motor determines the characteristics of the drive, and it also, requirements on the power semiconductors, the converter circuit, and the control circuit. For motor drive three criterions must be satisfied:

- they produce constant instantaneous torque,
- they can operate either on pure dc, or sinusoidal ac supply,
- they can quickly and smoothly start and run without electronic controller.

Now in present era, brushless dc motor is used as a drive motor in various applications like robot etc. due to satisfying their all criterion and advantage over conventional motors. In small drives conventional d.c. motors, are replaced by permanent magnet brushless dc motor which reduce the stator diameter, due to efficient use of radial space by the magnet and the reduction of field losses. Armature reaction is usually reduced and commutation is improved, because of low permeability of the magnet. In a large rating drives a.c. induction or synchronous motors are preferred over dc motor because of the limitations of commutation and rotor speed. In a fractional and low integral-horsepower rating drive the complexity of the a.c. motors are not sufficient, especially when dynamic performance, high efficiency, and a variable speed are required. Hence brushless DC motor is perfect for low rating drive.

4.3 Construction of Brushless DC Motor:

A construction of brushless dc motor is similar to normal ac motor. A BLDC motor is a permanent magnet synchronous motor which uses position sensor and inverter device to control the armature current. In brushless dc motor instead of having mechanical commutation, it uses electronics commutation which makes it more comfort and maintenance free. There are basically two types of brushless dc motors are used: trapezoidal type and sinusoidal type. In trapezoidal motor back emf which is induced in stator winding is of trapezoidal nature on its all phases, and the current is of quasi square nature for ripple free and constant torque. And in sinusoidal motor back emf is of sinusoidal nature and current also due to ripple free and constant torque.

As normal motors, BLDC is also divided in two parts:

- Stator
- Rotor

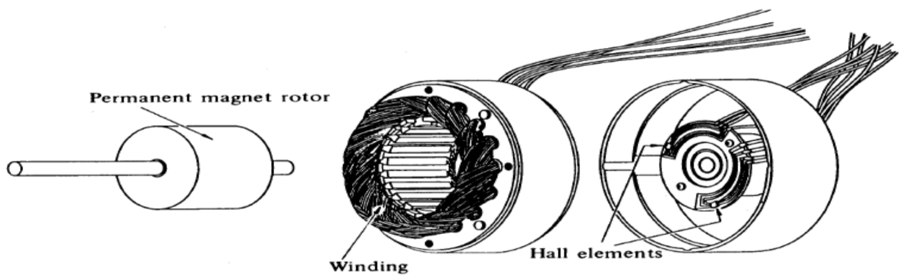
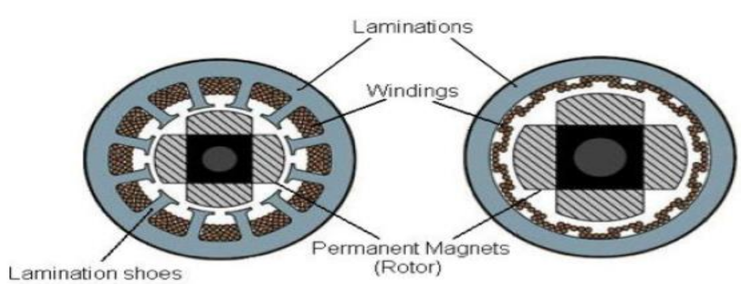


Fig 4.1 Disassembled view of a brushless dc motor

Stator:

Stator of brushless dc motor is same as ac induction motor made up of laminated steel and stacked up to carry the windings. Windings of stator can be arranged in two forms, either in star or in delta. The basic difference in both winding is star give high torque at lower speed and, delta gives low torque at low speed, because in delta only half of voltage is applied across windings which increases losses. In stator core laminations may be either slotted or slotless. A slotless core runs at higher speed as it has lower reluctance. In laminated stack since the teeth are absent, it make it ideal for lower speeds as it decreases the cogging torque. In slotless core more windings is needed to compensate larger air gap hence it is costlier in nature.

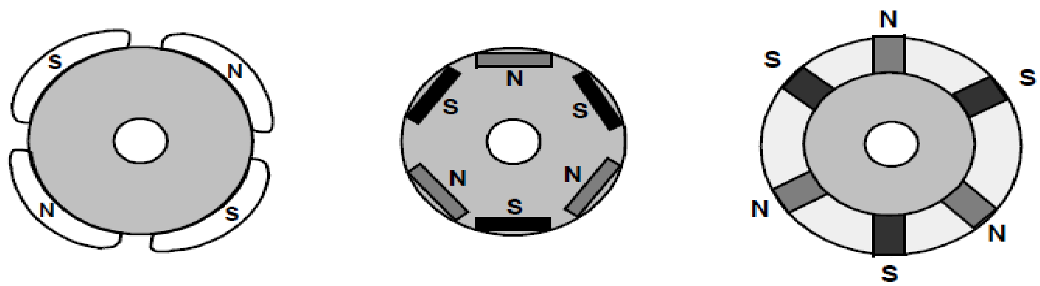


Slotted motor Slotless motor

Fig 4.2 Sloted and Slotless motor

Rotor:

Rotor of brushless dc motor is made of permanent magnet. And vary from two to eight poles according to the applications. As per the requirement of magnetic flux density, material of permanent magnet is chosen in rotor. Generally ferrite magnet is used for permanent magnet, but the ferrite materials have disadvantage that its flux density is low for a particular volume or area. Alloy materials are also used as permanent magnet and it have high flux density per volume. The advantage of alloy magnets are that it modifies the size to weight ratio and for the same size of motor uses in ferrite magnet motor gives higher torque.



Circular core with magnets on the periphery	Circular core with rectangular magnets in the rotor	Circular core with rectangular magnets inserted into the rotor core
(a)	(b)	(c)

Fig: 4.3 Rotor structure

The rotor of permanent magnet machine can be defined in two ways according to its flux alignment

- radial field (the flux directions will be along the radius of machine)
- axial field (the flux direction parallel to the rotor shaft)

The magnet on rotor can be mounted by many ways; surface version magnet is generally used for low speed applications, whereas for higher speed applications interior magnet version is used. The operation of the machine will be similar despite the mounting method of magnet,. There will be difference in direct axis and quadrature axis depending upon the magnet mounting rotor. Since the direct axis reluctance is more than quadrature axis reluctance because air gap is more of direct axis is seen by quadrature axis, which consequence unequal inductance of both magnet axes. The surface mounted magnetic rotor gives high flux density but have drawback that it has lower structural integrity and mechanical robustness. And generally not prefer for high speed applications.

4.4 Operation:

Brushless dc motor is used in many configurations but three phase configuration is mostly used because of high efficiency and low torque ripple. Three phase configurations is also best for precise control system. Figure below shows a transverse section of bldc motor in which position detect system is used by hall sensor that seen the presence of small magnet which is installed on rotor shaft. If the direction of motor is reversed the voltage is reversed as well. In BLDC motor whenever the magnetic poles (N and S) passes near the hall sensors they generate high low level which determine the position of shaft. Maximum torque will be achieve when rotor start to move, similarly the minimum torque exist when the two fields align with each other. For preserving the torque and building up the rotation, the magnetic field generated by the stator is kept on switching.

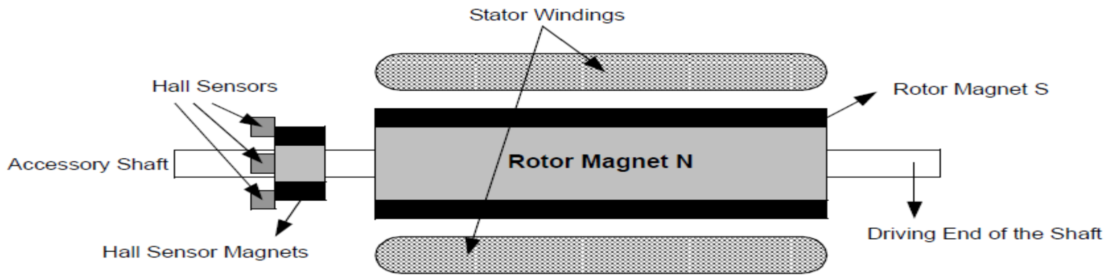


Fig 4.4 BLDC motor transverse action

4.5 Unipolar Drive:

Fig shows the three phases unipolar drive operated motor that uses optical sensors as position detector. Three Photo transistors are placed at the end of intervals 120^0 apart and expose to light sequence through coupled to the motor shaft. In fig the north pole faces the salient pole P2 of the stator and one transistor detect the light and then transistors Tr1 on .Under this condition the south pole which is created at the salient pole P1by electrical current flowing through the winding W1which attracts the north pole of rotor to move it in direction of arrow. When the north pole faces P1,coupled shutter to shaft ,will shade PT1and PT2 will be exposed to light and current will flow through transistor Tr2[57].

When a current flows through W2 and creates a south pole on salient pole P2,then north pole revolve in direction of arrow and face a salient pole P2.These actions steer the current from winding W2 to W3.Thus salient pole P2 is de-energized, while the salient pole P3 is energized and creates poles.

4.6 Bipolar drive

The positioning feedback of internal shaft in case of BLDC is same for brushed dc motor. In brushed dc motors commutators and brushes are used for feedback implementation. With the help of multiple feedback sensors it is achieves by brushless DC motor.

On fashion the BLDC motor is operated in two phases i.e. the two phases produces highest torque when energized while the third phase is remain off. This energisation depends on rotor position. A 3 digit number which changes every 60^0 produces from a signal of position sensors as shown in figure.

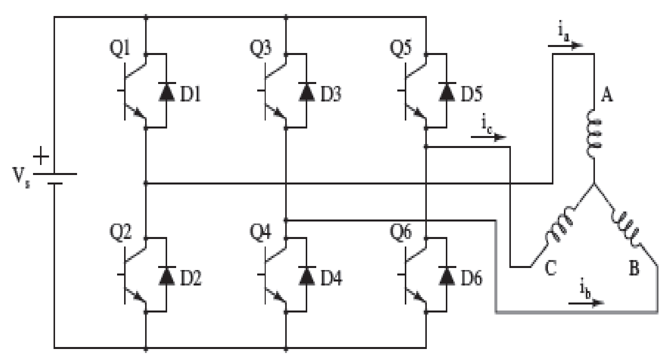


Fig 4.5 Simplified BLDC drive system

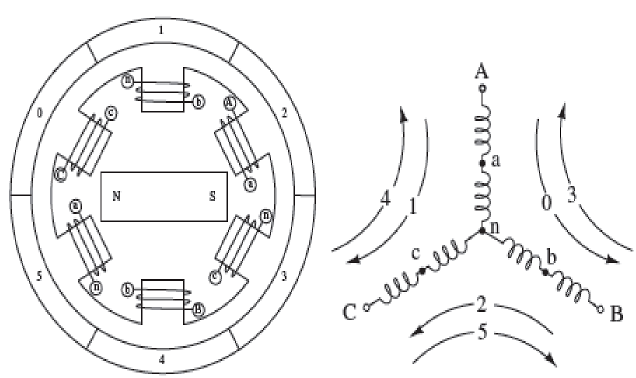


Fig 4.6 BLDC cross section and phase energizing sequence

Each interval start with the rotor and stator field lines are 120^0 apart at ends when 60^0 apart.

Whenever the field lines are perpendicular the torque will be maximum.

4.7 FIELD-WEAKENING OPERATION OF PM BLDC MOTORS:

The purpose of this section is to introduce the principle of field-weakening operations in PM motors and to summarize the findings and conclusions from various studies.

4.7.1 Principle of Field-Weakening Operation: Motor characteristics of a separately excited DC commutator (or a synchronous motor) can be used to explain the field-weakening operation. By variation in the dc current through the field winding help in controlling the excitation flux A rated speed is reached when the voltage equals to the rated voltage that is defined as the maximum voltage available from the drive. Therefore, in order to increase the speed above the rated speed, the flux must be decreased or weakened while the voltage is kept constant at rated value [59].The torque is inversely proportional to the speed so that the output power remains constant beyond the base speed. As shown in fig. this operating region is called the flux-weakening or field-weakening region.

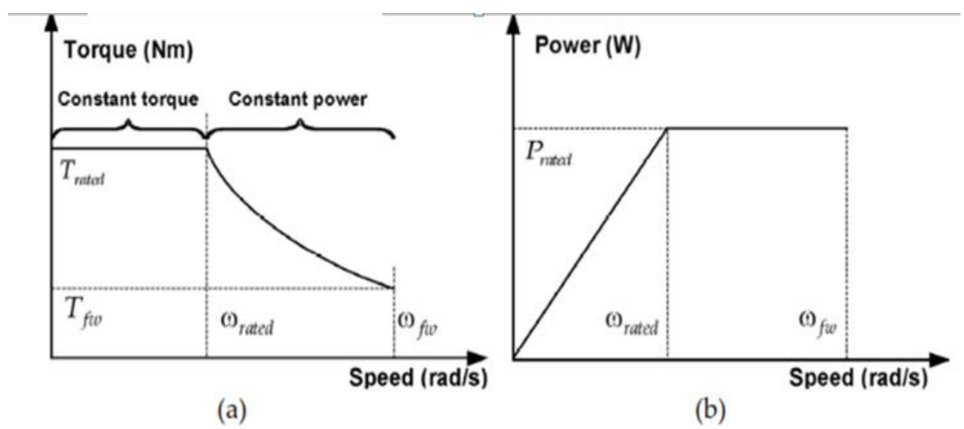


Fig 4.7 Ideal field weakening characteristics: (a) Torque characteristic (b) Power characteristic

4.7.2 Field-weakening Operation of Permanent Magnet Motors:

In permanent magnet motors, with the help of magnets the excitation flux is produced. As the magnets resemble a “fixed excitation flux” source, the magnetic field cannot be varied as in a separately excited DC motor by controlling the field current. However, a control of the total flux in the d-axis (or field-weakening) is achieved by introducing an armature flux against the fixed excitation field from the magnets. It is accomplished by injecting a negative d-axis current Id, as illustrated in fig.

$$V_b^2 \geq \omega^2[(\varphi_m + L_d L_d)^2 + (L_q I_q)^2]$$

Where ω is the electrical operating speed, φ_m is the magnet flux, L_d and L_q are the d-axis and q-axis inductance respectively. The saliency ratio is defined as the ratio between the q-axis inductance (L_q) over the d-axis inductance (L_d). Depending on the rotor configuration, a PM motor is then referred to salient when L_q is not equal to L_d, and non-salient if L_q is equal to L_d. Saliency ratio plays a significant role on the field-weakening performance as it will be shown in the subsequent reviewed literatures.

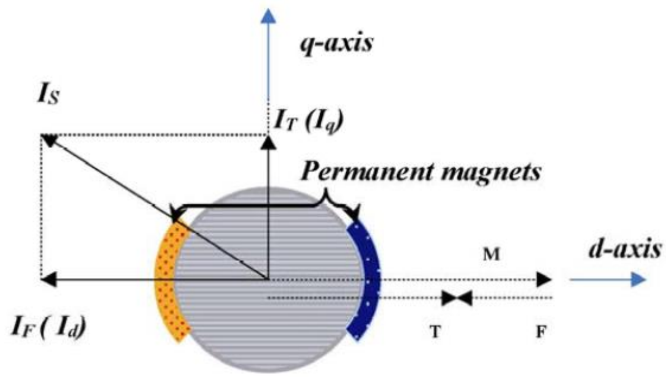


Figure 4.8 Flux-weakening of permanent magnet motors.

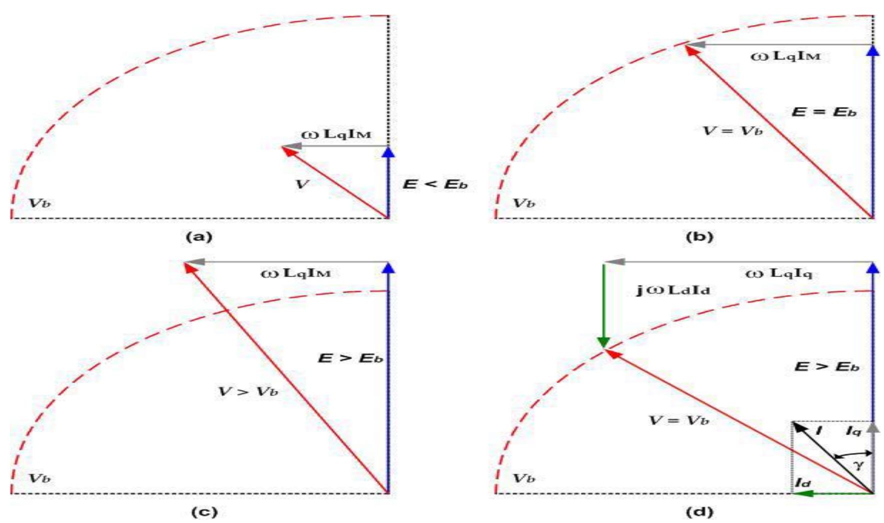


Figure 4.9 Phasor diagram of the PM motor (ideal condition assumed): (a) At low speed; (b) At rated speed; (c) Beyond rated speed without I_d (impossible); (d) Beyond rated speed with I_d.

It was in 1990 that Schifer land Lipo [60] made the first serious attempt to determine the influences of varying parameters on the field-weakening performance. Their study was criticized for not fully normalizing the motor parameters to unity rated speed and hence they had three parameters instead of two. In addition they did not use the most suitable control strategy at high speed for drives with theoretical infinite maximum speed. Despite these drawbacks, their work laid the foundation for the subsequent analyses and showed the optimal field-weakening design criterion that states the magnet flux linkage φ_m should be equal to the maximum d-axis stator flux linkage to reach the theoretical infinite maximum speed:

$$\varphi_m = L_d I_b$$

Where L_d is the d-axis inductance and I_b is the rated stator current.

Morimoto et al. [62] comprehensively analyzed the armature current control method in expending the operating limits within the inverter capacity. The study was also examined considering the possible demagnetization of the permanent magnet due to the d-axis current. Soong and Miller [62] later applied this maximum torque field-weakening control strategy and fully normalized the parameters in their investigations. They introduced the concept of the IPM parameter plane that can be used to visualize graphically the effect of parameter changes on the field-weakening performance. The two normalize d parameters they considered dare the magnet flux linkage and the saliency ratio. They concluded that the interior PM motors with their high saliency ratio are the most promising designs for applications requiring a wide field-weakening

region. Among dozens of the articles published by the authors mentioned above,

several research outputs from Soong and Miller are particularly interesting.

4.8 Performance of BLDC motor:

4.8.1 Speed –torque (T-ω curve):

Since the flux is constant ,the speed of a PMDC motor cannot controlled by using flux control method.The speed and torque of PMDC motor can be controlled by armature voltage control armature rheostat control and chopper control.These motors operate speed below base speed.They cannot be operated above base speed.

Let position feed back V,E and I is in phase and

Also, $\omega L \gg R$

V=E+RI

Put the relationship E$\sim\omega_r$ and T$\sim$I

$$V = \frac{p}{2}\omega_r\lambda_m + \frac{2R}{mp\lambda_m}T_{em}$$

$$\omega_r = \frac{V}{p\frac{\lambda_m}{2}} - \frac{R}{m(\frac{p\lambda_m}{2})^2}T_{em}$$

4.8.2 Efficiency:

Efficiency (η) = P_{out} / P_{in}

Where $P_{out} = T_{load}\,\omega_r$

$P_{in} = m*VI$

$P_{in} = P_{cu} + P_{fe} + P_{mech} + P_{out}$

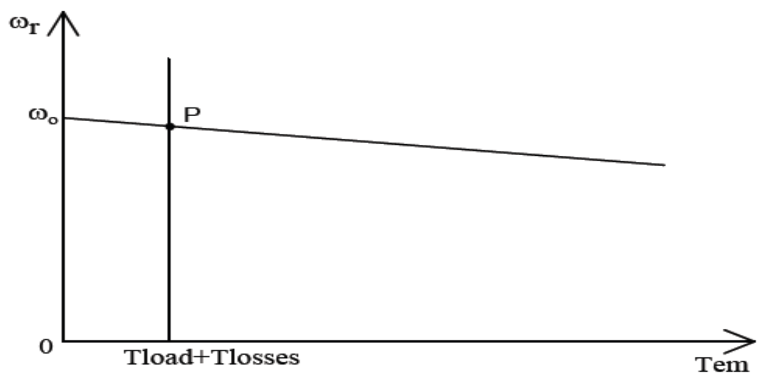


Fig 4.10 T-ω curve for a brushless DC motor with constant voltage supply

4.9 Application:

BLDC motor is used in many applications ranging from fractions to several horse powers. They are used extensible in automobiles to operate windshield, wipers, for driving blower in heater and air conditioning, vacuum cleaners drills, saber saws, hedge trimmers.

1. Single-speed – BLDC motor are better option for variation in speed because of the flat speed-torque curve.

2. Adjustable speed – These motors become more suitable for such applications because variable speed induction motors will also need an additional controller, thus adding to system cost. Hence it is costlier from maintenance point of view.

3. Position control – Precise control is not required applications like an induction cooker and because of low maintenance. However, for such applications, BLDC motors use optical encoders, and complex controllers are required to monitor torque, speed, and position.

4. Low-noise applications – More EMI noise is generated from Brushed DC motors, so BLDC is a better fit but controlling requirements for BLDC motors also generate EMI and audible noise. This can, conversely, be addressed using Field-Oriented Control (FOC) sinusoidal BLDC motor control. Some more examples of application in Brushless DC motors are:

a) Laser printer: In laser printer the speed is controlled by coupling motor shaft to polygon mirror which is in the range upto 40,000 rpm. When an intensity modulated laser beam strikes the revolving polygon mirror, the reflected beam travels in different direction according to the position of rotor at that moment. This reflected beam can be used as scanning.

b) Hard Disk drive: Hard disk drives provide a greater information storage capacity and shorter access time either a magnetic tape or floppy disk. Ac synchronous motors were used as the spindle motor in floppy or hard disk drives. The brushless dc motors have contributed to miniaturization and increase in memory capacity in computer systems.

CHAPTER 5

MODELLING OF POSITION CONTROL OF TWO LINK ROBOT SYSTEM

A simulation model has been designed for robot axis control. Several parameters and responses have been studied through this modeling. In the present work robot model has been simulated considering two types of controllers. Different responses are analyzed for this study for proportional derivative (PD) & fuzzy logic controller. The given robot is six degree of freedom robot manipulator, which has two joints drive by brushless DC motor through speed reducers.

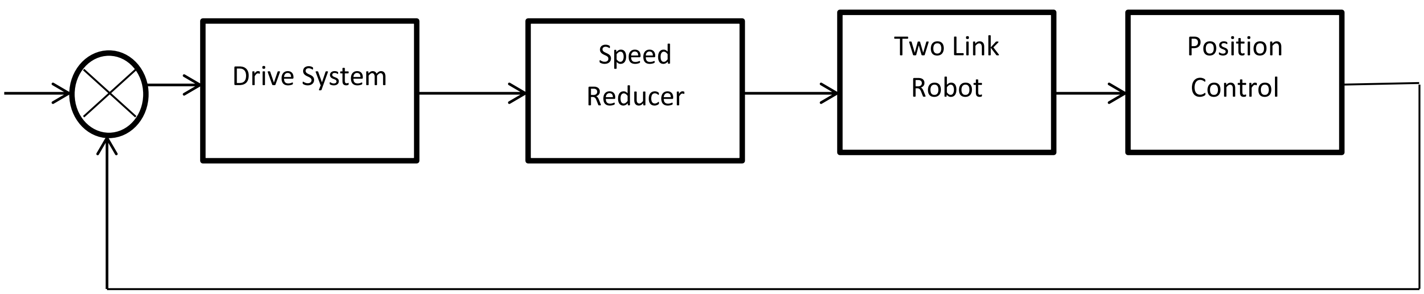


Fig 5.1 block diagram of position control of two link robot system

5.1 Description of Robot Manipulator:

A robot manipulator is basically a robotic arm which is desired to perform specific moment or motion. The robots consider here is a six degree of freedom manipulator with parallelogram linkage type. The robot has six axes. The three axes are used for arm positioning (θ_1, θ_2, θ_3) and the other three is used for orientation of end effector (α, β, γ). In the horizontal plane robot can cover 300^0 arc.

The input signal required as the driving force for the robot block i.e. the robot structure is torque. Here, T_1,T_2 are the torques at joints 1 and 2 respectively. This is given by speed reducer block which calculates effective torque related to each joint. For each joint the corresponding torque functions are given in equation (5.1) and (5.3).

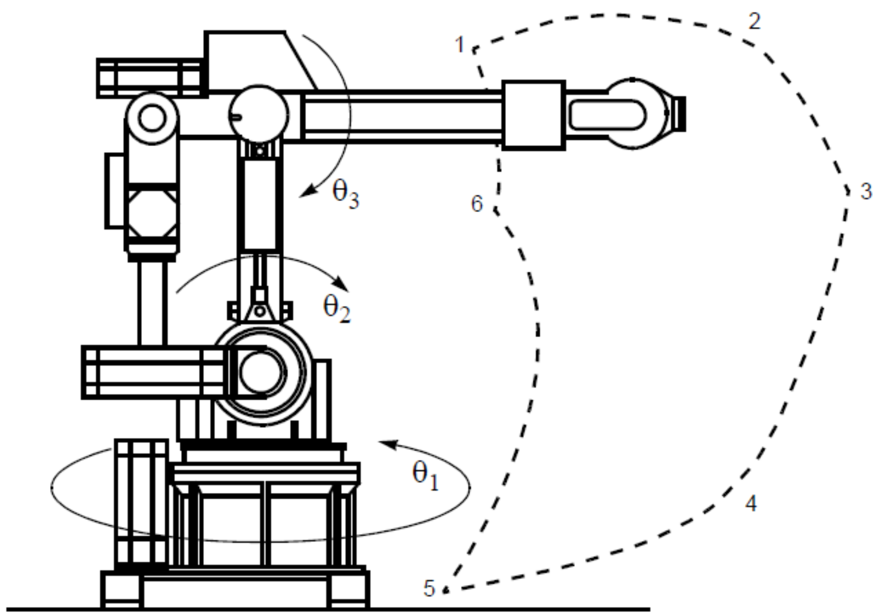


Fig 5.2: Six degree of freedom robot manipulator

$$T_1 = J\frac{d^2\theta_1}{dt^2} + C\frac{d\theta_1}{dt} + G\theta_1 \quad \text{For joint 1} \tag{5.1}$$

From above equation we can write as;

$$\frac{d^2\theta_1}{dt^2} = \frac{T_1}{J} - \frac{C}{J}\frac{d\theta_1}{dt} - \frac{G}{J}\theta_1 \tag{5.2}$$

Similarly,

$$T_2 = J\frac{d^2\theta_2}{dt^2} + C\frac{d\theta_2}{dt} + G\theta_2 \quad \text{For joint 2} \tag{5.3}$$

$$\frac{d^2\theta_2}{dt^2} = \frac{T_2}{J} - \frac{C}{J}\frac{d\theta_2}{dt} - \frac{G}{J}\theta_2 \tag{5.4}$$

Equation (5.2) and (5.4) represent the corresponding accelerations due to T_1 and T_2

Where J = Inertia
C = coriolis force
G = gravitational force
$\frac{d^2\theta}{dt^2}$ = α = acceleration
$\frac{d\theta}{dt}$ = ω = speed
θ = angle

Simulink model of Robot block is given below in figure 5.3-

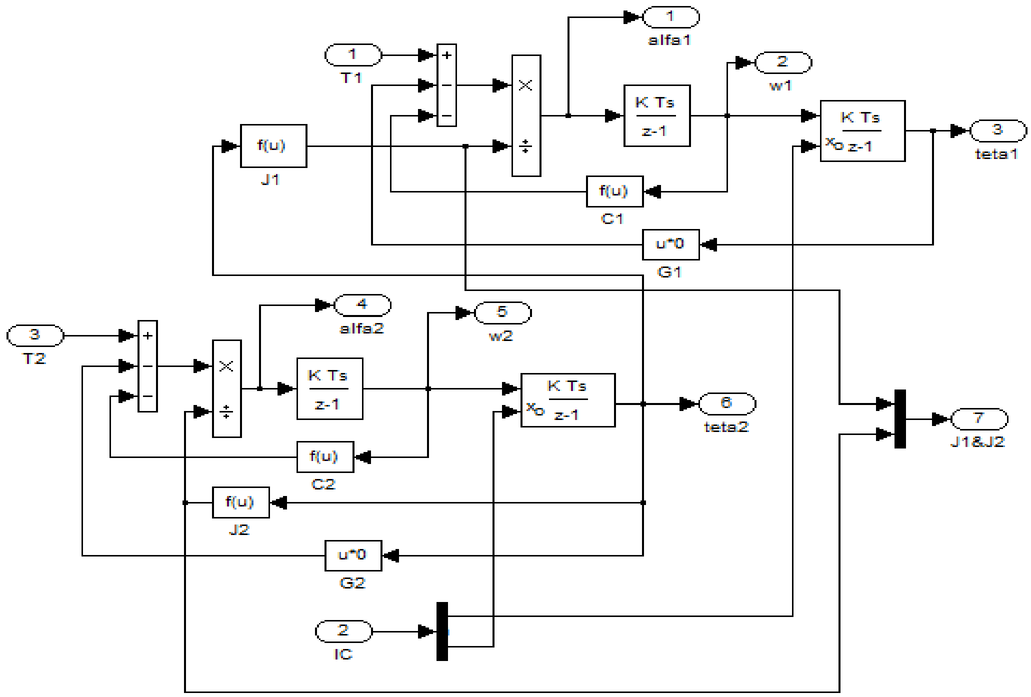
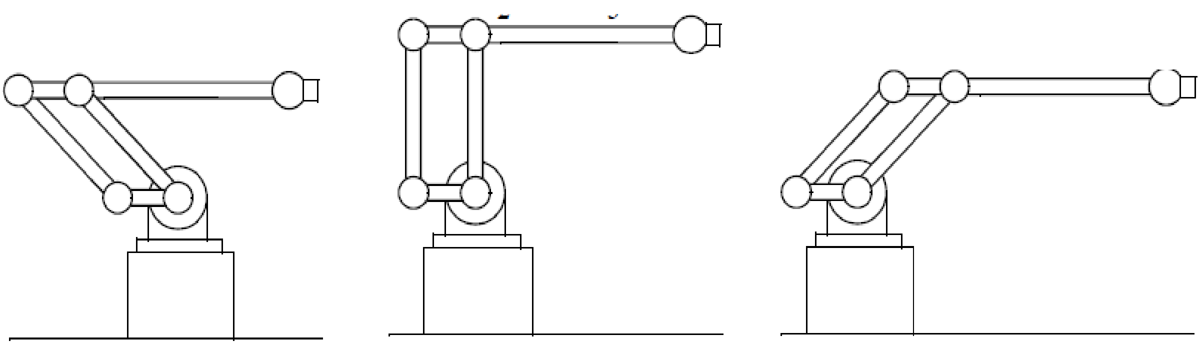


Fig. 5.3: Simulink model of robot

After applying torque to joint of robot system it will move in direction of reference position given by reference trajectory. The position of robot arm changes from position 6 to position 3 in workspace according to the trajectory generator. With change in position of robot arm at different points following reference trajectory, the moment of inertia also changes as shown in figure 5.4.



(a) (b) (c)

Fig 5.4. Different position of robotic arm

As shown in the above figure, the moment of interia is changing at different axis angles. The inertia will be medium in fig (a) of 5.4, it will be lowest in fig (b) of 5.4 and highest in (c) of

5.4 This change occur, as the moment of inertia increases when robotic arm extends itself during movement, and the inertia decreases when it compress itself.

5.2 Trajecory Generator:

Trajectory generator is a function of time θ(t), which is used to provide reference path to robot arms. Trajectory depend on its θ(initial) and θ(final) values which represent time to execute trajectory. Since trajectory is describe by time, so speed and accelerations can also be defined by diffrentiation of trajectory.

There are three types of trajectory planner.

- Cubic Polynomial Trajectory
- Quintic Polynomial Trajectory
- Linear Segments with Parabolic Blends (LSPB) Trajectory

Among the three types of the above mentioned trajectories, here we are using cubic polynomial trajectory, for trajectory generator**.** For the generation of trajectory we need a start and end velocity. One way for generation of smooth curve is we require a polynomial with function of t. The polynomial considered here is shown in equation (5.5)

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \tag{5.5}$$

And desired velocity is given by equation (6.6)

$$\theta^0{}_0 = a_1 + 2a_2 t + 3a_3 t^2 \tag{5.6}$$

The resulted equation for initial condition obtained by combining equation (5.5) and (5.6), is shown in equation (5.7)

$$\theta_0(t) = a_0 + a_1 t_0 + a_2 t_0^2 + a_3 t_0^3 \tag{5.7}$$

$$w_0 = a_1 + 2a_2 t_0 + 3a_3 t_0^2 \tag{5.8}$$

Similarly for final conditions,

$$\theta_f(t) = a_0 + a_1 t_f + a_2 t_f^2 + a_3 t_f^3 \tag{5.9}$$

$$w_f = a_1 + 2a_2 t_f + 3a_3 t_f^2 \tag{5.10}$$

In matrix form it can be represented as;

$$\begin{bmatrix} 1 & t_0 & t_0^2 & t_0^3 \\ 0 & 1 & 2t_0 & 3t_0^2 \\ 1 & t_f & t_f^2 & t_f^3 \\ 0 & 1 & 2t_f & 3t_f^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} q_0 \\ v_0 \\ q_f \\ v_f \end{bmatrix}$$

Here, we have considered the initial and final velocities as zero, and initial time (t_0) = 0, and final time (t_f) = 1 sec
Then the matrix will be

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 2 & 3 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} q_0 \\ 0 \\ q_f \\ 0 \end{bmatrix}$$

And hence the required cubic polynomial trajectory is represented as shown in equation (5.11)

$$q_i(t) = q_o + 3(q_f - q_o)t^2 - 2(q_f - q_o)t^3 \qquad (5.11)$$

The Simulink block for trajectory generator block is given in figure 5.5 -

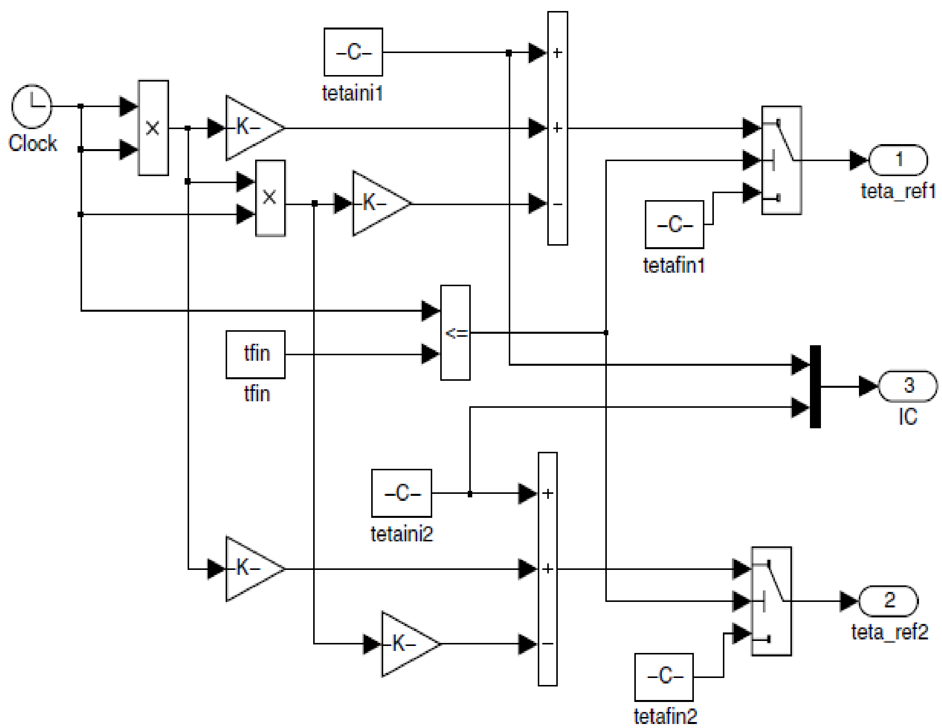


Fig 5.5 Simulink Block for trajectory Generator

The test trajectory comprises moment from point 6 to point 3, where θ_2 vary from -45^0 to $+45^0$ and θ_1 vary from -30^0 to $+30^0$. The parameter specified in the matlab blocks are for denoting the initial position are given as θ_{1ini} , θ_{2ini} and that for the final position are presented as θ_{1fin}, θ_{2fin} , during the period of movement.

5.3 Drive System:

For drive system, we are using here permanent magnet synchronous motor to provide sufficient torque to robot links. We are considering here two first joint axis which drive whole robot system and its load. For first axis we are using 2KW brushless dc motor with a 1:130 speed reducer. Next, for the second axis, 1KW brushless dc motor is used with speed reducers having a ratio of 1:100. The complete brushless dc motor drive system includes PMSM with IGBT inverter, speed controller and current controller. The inputs for the systems are speed command and outputs are the motor speed, which is input for speed reducer. Speed reducer is basically used to control the torque and speed of the robot system. Basically if we increase the torque of motor in proportion, to reduce the motor rotation per minute; a sudden force will be generated. The purpose of speed reducer is not only to increase the torque but also reach the motor at idle torque, and this can be done by reducing the speed input rotation by a ratio of 1/x. Here ‘x’ represents reduction ratio. Here we are using two speed reducer for two drive systems one is 1:130 and second is 1:100 of gear box ratio type. The speed reducers are also categorized by their inertia, stiffness and damping of input and output shafts.

The complete system consist three control loops connected in cascade manner. The outer loop is used for position control, middle one is used for speed control and inner most is used for current control. Since the permanent synchronous motor is fed by three phase PWM inverter, which is operated in current control mode.

The permanent synchronous motor is operate in field oriented scheme, which is useful to decouple the variables as flux and torque can control separately by controlling quadrature current and direct current respectively. The speed control loop used quadrature axis current (i_{qs}) as a reference signal for torque command, and direct axis current (i_{ds}) put to zero. A speed/position sensor is used for speed/position control scheme, and rotor position is used for coordinate conversion from dq to abc.

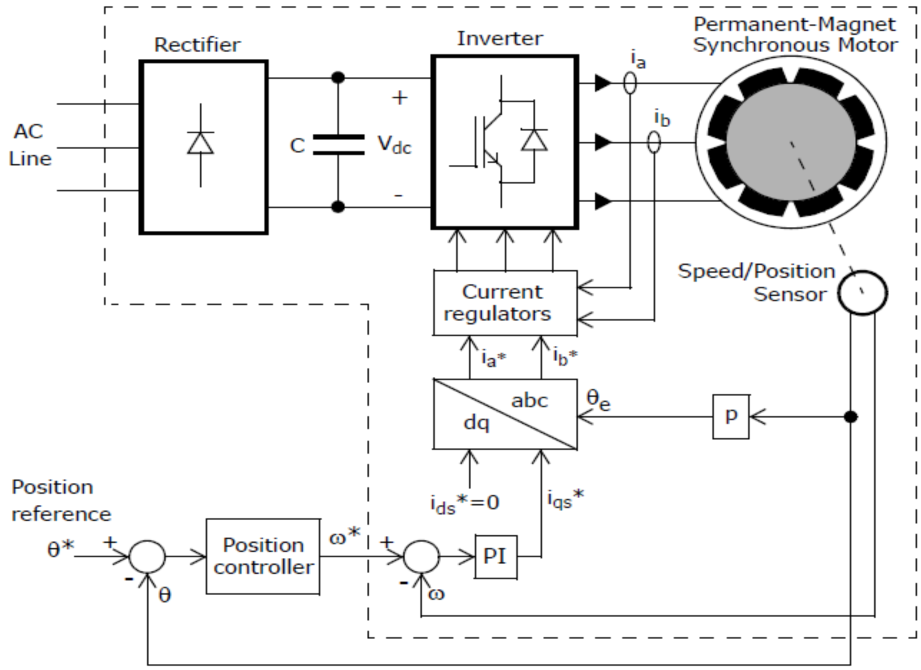


Fig 5.6 Brushless DC motor drive for control of two link robot system

5.4 Position Control:

Dynamics analysis and trajectory planning for multiple degree freedom of Robots have been studied by several researchers through implementation of control mechanisms. Here for position control of two link robot system we are using two type of controllers, as follows –

- Conventional controller (PD)
- Intelligence Controller (Fuzzy system)

Basically, control system can be defined as tool by which any quantity of interest in a machine, circuit, or other equipment is preserved or changed according to the desired requirement. A control system generally comprises different set of methodologies, on the basis of theoretical software logics and hardware components.

The variables or signals which are generally dependent on time can be controlled for a desired stable system pertaining to some specification. Hence, main function of the control system is to meet three types of time response specifications as the following;

i. Damping ratio (or peak overshoot to input)
ii. Steady state accuracy (specified in terms of permissible error)
iii. Settling time

Where, the damping ratio is a dimensionless measure describing how the system behaves (how the oscillations in a system decay) just after a perturbation or some source is given into it. The settling time (t_s) is the time taken for a measuring or control instrument to get within a certain distance of a new equilibrium value without subsequently deviating from specified error band. Moreover, if the rise time (the time taken by a signal to change from one value to another, generally, from a low value to a large value) is specified (t_r) then it should be consistent with specification of t_s. Again, the rise time and settling time both depends on ξ (damping ratio) and ω_n (frequency); which further makes an effect on the output response of a prototype system of any order.

5.4.1 Conventional Controller:

With the requirement of performing complex tasks with good accuracy, more complexities have been aroused in controlling the modern systems. This involves control of multiple inputs and multiple outputs with varying time simultaneously. The conventional controllers generally have simple structures and acceptable performance. It generally serves a wide range of function in industry because of its simple structure.

5.4.1.1 Proportional Derivative Control:

Proportional derivative controller involves proportional and differential gain parameters in the controlling mechanism. The rate at which the process error is evaluated is done by calculating the slope of error time at first and then this rate of change is multiplied by a gain know as derivative gain K_d.

The contribution comprising both proportional and derivative control forms the proportional and derivative control, which term is presented as follows;

$$PD_{out} = K_d \frac{de}{dt} + K_p e(\tau) \tag{5.13}$$

Where, PD_{out} is the proportional-derivative output, during time t, k_d is the derivative Gain, a tuning parameter, k_p is the proportional gain, e is the error defined as product of Set point and process variable.

The derivative portion of control scheme generally makes an adverse effect by reducing the rate in which output changes. So they are most preferable for the reduction in the value of overshoots produced by the integral control. Thus it improves the overall process stability.

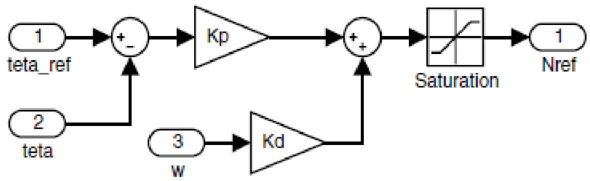


Fig 5.7 Simulink block of PD controller for position control

In the above PD model proportional gain Kp = 2000

And, derivative gain Kd = 500.

K_p (Proportional Gain): The value of the proportional gain governs and evaluates the response to the present error. The value of K_p is generally set as large for fast response. While on the other hand very large proportional gain results oscillations and therefore instability in the system.

K_d (Derivative Gain): The value of the derivative gain denotes the response to the rate through which the error changes**.** Large value of K_d decreases overshoot, but slows down the transient responses. Moreover, the noise amplification during differentiation of errors causes instability to the system.

5.4.1.2 Limitations of Conventional Control:

Though the conventional control systems find a good application in many organizations but it often suffers poor performance in some areas.

The conventional or classical control methods generally result in poor and in-effective outputs, when the controlling parameters are not tuned properly. The performance of control system is usually enhanced by using closed feedback loop. The conventional or classical control system sometimes uses the combination of information of the system and tuning parameters to improve its operating efficiency.

The derivative control system suffers a problem in handling high frequency noise component in the input responses. Though the filters help in performing good operation but still small amount of noises causes disturbance in its output.

5.4.2 Intelligence Controller:

Nowadays systems are getting complicated introducing higher order plants which increases the dead time so resulting the instability in the systems. For proper controlling operation the conventional controllers requires precise data, accurate amount and high sampling rate. To overcome the disadvantage of conventional controller, the performance of the controller is enhanced through the scheduling of PID gains and implementation of fuzzy system. Mainly, the difficulties found by conventional controllers in controlling mechanism are for non-linear, high order and high dead time systems. The fuzzy system is very useful mainly for third order system and design can be done through tuning of non-linear system.

At present, different types of non-conventional methods are emerging for controlling various desired functions of a system. These modern controlling techniques, includes neural network-based method, heuristic methods of control through various optimizations, viz genetic algorithms, particle swarm optimization, simulated annealing, ant colony optimization, differential evolution, bee-colony optimization, harmony search algorithm, bat-algorithm, Cuckoo search, and fuzzy control. These methods operate by considering the issues such as imprecision, partial truth, uncertainty, and approximation which are often present in few real world problems.

5.4.2.1 Fuzzy Logic:

Fuzzy logic theories generally involve vague and imprecise information to model and design systems. The objective and constraint functions are presented as a classical subset, of classical crisp sets of objects, known as the membership functions in a fuzzy system.

In many real-world problems, the design data, objective function, and constraints are stated in vague and linguistic terms. Requirement for more efficient and simple computing techniques cannot always be met by heuristic technique based on natural behavior of both animate and inanimate object. For the sake of simplicity and reduction in operational time the control logic based on fuzzy theory gained more popularity and importance in dealing such cases.

In, the present problem fuzzy logic controller has been implemented for its attributes which may yield a better result than the conventional and other non-conventional methods.

5.4.2.2 Fuzzy Control Rules:

Fuzzy control rules are defined as the procedure for process control using fuzzy relation between various information regarding the ailment of the system to be controlled, For example; if x and y, are the inputs of any system, and z is the outcome or result. The control technique is represented in the form of “if –then” conditions such as; If a is low and b is high, then T is poor; and If a is medium and b is high, then T is fairly good. These are called fuzzy control rules. The ‘if’ phrase of the rules is known as antecedent, and the ‘then’ phrase is known as the consequence. “Small” and “big” are fuzzy values for x and y, and they are expressed by fuzzy sets. These fuzzy based rules build the fuzzy controller.[80] In case of real based input values, a fuzzy inference is used to evaluate the output. Thus, the forms taken by fuzzy control rules comprises four components to perform the operation; which are as; (i) the form of the antecedent, (ii) the consequent, (iii) the form of fuzzy variables, and (iv) the inference method. These are not always independent.

The inference methods generally follow three steps;

- The compatibility between the inputs and the rules governing the antecedents are evaluated.
- The results are obtained for every rules using inference technique.
- Finally the total weighted result is evaluated considering the individual inference rule according to the compatibility of every rules

The calculations performed in the inference method generally depend on the type of variables and the parameters included in the function to be controlled.

5.4.2.3 Features of fuzzy logic control:

Fuzzy logic controls are mainly based on the "If-Then" rules that are generally stated in human language. Fuzzy control normally has the following three features;

[A] Logical control: This gives the free expression of control algorithms using the 'if-then' form. The 'if' clause, in particular describes a wide variety of conditions using logical combination with 'or' and 'and'.

[B] Parallel (disbursed) control: This is the general control policies which are made to work in a disbursed manner by means of a control rule. Here co-existence of control with different logics is possible.

[C] Linguistic control: This makes the possibility to use ambiguous linguistic variables, specially in the antecedents of the rule.

The fuzzy control method can be analyzed and depicted as as shown in figure 5.8;

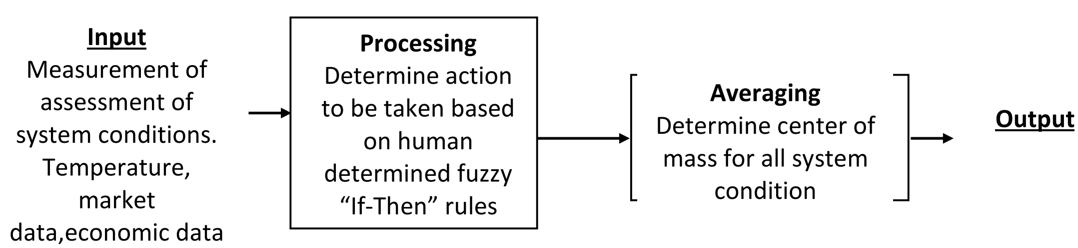


Fig 5.8 Fuzzy Logic-Control analysis method

The pictorial representation of the whole fuzzy logic controller can be expressed in following steps as

- One input is received as a large number of measurements in the form of the valuation of the parameters present in the system, which are to be analyzed or controlled.
- Next, on the basis of human language based fuzzy rules along with some conventional rules the inputs are put through the control logics.
- The individual results are then averaged with some weights and finally defuzzyfied to a crisp value.

Input		thetharef								
		VVHN	**VHN**	**HN**	**N**	**Z**	**P**	**HP**	**VHP**	**VVHP**
thetha	**VVHN**	Z	Z	Z	Z	Z	Z	Z	Z	Z
	VHN	P	P	P	P	P	P	P	P	P
	HN	HP	HP	HP	HP	HP	HP	HP	HP	HP
	N	VHP	VHP	VHP	VHP	VHP	VHP	VHP	VHP	VHP
	Z	VVHP	VVHP	VVHP	VVHP	VVHP	VVHP	VVHP	VVHP	VVHP
	P	VHP	VHP	VHP	VHP	VHP	VHP	VHP	VHP	VHP
	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP
	VHP	P	P	P	P	P	P	P	P	P
	VVHP	Z	Z	Z	Z	Z	Z	Z	Z	Z

Table 5.1. Rule base for fuzzy logic controller

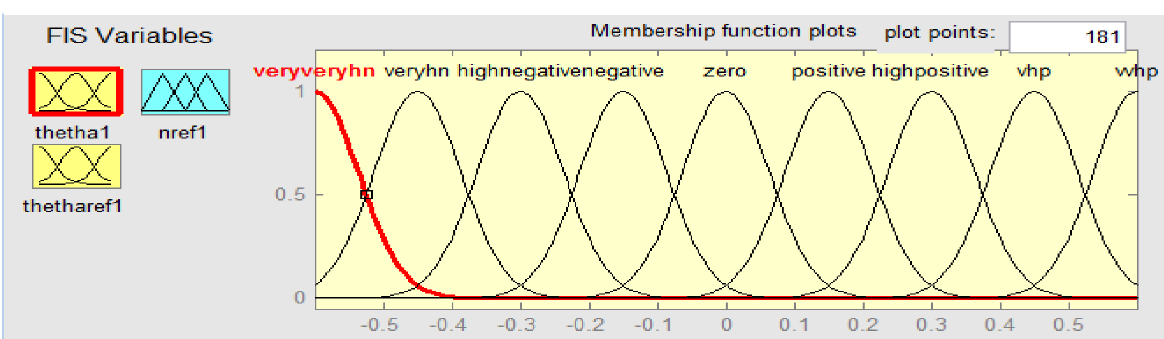


Fig 5.9: Membership function of input theta 1 for position control 1

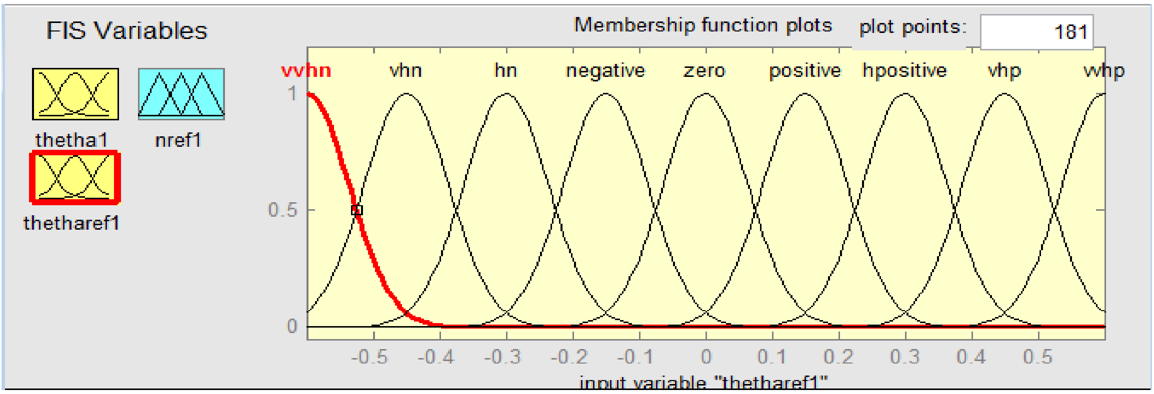


Fig 5.10: Membership function of input thetaref1 for position control 1

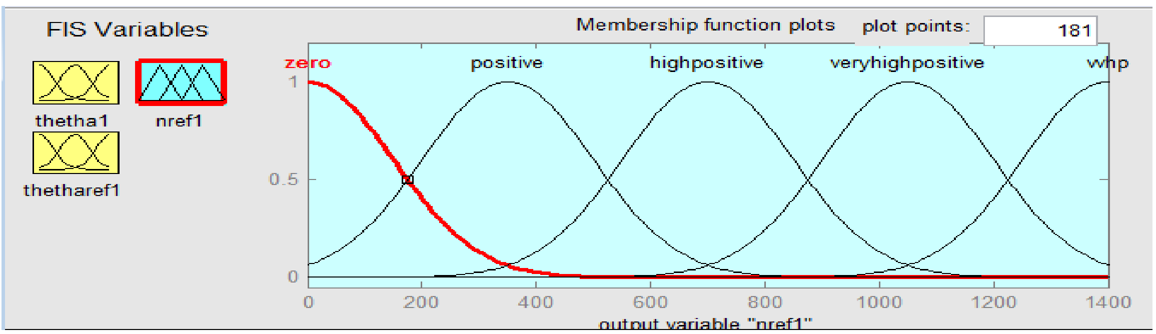


Fig 5.11: Membership function of output nref1 for position control 1

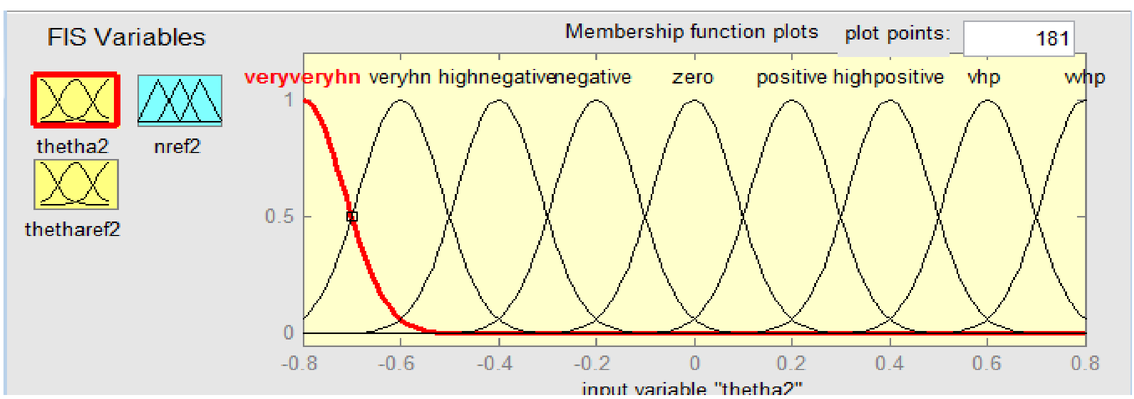


Fig 5.12: Membership function of input theta 2 for position control 2

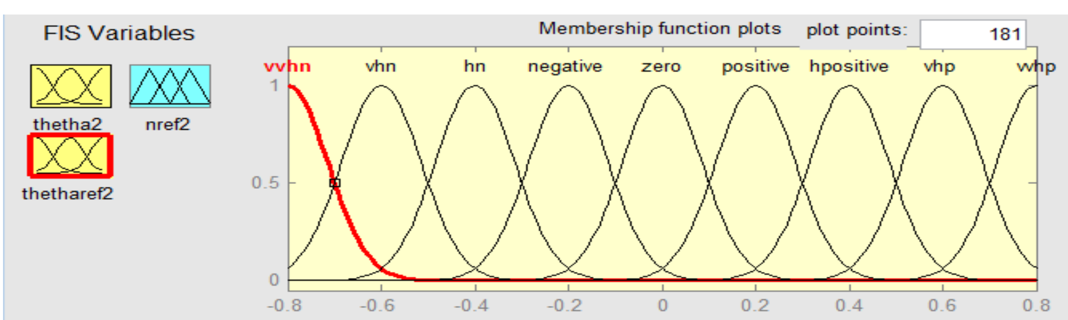


Fig 5.13: Membership function of input thetaref2 for position control 2

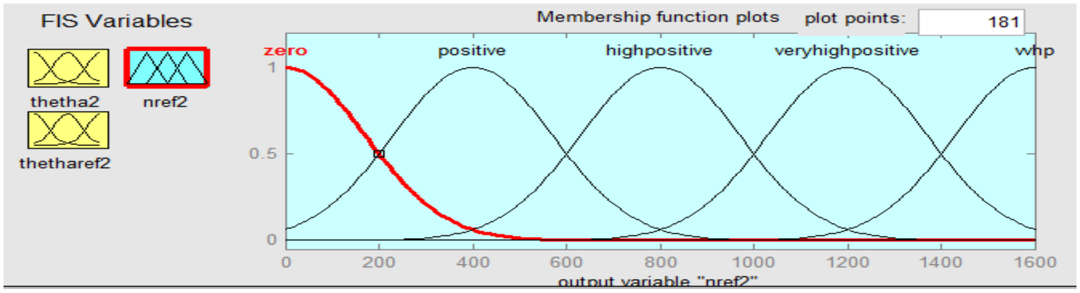


Fig 5.14: Membership function of output nref2 for position control 2

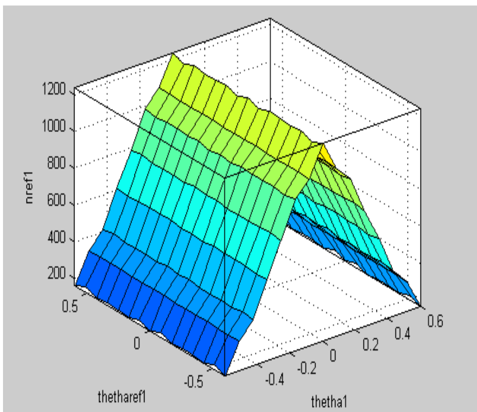


Fig 5.15: Surface view of fuzzy controller1

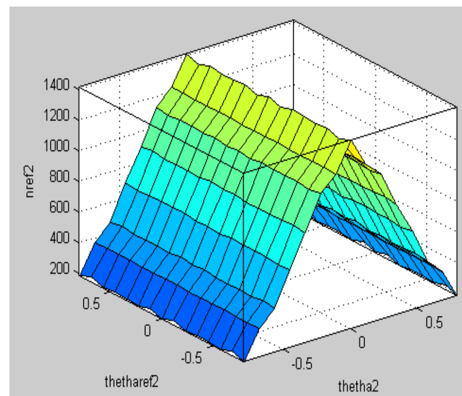


Fig 5.16: Surface view of fuzzy controller2

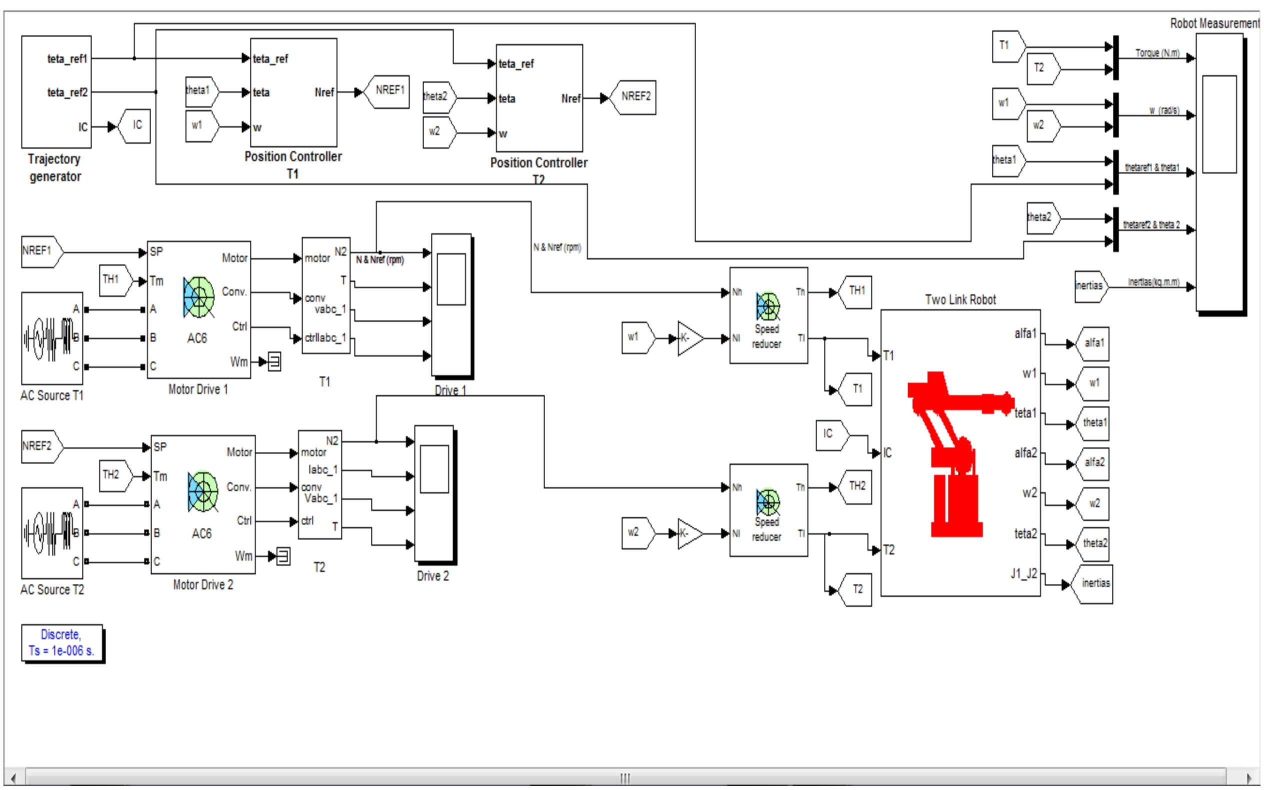


Fig 5.17: Simulink model for position control of two link robot by PD controller

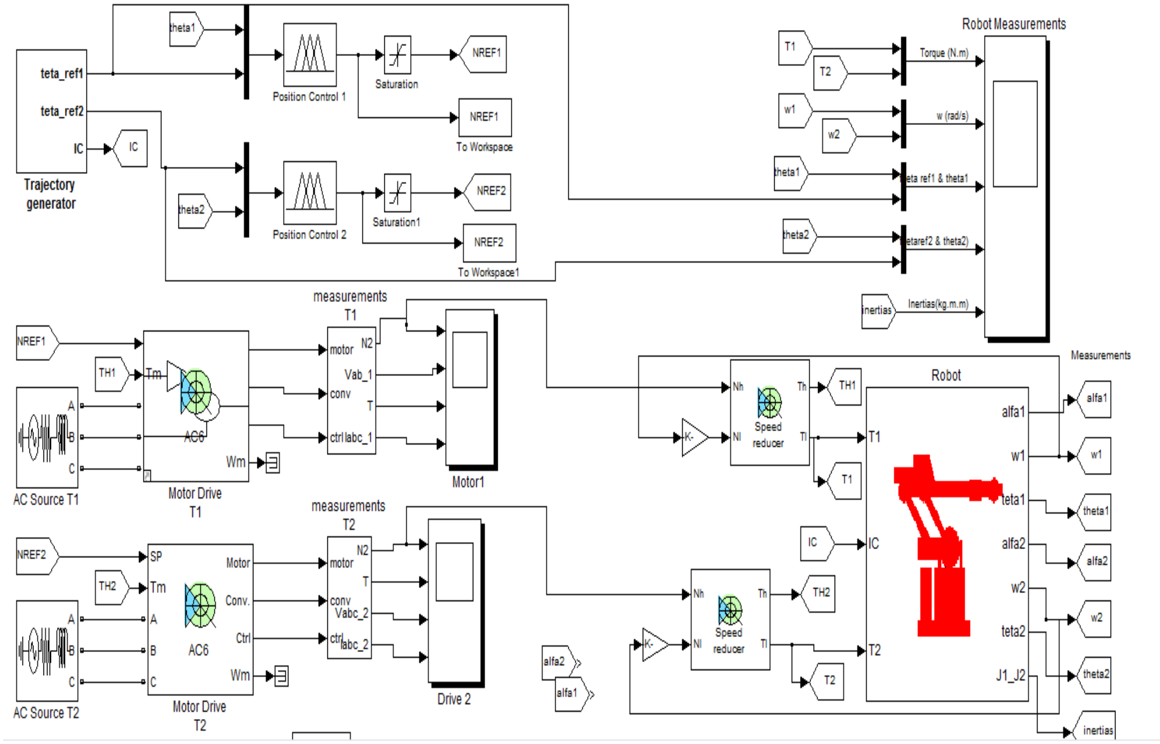


Fig 5.18: Simulink model for position control of two link robot system by fuzzy controller

Two approaches has been tested for positional control, firstly with conventional PD control and secondly by fuzzy mechanisms. The complete simulink diagram for position control of two link robotic manipulator is shown in fig. 5.20 and 5.21

CHAPTER 6
RESULT & DISCUSSION

Several responses with different varying parameters have been studied and analyzed while simulating a two link robot system. The position control of the modeled robot has been performed over two axes, considering two set of angular variations, by the application of a conventional proportional derivative controller and non-conventional fuzzy logic controller.
The responses regarding the parameters of both robot and drives have been resulted better towards a more desired set of values, by the implementation of fuzzy logic controller. However, more detailed analyses for the varying nature of the parameters obtained by using both conventional and non-conventional techniques have been mentioned in the next section.

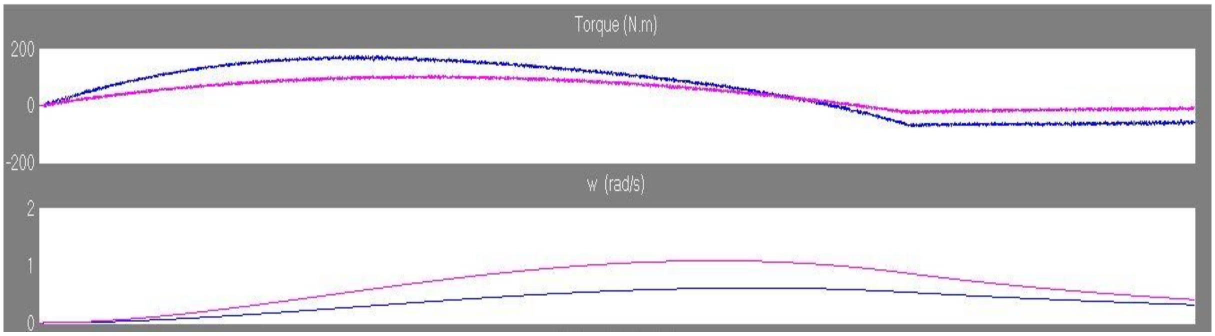
6.1 Responses Using Proportional-Derivative Controller

Matlab version 7.11 has been used to obtain the dynamic responses for robot in terms of their angular positon (θ), angular velocity (ω), torque (T), and moment of inertia over different axes (J). In achieving the angular positions following a pre-specified trajectory, brushless DC motor has been used and modeled with the controlling feedback loop over the axes on which the position varies.
The parameters of a brushless DC motor that has been studied and controlled over a rated range involves, electrical torque (T), current (I), voltage (V) and speed (N). The feedback signals from two-link-robot when sent through the DC motor, has been controlled by using a proportional derivative control. A proportional gain of 2000 and a derivative gain of 500 have been considered for the following case study.

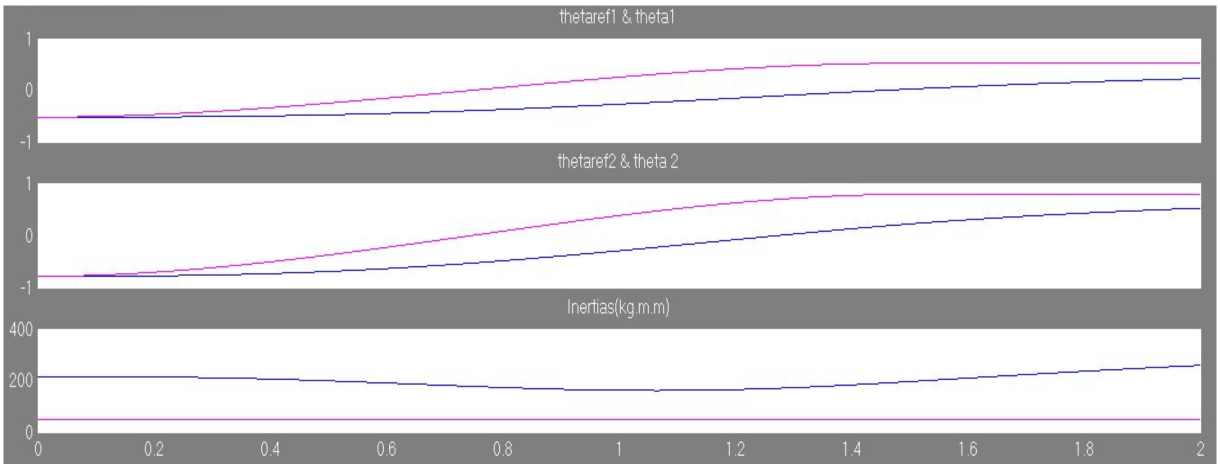
6.1.1. Results for Robot

The responses achieved by the application of proportional derivative controller in the feedback section, when the angular variation ranges from 30 to 45 degree, have been depicted in figure 6.1
The first subplot in figure (a) represents the variation of torque with respect to the time. The pink line is reference line, and blue one is actual response of manipulator. Manipulator arm torque keeps overshooting the reference torque during up to 1.2 seconds, thereafter it starts to

show undershoot. Second subplot is for angular velocity, it can be observed that actual angular velocity is always less than reference.



(a)



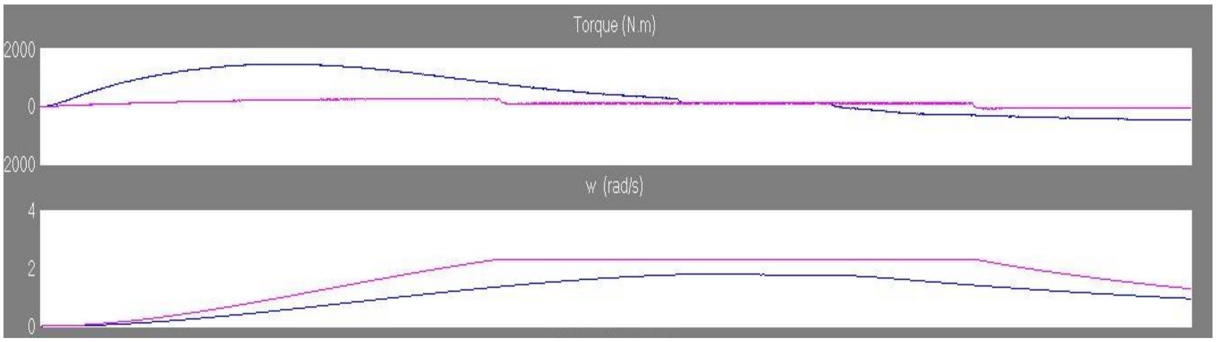
(b)

Fig 6.1 Performance (a: torque, speed & b: theta1, theta2, inertia) of proportional derivative controlled robotic manipulator in trajectory range 30 to 45 degrees

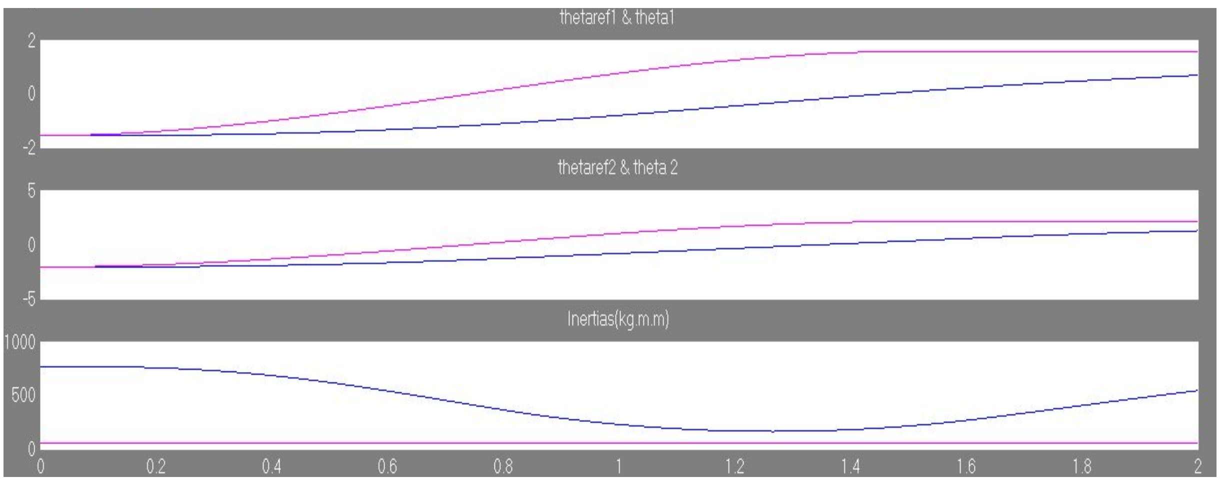
In figure (b) first and second subplot is for angular variation for joint one and joint two. Angular position is behind reference position except initial stages of operation. Last subplot represent is for inertia of robotic arm. The actual inertia of robotic arms is way above reference inertia.

Similarly, the variations obtained in the responses for the angular variation over 90 to 120 degree by the application of proportional derivative controller in the feedback section, have been shown in figure 6.2

From the below figure, it is observed that actual torque undershoots reference torque upto half period .the reference torque remain almost constant with time. After half period, actual torques starts to decrease and undershoots reference torque. Both actual and reference angular velocity shows parabolic variation. It can be seen that actual angular velocity is always less than reference. Angular variation for both joints lags the reference angular position. Inertia show a steady value during initial states ,thereafter it starts decreasing and attains negative peak at around 1.2 sec. after negative peak it starts to increase. The reference inertia remains constant throughout the operation.



(a)



(b)

Fig 6.2 Performance (a: torque, speed & b: theta1, theta2, inertia) of derivative controlled robotic manipulator in trajectory range 90 to 120 degrees.

6.1.2. Results for Brushless DC Drives

The varying nature of the parameters of a brushless DC drive during the positional control of robot from 30 to 45 degree for the first drive controlling the position over the axis at joint 1 have been shown in figure 6.3

The responses achieved for first drive, through the variation of angle from 30 to 45 are presented as speed, torque, voltage, and current in first, second, third and fourth sub plots respectively. The speed is observed to be varying in nature and reaches at a value of 800 rpm, for the time period of 1.2 to 1.4 sec. The torque response increases upto 3 Nm, and reaches at a steady state value at a time 1.5 sec.

Similarly, the performances for the first dc drive when used to vary the angular position of robot corresponding to the change of angular position from 90 to 120 over the axis at joint 1 is resulted in the figure 6.4, given below.

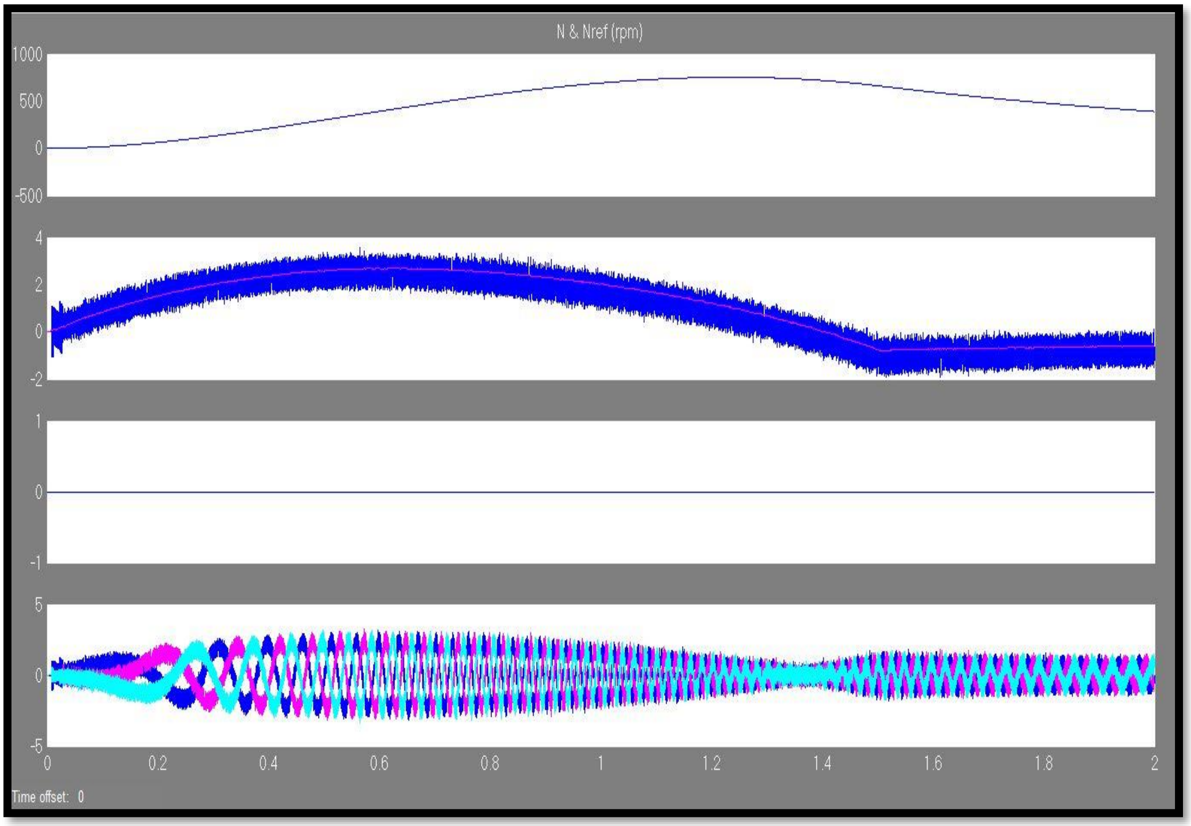


Fig 6.3 Performance (speed, torque, voltage, current) of first drive in trajectory range of 30-45 degrees with proportional derivative controller

For the control of angular position within 90 to 120 degree, the responses of the parameters of first drive in terms of speed, torque, voltage and current have been depicted in first, second, third and fourth sub plots. The speed is found to reach a maximum value of 2000 rpm, and remain constant at this value over a time period of 1.1 to 1.4 sec. During this time period the value of torque and current are also found to remain at a constant value of about 0 Nm and 0 Amp respectively. The torque and current values are observed to settle down at a steady state value at around 1.5 sec.

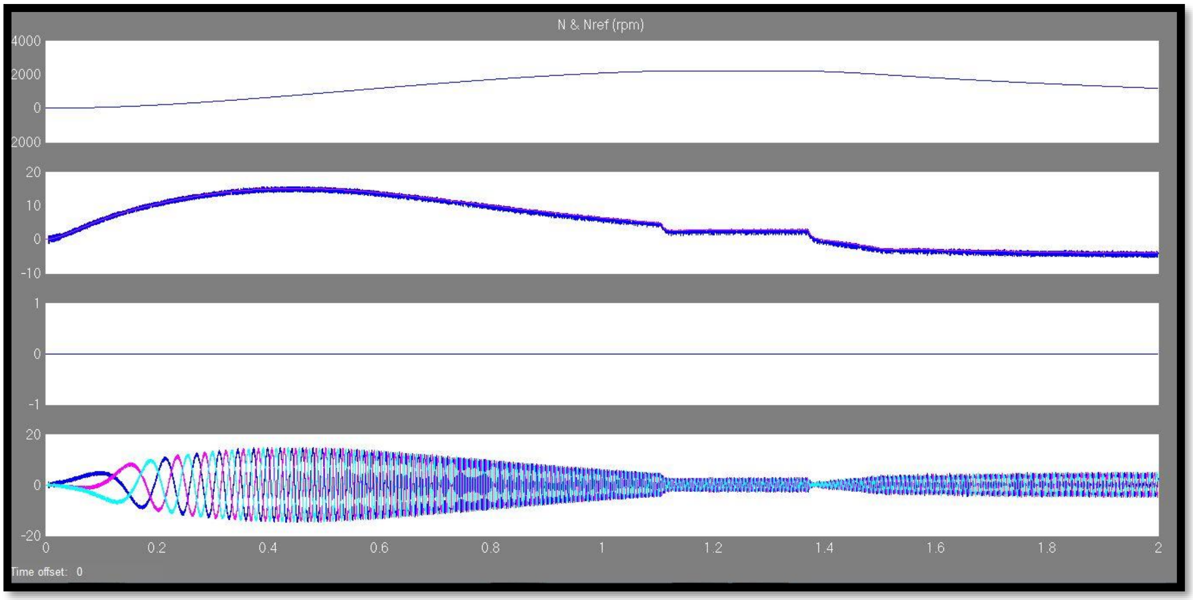


Fig. 6.4: Performance (speed, torque, voltage, current) of first drive in trajectory range of 90-120 degrees with proportional derivative controller

The responses for the second drives obtained while controlling the angular positions from 30 to 45 degree, over the axis at joint 2 by proportional derivative controller is depicted in figure 6.5.

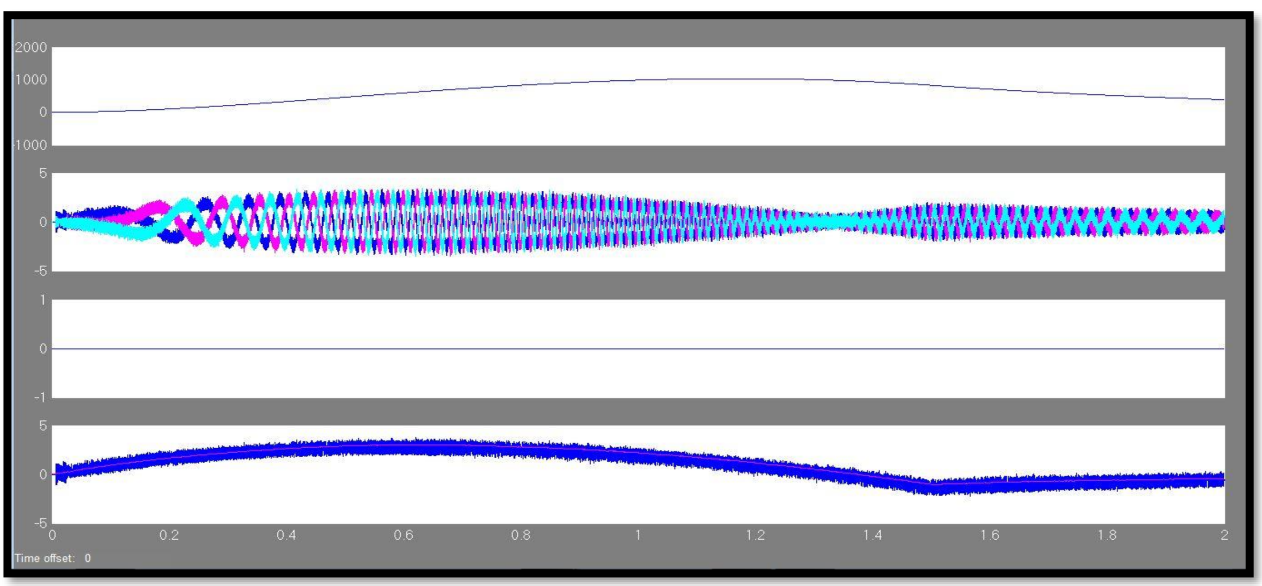


Fig 6.5: Performance of second drive in trajectory range of 30-45 degrees with proportional derivative controller

The responses for speed, current, voltage and torque have been present over a fixed simulated time, for the second drive in first, second, third and fourth sub plots respectively. Here, the speed has been found to be varying throughout the time, except during the period of 1 sec to 1.4 sec at about 100 rpm. Similar pattern of variation is also observed in torque, where it reaches at a steady value at 1.5 sec. The maximum torque value observed here is about 4.8 Nm.

Similarly, the responses for the second drives obtained while controlling the angular positions from 90 to 120 degree, over the axis at joint 2 is portrayed in figure 6.5.

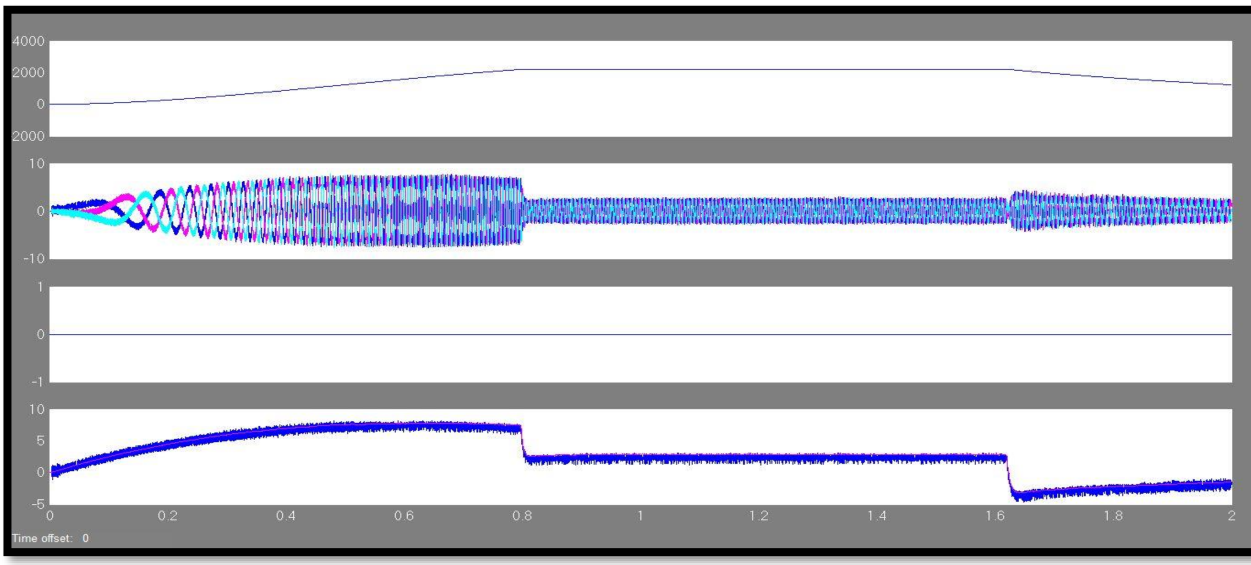


Fig 6.6: Performance of derivative controlled second drive system in trajectory range of 90-120 degrees with derivative controller

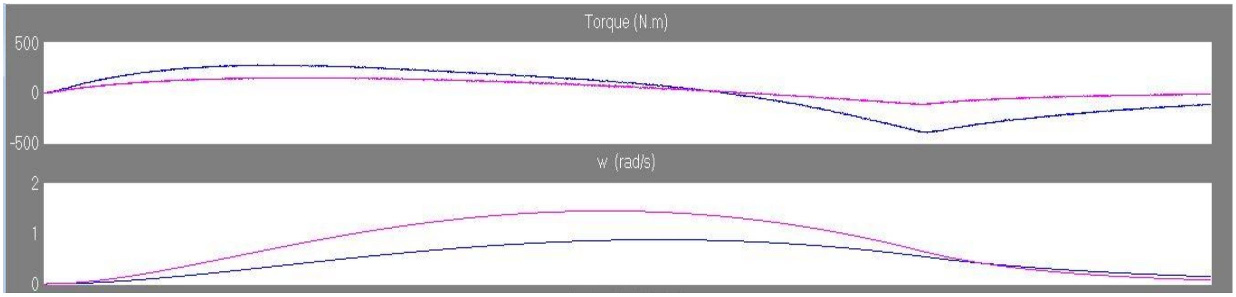
The speed, current, voltage and torque responses have been shown in first, second, third and fourth sub plots respectively for the second drive controlling angular motions between 90 to 120 degree. The speed has been found to be at a constant value of about 200 rpm from 0.8 to 1.7 secs. During this time period, the torque and current remained at a constant value of zero. The value of torque reduced at 0.8 sec to zero and finally at 1.7 sec it again reaches to its steady value.

6.2 Responses Using Fuzzy Logic Controller

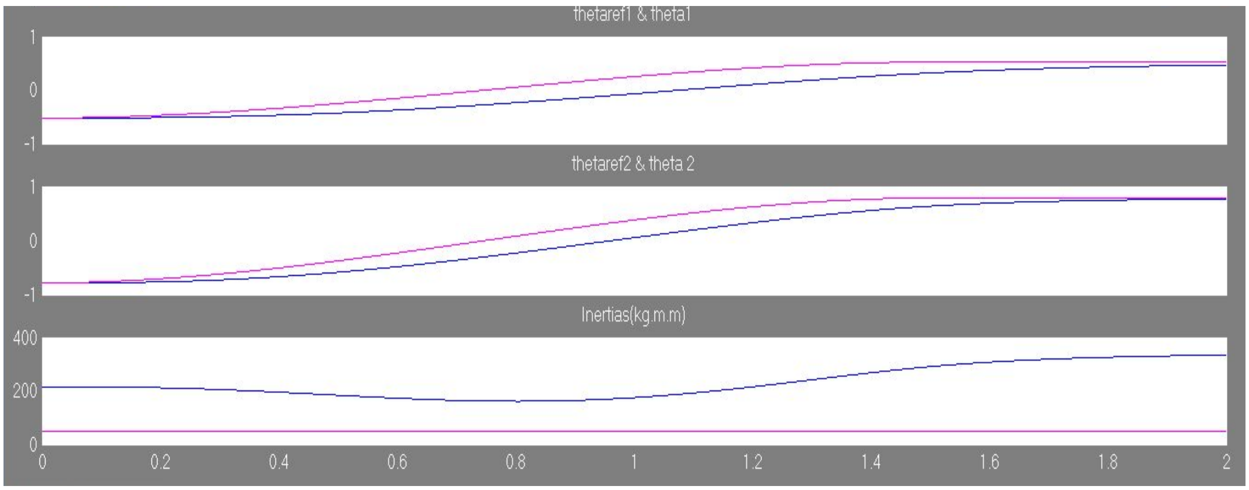
The dynamic responses of two drives used for controlling the angular positions of the modeled two link robot over two corresponding axis have been studied by using fuzzy logic rules developed on the basis of sigmoid function. The responses of the robot parameters have also been analyzed with the help of fuzzy logic controller for different ranges of varied angle following different specified trajectories.

6.2.1. Results for Robot

The responses achieved by the application of fuzzy logic controller in the feedback section, when the angular variation ranges from 30 to 45 degree, have been depicted in figure 6.7;



(a)



(b)

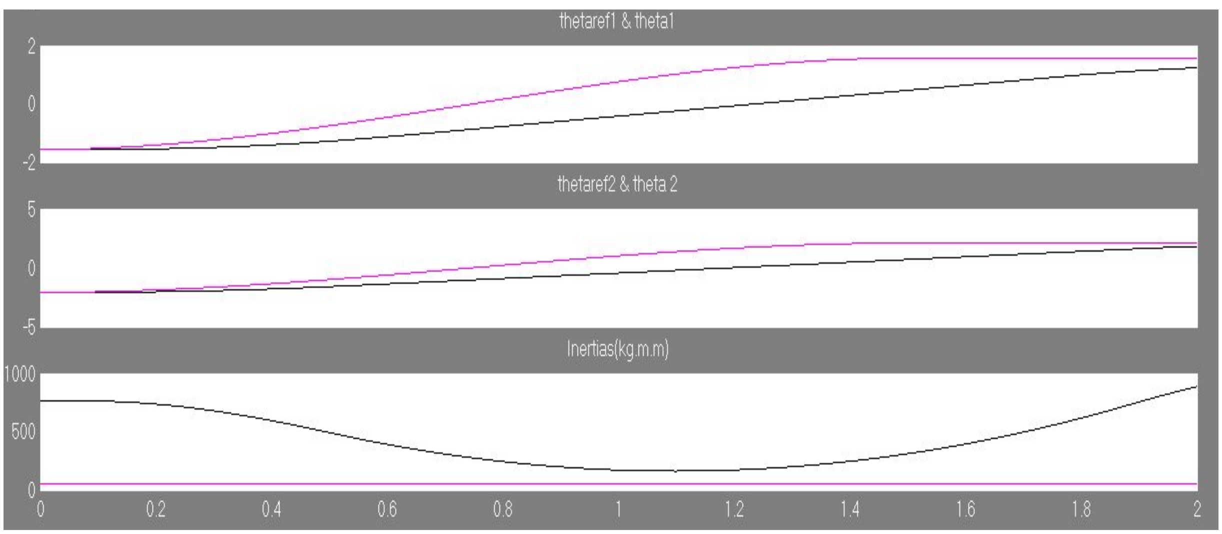
Fig 6.7: Performance of fuzzy controlled robotic manipulator in trajectory range 30 to 45 degrees.

The first subplot in figure depicts the variation of torque with respect to the time. Manipulator arm torque arm reference torque starts from same initial value, however manipulator arm torque overtakes reference torque, reaches maximum divergence at 0.4 sec, thereafter starts to decrease. Negative peak is attained at 1.4 second .afterward manipulator arm torque again rises. Angular velocity as shown in second subplot displays diversion between reference and actual angular velocity. However after 1.6 seconds, both of these parameters get submerged.

Angular variation for joint one and joint two has almost symmetrical variation, as seen in subplot three and four. There is overlapping between reference angle position and actual angle position at initial and final stages. The actual inertia remains at constant value of 200kg.m.m for some time, thereafter goes down at level of 180 kg.m^2 at 1 sec, then it starts to increase and attains value of 370 kg m^2.

The responses obtained by the implementation of fuzzy logic controller in the feedback section, when the angular variation ranges from 90 to 120 degree, have been depicted in figure 6.8;

(a)



(b)

Fig.6.8: Performance (a: torque, speed & b: theta1, theta2, inertia) of derivative controlled robotic manipulator in trajectory range 90 to 120 degrees.

The actual torque shows some disturbance initially, there after it attains desired value and matches reference torques. However some disturbance occurs at concluding stages (near 1.8

sec) and actual torques undershoots as depicted in first subplot. Angular velocity show trapezoidal characteristics first having positive slope then constant value and at last having negative slope. Maximum value of 2 rad/s is attained at 0.6 sec, this value is held on till 1.8 sec, then it starts decaying. Reference angular velocity always keeps ahead of actual Angular velocity. The angular position for both joints show positive slope till 1.4 sec, afterward saturation comes in them. the inertia have initial value of 853 kg m^2 and then attains negative peak of 112 kg m^2, at one sec, thereafter it starts increasing and attains 853 kg m^2.

6.2.2. Results for Brushless DC Drives:

The parametric variation observed in DC drives while controlling the angular positions of robot over a specified range has been observed by the application of a 81 rule based fuzzy logic controller. The two drives used for controlling the variations over two respective joints, resulted in different responses as a function of speed, torque, current and voltage. These responses for the first drive achieved by the application of fuzzy rule, when the range of angular variation is from 30 to 45 have been shown in figure 6.9.

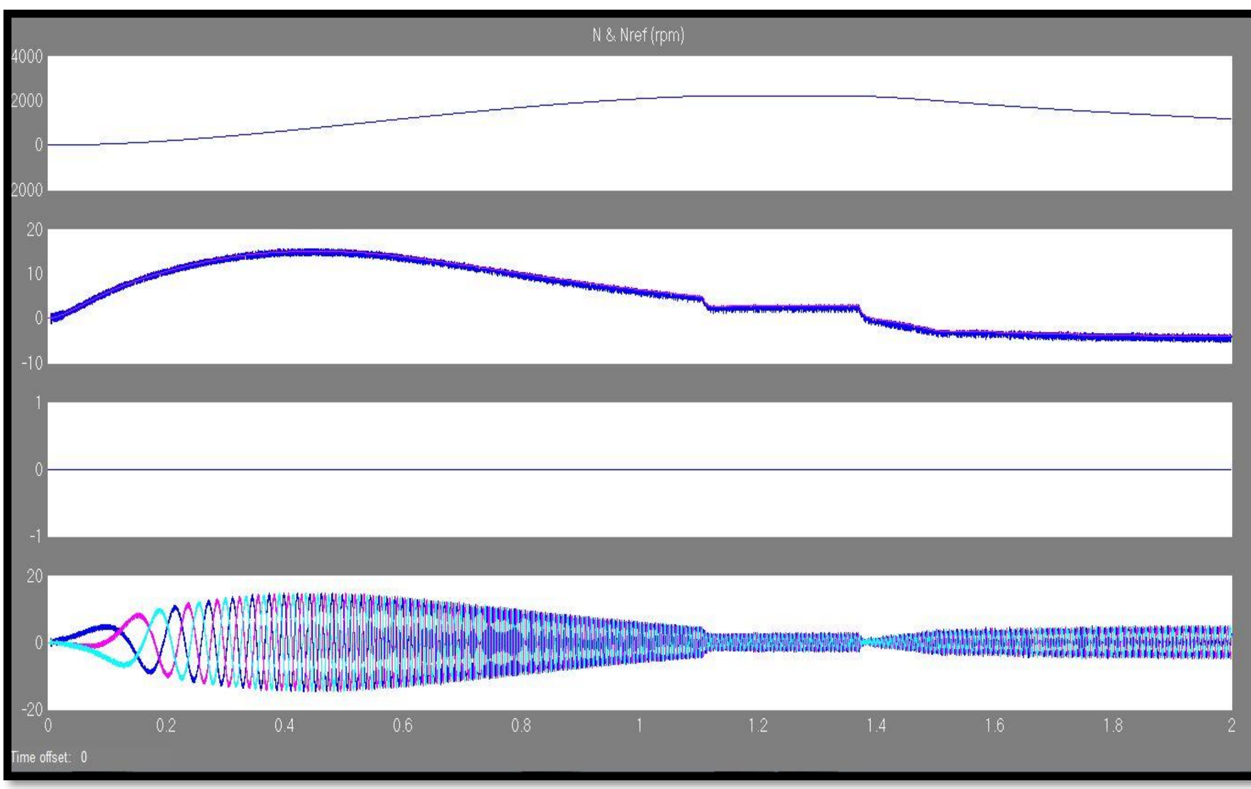


Fig 6.9: Performance of first drive in trajectory range of 30-45 degrees with fuzzy controller

The above figure shows the responses for speed, torque, voltage and current for first drive in first, second, third and fourth sub plots. It has been noticed that the speed remains constant for a very short inter-val of time at a value of 2000 rpm from 1.1 to 1.4. In this time period the values of current and torque have also been found to be at a zero constant value. At around 1.6 sec the torque reaches to a steady state value. Similarly the responses obtained for the same drive, used during the angular variation from 90 to 120 has been presented in the figure below, 6.10

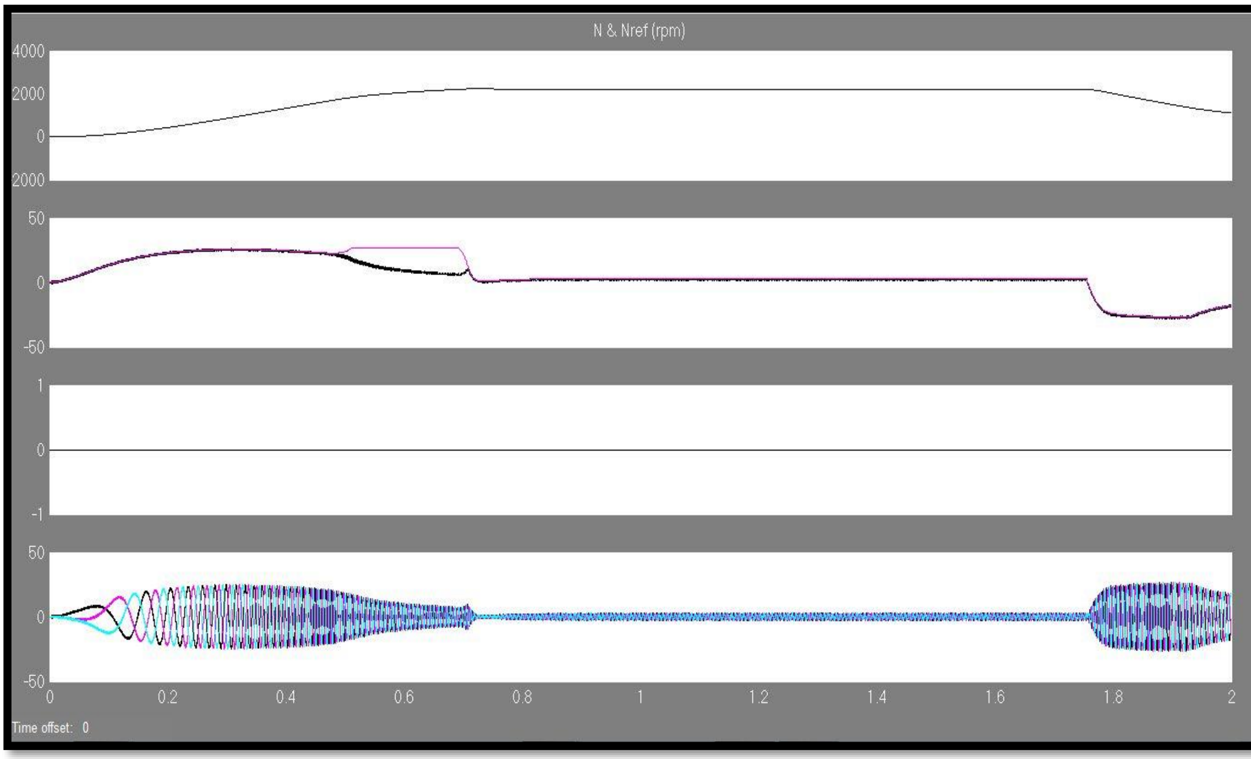


Fig 6.10: Performance of first drive in trajectory range of 90-120 degrees with fuzzy controller

The performances for the first drive when simulated for 90 to 120 degree of angular variation, gives the responses for speed in first sub plot, and current in the second sub plot, voltage in the third and current in the fourth sub plot. Here, the speed has been found to be at a constant value from 0.7 sec to 1.8 sec, at a maximum value of 2000 rpm. During this period of time torque has also been achieved at a constant value of zero, but it deviated from its reference value from 0.5 sec to 0.7 sec. The variations in the current values are found to occur from 0 to 0.7 sec and from 1.8 sec to 2 sec.

The varying responses for speed, current, voltage and torque in first, second, third and fourth subplots have been presented in the above figure. It has been observed that the speed is found to have a constant value from 1 to 1.2 sec at about 1000 rpm. However, the torque response is found to be at a steady value at around 1.5 sec at a minimum value, and again raised upto zero value. The current responses are observed varying all through the simulating time, except during 1.1 to 1.2 sec and at around 1.9sec.

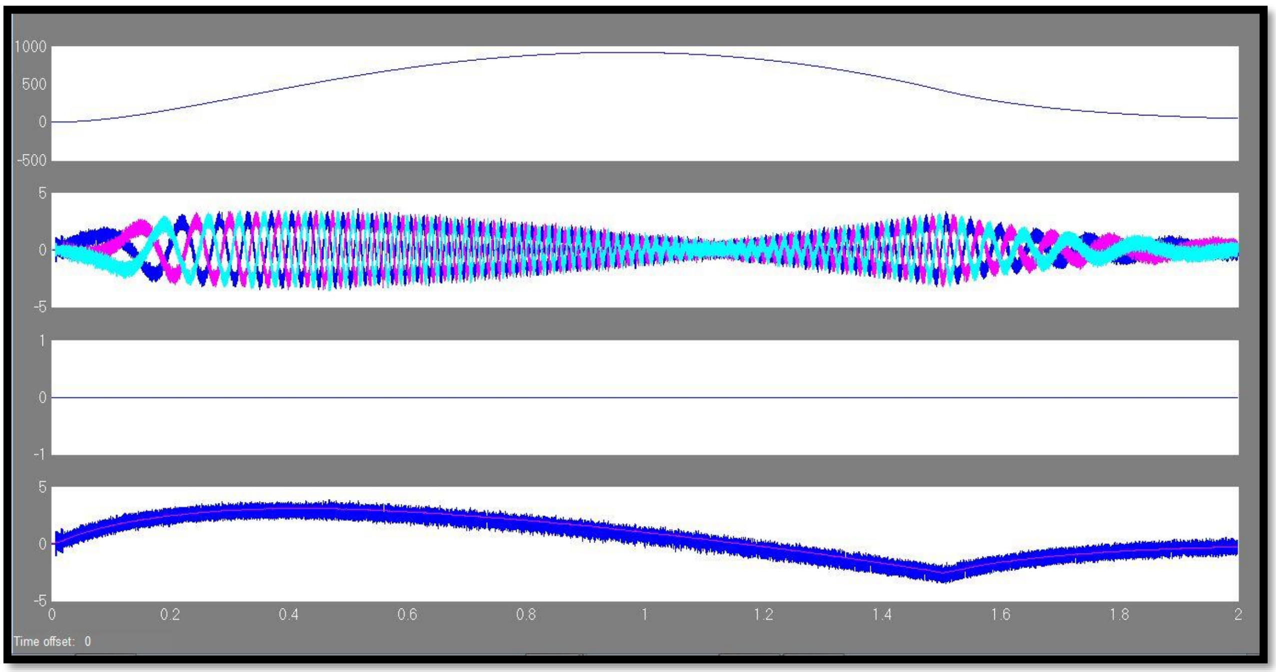


Fig 6.11 Performance of fuzzy controlled second drive system in trajectory range of 30-45 degrees.

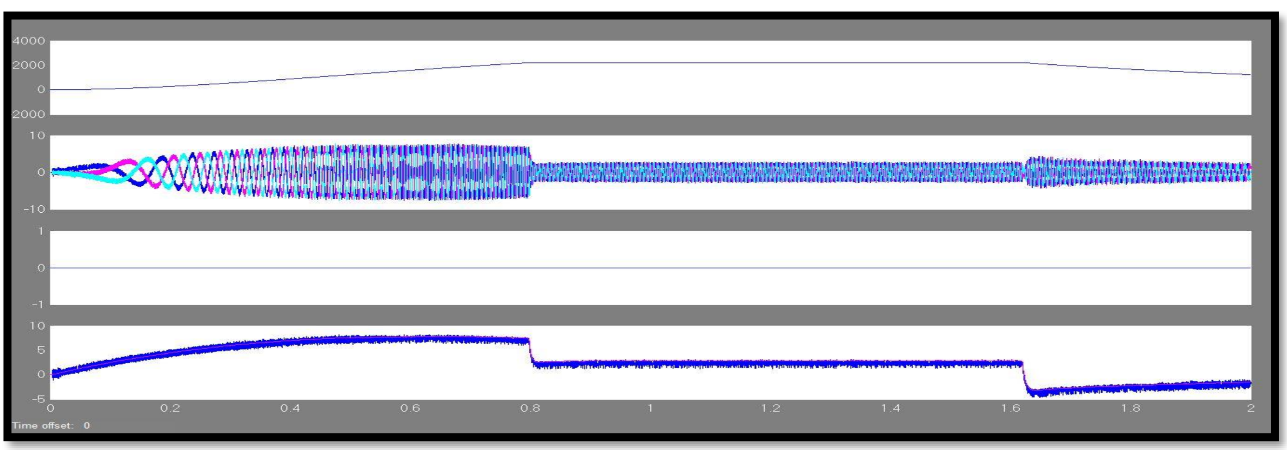


Fig6.12. Performance of fuzzy controlled second drive system in trajectory range of 90-120 degrees.

The results portrayed in the above figure shows the variation of speed in the first plot, current in the second plot, the voltage in third sub plot, and torque in the fourth sub plot. It has been observed that the obtained value of speed has been almost equal to the given reference value over all the simulation time. From 0.8 sec to 1.7 sec, it has been found to give a value of 2000 rpm. During this time period the three phases of current value has also been observed within a constant range. The torque is also found to increase upto 10 Nm from 0 to 0.8 second and further decreased to a value of 0 zero during the time period when the speed attains a constant value. Again, the torque value has been found to decrease from 1.6 seconds with decreasing trend of speed up to 2 sec. This variation of torque occurred almost close to its reference values over the time period. The voltage in the third sub plot has been observed at a constant value over the whole time period.

CHAPTER 7
CONCLUSION & FUTURE SCOPE

7.1. Conclusion:

In has been observed from the above mentioned responses for two link robots that the deviations from the reference values are found to occur more when proportional derivative controller is used instead of fuzzy logic controller.

By the application of proportional derivative controller, when the angular positions are varied from 90 to 120 degree over both the axes, the values are found to lag from its reference trajectory while the deviations are not observed during initial operative period for the angular variation of 30 to 45. The difference between the observed value of moment of inertia and its reference are found to occur high in case of proportional derivative controller than that of fuzzy logic controller, when the position were controlled over the range of 30 to 45 degree.

The responses resulted for the first and second drives resulted by the implementation of proportional derivative control are almost obtained in similar pattern for every parameters. However, the maximum speeds achieved by both the drives were much more in case of position control over a range of 90 to 120 degree, in comparison to that of 30 to 45 degrees. It has been observed that by the application of fuzzy logic controller, the electrical responses for both the first and second drives are observed to have more steady values over a longer time period, when the angular position control of robot is varied from 90 to 120 degree from that of 30 to 45 degree. From the fuzzy computed results, it has also been noticed that the responses for first drives generally reaches the settling point much earlier than that for the second drive. The deviations from the reference signals are found to occur less by the use of fuzzy logic controller than that obtained by proportional derivative controller. Hence, it can be concluded that the positional control of a two link robot can be achieved with a better responses by using fuzzy logic controller instead of conventional proportional derivative controller.

7.2 Future Scope of present work:

Robotics is a wide range application of research area. Position control is very interesting domain in field of robotics, and it can be steering up by limits the static and dynamics property of robots. In this work present we control only two axis of robot. In further work all the six axes can be controlled including end effector angle. Further other drive can also be used to provide the driving torque to robots links. Further its implementation can also be done by other intelligence controller for better response. In can also be implemented in real time.

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