DESIGN, MODELING and SIMULATION
of
PID CONTROLLED ROBOT ARM
for
PHYSIOTHERAPY

A THESIS

Submitted in partial fulfillment of the requirement

in Bachelor degree of science

in

Mechanical engineering

By

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DECLARATION

We hereby to declare that the work which is being presented in this thesis entitled "Designing, modeling and simulation of PID controlled robot arm for physiotherapy." is original work of our own, has not been presented for a degree of any other university and all the resource of materials used for the thesis have been duly acknowledged.

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

ACKNOWLEDGMENT

We would like to express our deepest and sincere gratitude and appreciation to all individuals who has been assisting us throughout our work and we would like to thank our advisor instructor Sirak Aregawi (MSc) and our co-advisor instructor Nebyat for their sincere devotion to achieve our goal.

ABSTRACT

Physiotherapy is a rehabilitation training given by a physiotherapist to disabled or stroke patients. The Number of disabilities who need a rehabilitation treatment is increasing on our country at a highest rate. Since last 10 years there have been a single physiotherapy school in whole country, clearly indicates there is a lack of physiotherapist among medical doctors. Due to this reason Taking care of those stroke patients is becoming a major problem. Therefore, assistive robotic technology is supposed to play an important role in rehabilitation. An exoskeleton robot is one of the most effective assistive robot that can assist the motions of the individuals from the outside of his body. Therefore, theaim of this thesis is to solve this particular problem that is to design PID Controlled Robot arm for Physiotherapy**.** Different methods such as data collection, reviewing of different literatures has been followed so as to design the robot.In this project we use microcontroller for controllingvariousoperation of robot arm.Sensors are used to provide feedback from outside world. Force sensor is selected to give a feedback on the patient active assisted rehabilitation. A PID (proportional integral derivative) controller is developed in order to precisely control the DC Servo motors that are responsible for each join movement of the robot. For this Robot arm,ARDUINO UNO microcontroller is utilized as the microcontroller.Furthermore, PROTEUS software was used to check the developed C++ Arduino program. Finally based on the results obtained, the PID controlled robot arm for physiotherapy is capable of solving the problem rise with the lack of physiotherapist and low cost that can be manufacturing in our country.

Key words: Physiotherapy, exoskeleton robot, Rehabilitation, PID, Proteus

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LIST OF SYMBOLS

SS error	Steadystateerror
PID	ProportionalIntegralDerivative
P_{cr}	Critical load
V.R	Speed (velocity) ratio
TF	Transfer Function
MATLAB	MatrixLaboratory
ROM	Range of Motion
DOF	Degree of Freedom
Kp	Proportional Gain
Ki	Integral Gain
Kd	Derivative Gain
σ_{ut}	Ultimate tensile strength
σ_y	Yield strength
σ_c	Allowable crushing stress
Dc	DirectCurrent
F.s	Safety factor

CHAPTER ONE

1 INTRODUCTION

1.1 BACK GROUND

With the rapid advancements in technology along with modernization of life style, Health Care Sector has been rapidly growing. One of the growing Health care sectors includes Physical therapy /Physiotherapy.

Physiotherapy is a health profession concerned with the assessment, diagnosis, and treatment of disease and disabilities through physical means. It is based up on principles of medical science, and is generally held to be with in the sphere of conventional (rather than alternative) medicine. Physiotherapy is practiced by physiotherapist (also known as physical therapist). Now days it is a branch of rehabilitative health that uses specially designed exercise and equipment to help patients regain or improve their physical abilities. Physical therapists work with many types of patients, from infants born with musculoskeletal birth defects, to adults suffering from the back pain or the defects of the injury, to elderly post stroke patients. Cases of physical disability emerge as a result of hemiplegia, paralysis, muscular diseases, etc. Physical medicine and rehabilitation are the most important treatment methods, because these methods help patients to reutilize their limbs at maximum capacity. The goal of the physiotherapist in this process is to help patients achieve normal standards of range of motion (ROM) in their limbs and to strengthen their muscles. [1, 2]

Based on the World Report on Disability jointly issued by the World Bank and World Health Organization, there are an estimated 15 million children, adults and elderly persons with disabilities in Ethiopia, representing 17.6 per cent of the population**.** The actual number of people with disabilities in Ethiopia is therefore likely to be much higher. Where government is fighting against the background of an ever increasing HIV/AIDS epidemic, a growing financial burden of an ageing population and raising costs of providing health care for chronic diseases, physiotherapy profession faces major challenges. [3, 4, 5]

Physiotherapy is a new emerging discipline to Ethiopia and since last 10 years there have been a single physiotherapy school in whole country, which clearly indicates the lack of physiotherapist among medical doctors.

So the design of robot arm for physiotherapy plays a vital role on decreasing the problems that happen due to lack of physiotherapist since, one physiotherapist can do the rehabilitation process by commanding different robots at a time.

1.2 PROBLEM STATEMENT

Physiotherapy is the major problem in our country generally in developing countriesbecause of the number of physiotherapists is lower than the number of patients, Difficulties in manual therapy which needs repeated movements andProblems with the objective evaluation of the results and with recording therapy data. In addition Physiotherapy using robot arm are mostly found in the United States, Japan, and Switzerland, where they are in practical use. But costs of these robot arm are very high. So these robot arms need low-cost production in order to be used in our countries with lower incomes.

Figure 1.1: Rehabilitation by physiotherapist.

Figure 1.2: Rehabilitation by physiotherapist.

1.3 OBJECTIVE

1.3.1 General objective

The principal objective the project is to design PID based robot arm for physiotherapy.

1.3.2 Specific objective

The Specific objective of this project includes:

- ✓ To model, analysis and design of 5 DOF robot arm.
- ✓ To design a PID controller to the model of robot and implement using the MATLAB/Simulink
- ✓ To design micro controller programming for all automatic parts (sensors and motors) and the simulation will be done by PROTEUS software.

1.4 METHODOLOGY

In modeling, designing and analysis of robot arm for rehabilitations, knowing the structure and motion of the human upper limb is crucial. The human upper limb is mainly composed of skeletons and skeletal muscles, and can be divided into shoulder joint, upper arm, elbow joint, forearm, wrist joint and hand.According to the human anatomy and mechanisms, the human upper limb can be simplified as a spatial linkage mechanism that is composed several rigid links connected through revolute pairs. In addition, even though the movements of the human hand are very complicated, they will not be considered all for modeling simplicity. In thiscase, there are only five independent DOFs in the human upper limb.

1.4.1 Kinematic Analysis

The link-frame attachment should clearly depicted before developing the kinematic model (Forward kinematics) since the kinematic model gives relations between the position and orientation of the end effector and spatial positions of the joint-links. The D-H algorithm used to analyze the forward kinematics.

1.4.2 Mechanical Design

The therapy robot arm comprises shoulder motion support, forearm motion support and wrist motion support. Hence, the robot arm should fabricated with a material have relatively lightweight and good strength characteristics. In addition, in order to perform the desired task the robot arm includes arm link, sliding link, fixed link, motor, bearing, gears… therefore to ensure the safety of the robot arm users, its mechanical design (Torque induced, required power, load applied) should properly evaluate and a complete 5 DOF robot arm CAD model prepared (Solid works)

1.4.3 Controller Design

Given the dynamics of human arm movement, which is nonlinear in nature. However, in this paper we focused on how to controller the actuators (motors) speed, position and orientation using PID controller to reduce theovershoot, rise time and steady state error. The transfer function of each joint motor is first develop and then Ziegler-Nichols rules for tuning PID controllers proposed for determining values of the gains (proportional, integral and derivative).

Moreover, the methods employed to achieve the objectives of this thesis are the following:

1. Data collection method using;
   - ✓ Primary data collection; by observing the related works, By Interview to physiotherapist in Aider referral hospital
   - ✓ Secondary data collection; by using different books, documentation, website.
2. Concept generation and selection method is;
   - ✓ The science that we have used to analyze the concept and score it during design of the robot arm is by following the phases of product design and development (PDD). Product development process type is Incremental improvements to existing products or modification.
3. Material Selection using material property text book to prepare any machine part, the type of material should be properly selected, considering design safety .The selection of material for engineering application is given by the following factors:-
   - ✓ Availability of materials
   - ✓ Suitability of the material for the required components
   - ✓ Cost of the materials
   - ✓ Substitutability of the materials
4. Design of the component analytically (static) and identifying part components which are needed for the machine.
5. The assembly will be done by **SOLIDWORK** software.
6. Developing a PID controller for the machine and test it using mat lab software.
7. The programming done by **ARDUINO**andTesting the programming and simulate it using **PROTEUS** software.

1.5 EXPECTED RESULT (OUTPUT)

The expected result (output) is a fully functional, compact, safe and economical robot arm for physiotherapy.

1.6 SIGNIFICANCE OF THE STUDY

The proposed Robot will help the medication system of upper limb rehabilitation (physical therapy) on our country, which will have the following advantages:

- ✓ Time saving, both for the patient and physiotherapist.
- ✓ Provide therapy in a consistence and precise manner.
- ✓ Allow a remarkable effort for the patient and physiotherapist.
- ✓ Provide Effective and repeated movementsthat can't be done by humans (physiotherapist).

1.7 SCOPE

Every components of the robot arm will be designed and analyzed using different engineering concepts, 3D model of the machine and drafting drawing of each components will be prepared, and finally the appropriate C^{++} program will be developed for the control system and simulation will be done.

1.8 THESIS ORGANIZATION

The thesis consists of four other chapters.

Chapter two covers the background information of upper-limb exoskeleton robots and related things such as review of related works. The third chapter explains the kinematic analysis of a 5DOF upper-limb exoskeleton robot, the mechanical design of the robot, the development of PID controller and Arduino code. The results obtained on chapter three will discuss briefly in chapter four. Finally, chapter five includes new contributions of the thesis, the conclusion, and suggestions for the future directions.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 INTRODUCTION

The development of upper limb rehabilitation devices has become a field of innovation due to rapid advances in robotic technology. The past decades have seen rapid and vast development of robots for rehabilitation robots. In the late of 1980s and early 90s a number of pioneering technological developments were launched. [6]

A new era of rehabilitation robotics began in 1989 with the development of the MIT-MANUS, which was first tasted clinically in 1994. Compared to industrial manipulators, this planar manipulandum presents inherently low mechanical output impedance (a frequency dependant resistance to motion perceived at the interface between the human user and robotic system) and provides unloading of the upper limb against gravity, thereby allowing to adapt support to the severity of the deficits.

A few years later, force controlled device for rehabilitation were developed. This new generation of devices, using torque controlled direct drive actuation, allow for more advanced interaction control, ranging from passive movements for the most severely impaired patients to active-assisted and active resisted movements in moderately impaired patients.

Some of products that are available on the market. The detail information of the products found on the manufacturer's website listed on the references.

1. Hand of Hope is an intention –driven exoskeleton hand that focuses on improving motion of the hand and fingers in stroke victims, developed by rehab robotics. The robotic hand is controlled by EMG signal in the forearm muscles, meaning that patients can move their hand using only their brain.
2. Tyro motion is currently developing and manufacturing a set of intelligent rehabilitation devices for upper extremity.
   - ✓ The hand rehabilitation robot called AMADEO offers a range of rehabilitation strategies including passive, assistive ROM, force and haptic training.
   - ✓ The arm rehabilitation robot called DIEGO offers bilateral arm therapy including assistive force for weight reduction and full 3D tracking of the arm movement for augmented feedback training in a virtual reality environment.

3. NeReBot (NEuro Rehabilitation Robot) is cable suspended device for upper limb rehabilitation. Three nylon wire convert the rotation motion of three DC motors in to a 3D trajectory of patient arm. A real time software performs both on-line point by point acquisition and repetition of the 3D trajectory obtained by interpolating acquired points.

2.2 BIOMECHANICS OF UPPER-LIMB - TOWARDS THE DESIGN OF AN EXOSKELETON ROBOT

Human upper-limb is made up of skeleton, muscles, nerves, skin etc. The skeleton mainly consists of clavicle, scapula, humerus, radius, ulna, carpal bones, metacarpal bones, and phalanges. Human upper-limb is shown in Fig. 2.1. It mainly consists of shoulder complex, elbow complex, and wrist joint. In addition, the hand consists of fingers which have several joints. Human upper-limb mainly consists of 7DOF: 3DOF in the shoulder, 2DOF in the elbow, and 2DOF in the wrist [7]. The main motions of upper-limb are shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension, forearm supination/pronation, wrist flexion/extension, and wrist radial/ulnar deviation.

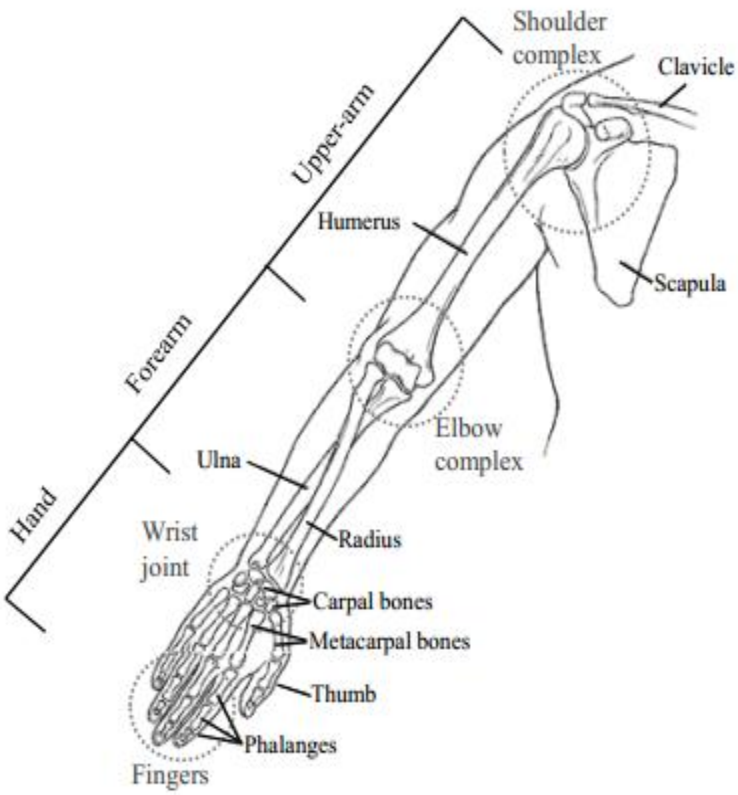


Figure 2.1: Human upper-limb. Human upper-limb consists of upper-arm, forearm, and hand.

2.3 REQUIREMENTS OF AN UPPER-LIMB EXOSKELETON ROBOT

The requirements of an upper-limb exoskeleton robot differ in accordance with the usage of the robot such as rehabilitation, power assist, human power amplification and/or haptic interaction. The important requirements of an upper-limb exoskeleton robot are briefly discussed in this section.

The main requirement of any system that interact with the human is the safety. As the upper-limb exoskeleton robots are also directly interact with the human user, safety is the highest priority. In addition, several another requirements have to be fulfilled. The wrist motion assisted exoskeleton robot should provide the axes deviation of wrist flexion/extension axis and wrist radial/ulnar axis. Also wrist joint should have four axes for wrist flexion, extension, radial deviation, and ulnar deviation to generate biomechanically similar natural wrist motions. Movement of the center of rotation of shoulder joint according to the upper-arm motions must be considered to cancel out the ill effect caused by that in design. If upper-arm motions also have to be assisted by the robot as well as forearm motion (i.e., if the exoskeleton robot has to be attached to both forearm and upper arm of the user), a mechanism that allows moving of the center of rotation of the shoulder joint must be considered in the upper-limb exoskeleton robot.

This mechanism should reduce the ill effects caused by the position difference between the center of rotation of the robot shoulder and the human shoulder. The hand-robot interface should be designed to eliminate the disturbance to the finger motions. The links, cables, pulleys, other mechanical components, and motors of the exoskeleton robot should be located to eliminate interference during upper-limb motion of the robot and the user. Moreover, the mechanical singularity should not occur within the workspace of the robot. The robot should be designed for the easy and the comfortable wear [8, 9]

2.4 DESIGN DIFFICULTIES OF UPPER-LIMB EXOSKELETON ROBOTS

There are many difficulties associated with the development of a proper upper-limb exoskeleton robot. Most of them are caused by the anatomy of the upper-limb. Shoulder complex is one of anatomically complex area in the human body. Its center of rotation is changing with its motions. If the robot generates the shoulder motion and is directly attached to the upper-arm of the user, the architecture of shoulder mechanism is very important. Designing of a proper shoulder mechanism for an upper-limb exoskeleton robot to change its center of rotation with its motions has become one of the difficulties to be resolved. Although some designs [10], [11] have proposed partial solutions for the shoulder complex, more research is essential to develop a proper shoulder joint of upper-limb exoskeleton robot.

In the case of the elbow joint, the joint is modeled as a uni-axial hinge joint [12], although it consists of three bones: humerus, ulna, and radius. Therefore, it is not difficult to locate the axis of the rotational center of the elbow joint of the exoskeleton robot as same as that of the user’s joint. In the case of the shoulder joint of upper-limb exoskeleton robot, it is not an easy task to locate the position of the rotational center of the robot’s shoulder joint as same as that of the user’s shoulder joint since the joint is modeled as a spherical joint and located inside of the user’s body.

So far several exoskeleton robots have been developed including the wrist joint motions. All of the designs have considered that wrist flexion and extension motions generate through one axis and wrist radial and ulnar deviation generate through one axis. Except the exoskeleton robots proposed in this thesis other designs of wrist joint found in literature have not considered about the axis offset of wrist axes. However, it is difficult to design the wrist joint of an upper-limb exoskeleton robot to generate the biomechanically similar motions of wrist.

2.5 RECENTLY PROPOSED UPPER-LIMB EXOSKELETON ROBOTS

Several upper-limb exoskeleton robots have been proposed in the recent years. The recent upper limb exoskeleton robots have been used for different purposes such as an assistive device, a rehabilitation device, a human amplifier, and a haptic interface. Most of them have less than seven DOF. The main specialty of the recent upper-limb exoskeleton robots is that serial manipulators have been used in almost all of the designs. Also electric motors or pneumatic actuators have been used as the actuator in almost all of the exoskeleton robots.

Some of the recently proposed upper-limb exoskeleton robots are reviewed briefly in next subsections of thischapter. The logic for selecting a particular design is the novelty of their mechanical design. Few other upper-limb exoskeleton robots are briefly presented in the latter subsection.

2.5.1 The Assisted Rehabilitation and Measurement (ARM) Guide

This paper basically focuses on how to allow stroke subjects to perform the reaching task. The subject's forearm/hand was attached to a handle/sprint that slide along linear constraint via a low-friction, linear bearing. A six axis force/torque sensors sensed contact force between the hand and constraint in the coordinate. A computer controlled motor attached to a chain drive was used to drive the hand along the constraint. An optical encoder measures the position of the hand along the constraint. The device is mounted on a stand for a height adjustment in passive mode, the patient remains passive while the robot moves the arm along a preprogrammed position trajectory using proportional-integral-derivative (PID) controller.in the active assisted mode the patient initiates the movement and the robot assists and guides the motion along the desired position trajectory [13].

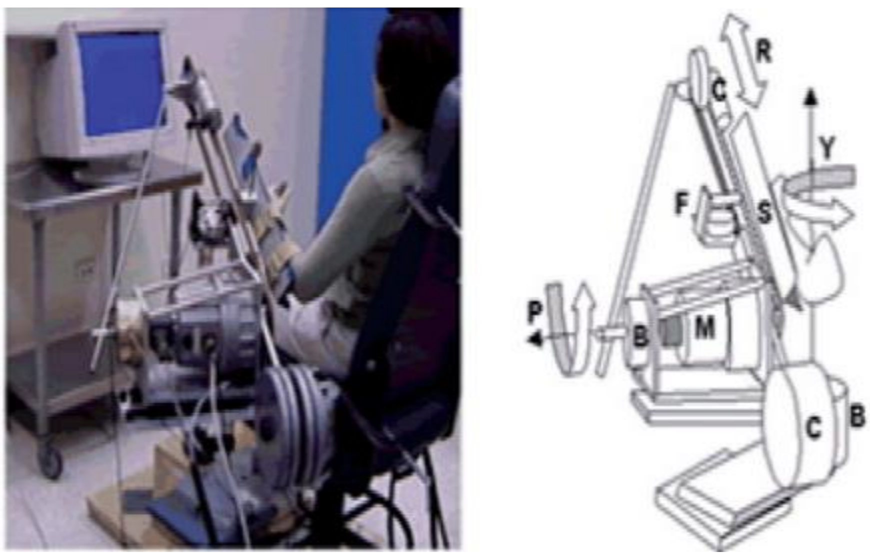


Figure 2.2: ARM Guide

2.5.2 Reharob

In this paper they have developed a 2-DOF robotic system. In this system, the position and force data are received and recorded for the robotic system during the learning phase. The aim of this phase is to learn the Physiotherapist's movements. In the therapy phase, the robotic system imitates the corresponding motions. In this study a rule based intelligent control methodology was proposed to imitate the facilities of an experienced physiotherapist. These involve interpretation of patient reactions. They used servo motors for driven the manipulator and force/torque and position sensors for controlling. In addition impedance control technique were selected for the force control [14].

2.5.3 Bi-Manu-Track

Inthis paper the author developed an electronically controlled medical device for all phases of rehabilitation. The electronically controlled device supports active and passive exercising with adjustable inverse or symmetrical motion sequence. Subjects sat at a table with their elbows bent 90 degrees and put their forearms in the mid position between pronation and supination. The device incorporates two handle sets, one with a horizontal axis of rotation for the elbow and one with a vertical axis for the wrist movement. Motor drives are position controlled and a display shows the number of performed cycles to motivate the patient to exercise more [15].

Figure 2.3: Bi-Manu-Track.

2.5.4 The GENTLE/s system

This paper discuss on haptic and VR visualization techniques. Haptic is the study of integrating tactile and other sensors into meaningful manner and haptic interfaces are group of robots that incorporate haptic and VR technology. The advantage of using such systems is that they attract patient's attention and motivates him/her to exercise for longer periods of time. GENTLE/s system incorporates a three-DOF haptic master in order to provide a haptic interface. The haptic master can provide reaching movements in three active DOFs. This couples to three passive DOFs to allow arbitrary positioning of the person's hand, so the overall DOFs are six (three passive and three active). The therapist based on the patient's profile chooses the right exercise for the patient using a 3D graphical user interface (GUI). Games incorporated in GENTLE/s system, consist of minimum jerk paths between a starting and ending point. It is proved that creation of human-like trajectories is essential for training upper limb movements after stroke.

Human by nature tend to minimize jerk parameter over the duration of the reaching movement of the arm. Jerk is the rate of the change of acceleration with respect to time. GENTLE/s includes three therapy modes: passive mode, active-assisted mode and active-resisted mode [16].

2.5.5 MGA-exoskeleton

Author developed an arm exoskeleton named Maryland-Georgetown-Army (MGA) exoskeleton. MGA exoskeleton incorporates five active DOFs for shoulder and elbow motion. Three DOFs is assigned for shoulder rotation, one DOF for elbow actuation and one active DOF for scapula motion. Each joint of the exoskeleton except for the forearm is driven by brushless DC motors and harmonic drive transmission. The elbow is equipped with a clutch that has an adjustable torque range which decouples the elbow axis from actuator in the case of applying excessive torque to the elbow joint. Motor position is determined by optical incremental encoders and at the output of the transmission, optical absoluteencoders determine absolute position on startup and monitor theincremental encoders.A force/torque sensor measures forces and torques on the handle. A single-axis torque sensor is placed on the output side of the scapula transmission. Two single-axis load cells are attached to mounting plates on either side of the elbow to measure axial load at the elbow.

The exoskeleton operates in two modes: (1) VR mode and (2) physical therapy mode. In the first mode, the forces exerted at the hand are sensed by a force sensor located at the hand gripper and controlled by interaction with a virtual environment generated by a computer. Computer-generated environment simulates daily living tasks for functional rehabilitation. The control architecture used in this mode is admittance control. Admittance controller converts the sensed contact forces at the hand and elbow into desired movement of the exoskeleton. In the second mode, the arm is allowed to rotate about an arbitrary axis through the shoulder using a resistance profile. In fact, the exoskeleton becomes a programmable resistance trainer.

The control architecture used in this mode is impedance control. The scapula joint is controlled independently from other arm joints. The controller used for scapula motion is admittance controller. A torque cell at the output of the transmission, directly measures the torque being exerted by the scapula joint. Sensors measure the position and orientation of the human arm and transmit them to the graphical display in which the patient can see his/her own movement on the computer screen [17].

Figure 2.4: MGA Exoskeleton.

2.5.6 ARMin

Author investigated one of the most advanced exoskeleton robots in arm rehabilitation. It had four DOFs, actuating the shoulder in 3D and flexing/extending the elbow. The upper arm is connected to the robot by an end-effector-based structure and the lower arm is connected through an exoskeleton structure. So, ARMin can be considered as semi-exoskeleton robot. In this version, three electric motors actuate the shoulder joint for shoulder flexion/extension, abduction/adduction and internal and external rotation. Two motors actuate the elbow joint for elbow flexion/extension and forearm pronation/supination and one motor actuates wrist for wrist flexion/extension. An optional module is incorporated for hand opening and closing. The motors are equipped with two position sensors for redundant measurements. Motors and gears are carefully selected for low friction, good back drivability which is an important requirement for sensor less force control. Impedance control strategy allows implementing patient-responsive control in which the patient is being assisted only as much as needed. Patient’s arm is affixed to the exoskeleton via two adjustable cuffs, one for the upper arm and one for the lower arm. To accommodate patients of different sizes, the shoulder height can be adjusted via an electric lifting column. The lengths of the upper and lower arms are also adjustable. Passive and active mobilization in which the robot moves the patient’s arm on a predefined trajectory.Demonstrates trajectories for passive mobilization. The thin lines show the recorded trajectories and the thick lines represent the smooth trajectories repeated by the robot. The robot is position controlled. The control architecture for mobilization therapy is computed torque position control. Regardless of what the patient is doing, the robot will follow the predefined trajectory because, feedback loops help the motors compensate for any resistance the patient produces. If the patient moves together with the robot in the desired direction, it is called active mobilization; in this case motors have less work if the patient remains passive, which is called passive mobilization. As it is desirable that the patient actively contributes to the movement, motor torque can be used as a performance measure to monitor how actively the patient contributes to the movement. The audio–visual display gives feedback on the performance of the patient. This position controlled training requires predefined trajectories [18].

Figure 2.5: ARMin.

2.5.7 The Mirror Image Motion Enabler (MIME) system

In this paper author fabricated a system designed for practice of upper extremity reaching, has been directly compared to conventional neurodevelopmental therapy for treatment of chronic stroke patients. This system incorporates an industrial robot that is coupled to the user’s hemi paretic arm. The subject moves in three dimensions while the force feedback of the robot assists or resists his or her movement. Relative to the group receiving neurodevelopmental therapy, the MIME treatment group had greater increases in reaching, strength, and Fugl-Meyer score for proximal movement. Thus, robotic therapy with MIME seems to speed recovery on some scales, but the long-term effect has not been found to be significantly different from that obtained with conventional therapy [19].

Generally, this chapter introduced the background information of upper-limb exoskeleton robots. Thebiomechanics of human upper-limb towards the design of an upper-limb exoskeleton robotwas described. The requirements and design difficulties of an upper-limb exoskeleton robot were explained. Most of the design difficulties are caused by the upper-limb anatomy. In the literature, upper-limb exoskeleton robots were classified according to: the applied segments of the upper limb, the DOF, the power transmission methods, the application of the robot, and the control methods. Here, upper-limb exoskeleton robots were classified, based on the type of applied actuators in the mechanical design, as actuated by electric motor, actuated by pneumatic actuators, and actuated by hydraulic actuators. Although many upper-limb exoskeleton robots and their control methods have been developed, still many issues are yet to be perfected to convert them as commercialized products. In the literature review, issues such as biomechanically similar motion generation, safety and accurate estimation of joint torqueswere identified.

CHAPTER THREE

3 DESIGN OF PID CONTROLLED ROBOTIC ARM FOR PHYSIOTHERAPY

3.1 CONCEPT GENERATION

A product concept is an approximate description of the technology, working principles, and form of the product. It is a concise description of how the product will satisfy the customer needs. A concept is usually expressed as a sketch or as a rough three-dimensional model and is often accompanied by a brief textual description.

Concept 1

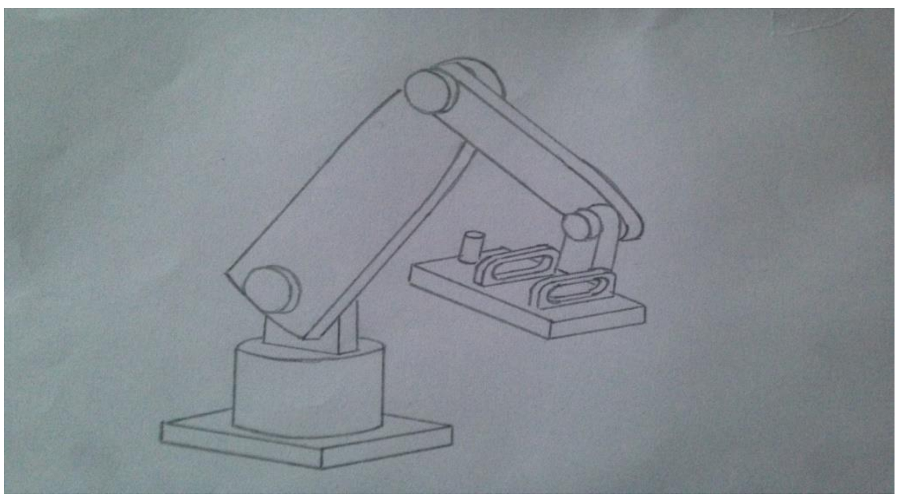


Figure 3.1: Grounded end-Effector upper extremity.

Advantage

- ✓ Simple structure
- ✓ Light weight
- ✓ Have Easier set up
- ✓ Have excessive freedom for shoulder

Disadvantage

- ✓ Less functionality
- ✓ Difficult to isolate specific movements of a particular joint
- ✓ Complicated control algorithm.
- ✓ Exclude palm movements.

Concept 2

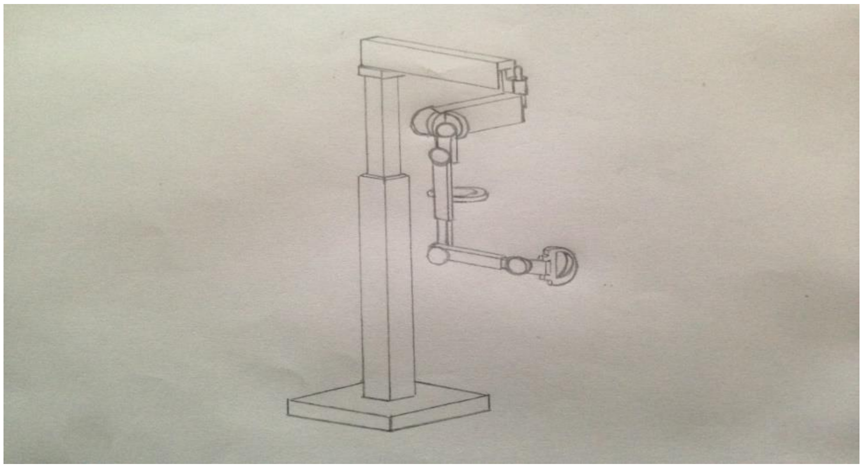


Figure 3.2: Grounded Exoskeleton upper extremity.

Advantage

- ✓ Flexible
- ✓ Control each joint easily
- ✓ More Functional

Disadvantage

- ✓ Difficulties on adjusting length of particular segment of the manipulator to the length of segments of the patient arm
- ✓ Special mechanism are necessary to ensure patient safety and comfort

Concept 3

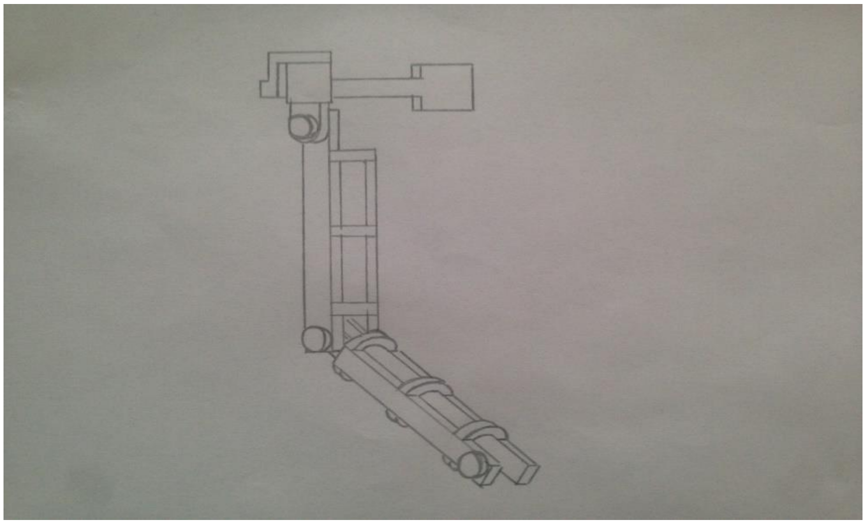


Figure 3.3: Semi grounded wearable upper extremity.

Advantage

- ✓ portable
- ✓ Control each joint easily

Disadvantage

- ✓ Limited degree of freedom
- ✓ Design complexity
- ✓ High cost

3.1.1 Concept Selection

Concept selection is the process of evaluating concepts with respect to customer needs and other criteria, comparing the relative strengths and weaknesses of the concepts, and selecting one or more concepts for further investigation, testing, or development. The goal of concept selection is not to select the best concept but it is to develop. There are to techniques for concept selection: screening and scoring.Screening is a quick, approximate evaluation aimed at producing a few viable alternatives.

- ✓ Scoring is a more careful analysis of these relatively few concepts in order to choose the single.

Concept most likely to lead to product success. Choice of a product concept would be based on the following selection criteria’s for PID Controlled robot for physiotherapy.

1. Cost
2. functionality
3. DOFs
4. Ease of maintenance
5. Safety
6. Range of motion
7. Usability
8. Smooth operation
9. Weight

In this project one main system of the machine is selected which is the driving system of the machine. As we have said on the above to get the best concept that can solve the problem different steps of product concept generation have been used.

3.1.2 Concept screening

Table 3.1: Concept screening.

Selection criteria	Concept-1	Concept-2	Concept-3	REF
Cost	+	-	+	0
Smooth operation	-	+	+	0
Design simplicity	-	+	-	0
Safety	-	+	+	0
Flexibility	-	+	-	0
Small weight	+	-	+	0
Maintainability	+	+	-	0
Plus	3	5	4	0
Minus	4	2	3	0
Same	0	0	0	0
Net	-1	3	2	0
Rank	3	1	2	0
Continue?	No	Yes	Yes	NO

3.1.3 Concept scoring

Table 3.2: Rating value for concept scoring.

Evaluation scale for design objective	
Value	Rating
0	Unsatisfactory
1	Just tolerable
2	Adequate
3	Good
4	Very good

Table 3.3: Concept scoring.

No	Criteria's of importance	Importance weight [%]	Concept alternatives			
			Concept 2		Concept 3	
			Rating	Weighted rating [%]	Rating	Weighted rating [%]
1	Cost	15	3	45	4	60
2	Safety	25	4	100	3	75
3	Flexibility	20	3	60	2	40
4	design simplicity	15	3	45	1	15
5	Simple operation	7	3	21	3	21
6	Maintainability	7	3	21	2	14
7	Weight	11	2	22	4	44
8	Total	100	NA	314	NA	269
10	Continue			Yes!		No!

Therefore concept 2 is selected for further analysis.

3.2 KINEMATIC ANALYSIS OF UPPER ARM

The kinematic model gives relations between the position and orientation of the end effector and spatial positions of the joint links.

3.2.1 Principle of the 5-DOF Upper-Limb Exoskeleton

The structure of the human arm is complex, so the joints and segments of a human arm are usually simplified into a 7-DOF kinematic system, as shown on the Figure below. The shoulder joint can be modeled as a 3-DOF ball-and-socket joint: flexion/extension (Z2), abduction/adduction (Z3) and internal/external-rotation (Z1); The wrist joint can be modeled as a 3-DOF ball-and-socket joint: palmar flexion/dorsiflexion (Z6), ulnar deviation/radial deviation (Z7) and medial rotation (Z5); The elbow joint can be modeled as a 1-DOF hinge joint with (Z4). The motion range of the joints is shown in Table below. To further simplify the structure, only the wrist internal/external-rotation is retained. The elbow joint is considered a DOF joint, i.e., flexion/extension and pronation/supination.

Shoulder Complex

The shoulder complex and its main motions are illustrated in Fig. 4.1. Average movable ranges of human shoulder are 180 degrees in flexion, 60 degrees in extension, 180 degrees in abduction, 75 degrees in adduction [10]. Average movable ranges of shoulder internal and external rotation are 100-110 degrees and 80-90 degrees, respectively [10].

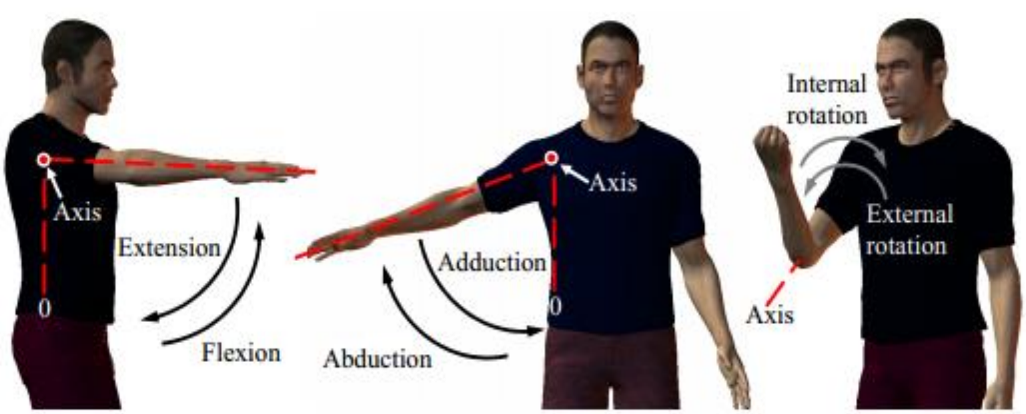


Figure 3.4: Shoulder Complex.

Elbow Complex

The elbow complex and its motions are shown in Fig. 4.2.Average movable ranges of the human elbow are 5 degrees in extension, 145 degrees in flexion. Forearm supination and forearm pronation each has average movable range of 90 degrees [10].

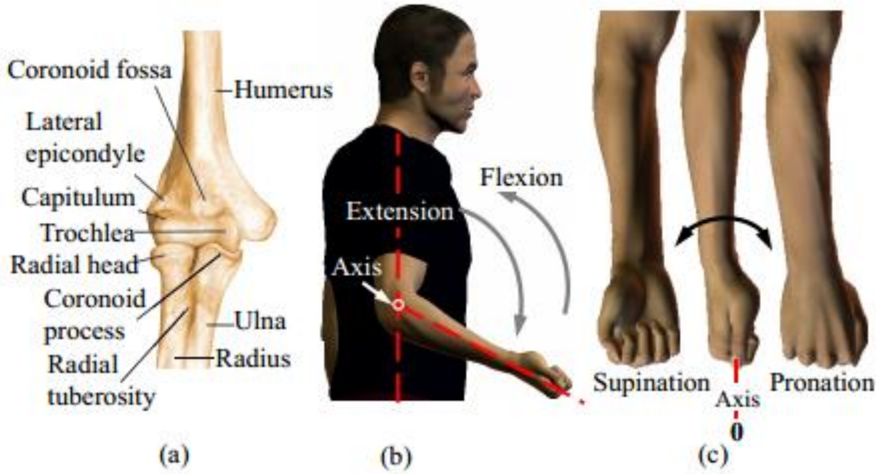


Figure 3.5: Elbow Complex.

Wrist complex

Figure 4.3 illustrates the wrist joint and its motions. Average movable ranges of wrist are 60 degrees in extension, 70 degrees in flexion, and 35 degrees in ulnar deviation, and 25 degrees in radial deviation [20].

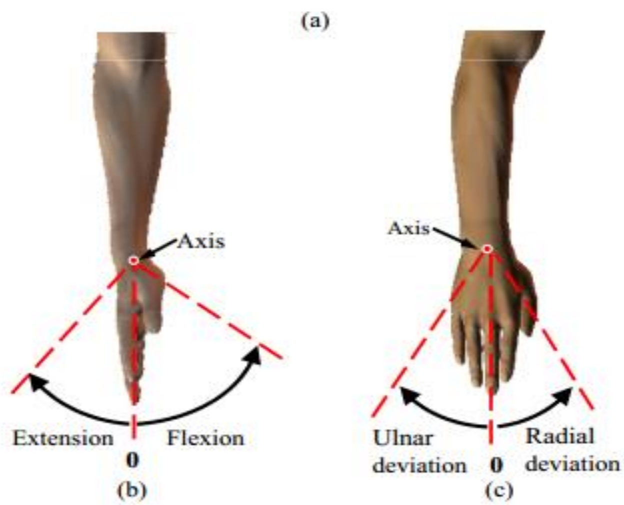


Figure 3.6: Wrist Complex.

Based on the above analysis, 5-DOF upper-limb exoskeleton was designed, as shown in Figure 4.4. The joint torque and the power consumption of the anthropomorphic upper-limb exoskeleton are obtained by analyzing the 5-DOF upper-limb exoskeleton.

The 5 DOFs are as follows: shoulder adduction/abduction θ_1^5, shoulder flexion/extensionθ_2^5, elbow flexion/extension θ_3^5 , elbow pronation/ supination $\theta_4^5$and palmar flexion/dorsiflexion θ_5^5. The exoskeleton upper-arm and forearm fit perfectly with the upper-arm and the forearm of the human body.

3.2.2 Forward kinematics

Forward kinematics is calculating the position and orientation of the end-effector in terms of the joint variables. In forward kinematics we will assume the angles and we are going to find the position of the end effector.

Forward kinematics of the exoskeleton is analyzed using D-H (Denavit-Hartenberg) Convection. The exoskeleton is modelled as a chain of rigid links interconnected by revolute and/or prismatic joints. To describe the position and orientation of a link in space, a co-ordinate frame is attached to each link. The position and orientation of frames relative to the previous frame can be described by a homogeneous transformation matrix.

Table 3.4: Motion range of 5-DOF upper limb exoskeleton.

Motion	Range
Shoulder adduction/abduction θ_1^5	$90^0/30^0$
Shoulder flexion/extensionθ_2^5	$135^0/30^0$
Elbow flexion/extension θ_3^5	$118^0/0^0$
Elbow pronation/ supination θ_4^5	$45^0/45^0$
Palmar flexion/dorsiflexion θ_5^5	$80^0/60^0$

D-H parameter of the model

While it is possible to carry out all of the analysis using an arbitrary frame attached to each link, it is helpful to be systematic in the choice of these frames The first step was to determine the co-ordinates forms according to D-H convection for the upper limb. In order to allow for the common base form for both arm, the base coordinate system (X0, Y0, Z0) was located in the body, midway between the shoulders.

Table 3.5: DH parameters of the 5-DOF upper-limb exoskeleton.

Links	α_i	a_i	θ_i^5	d_i
1	0^0	0	θ_1^5	0
2	-90^0	a_2	θ_2^5	0
3	0^0	a_3	θ_3^5	0
4	-90^0	0	θ_4^5	d_4
5	-90^0	0	θ_5^5	0

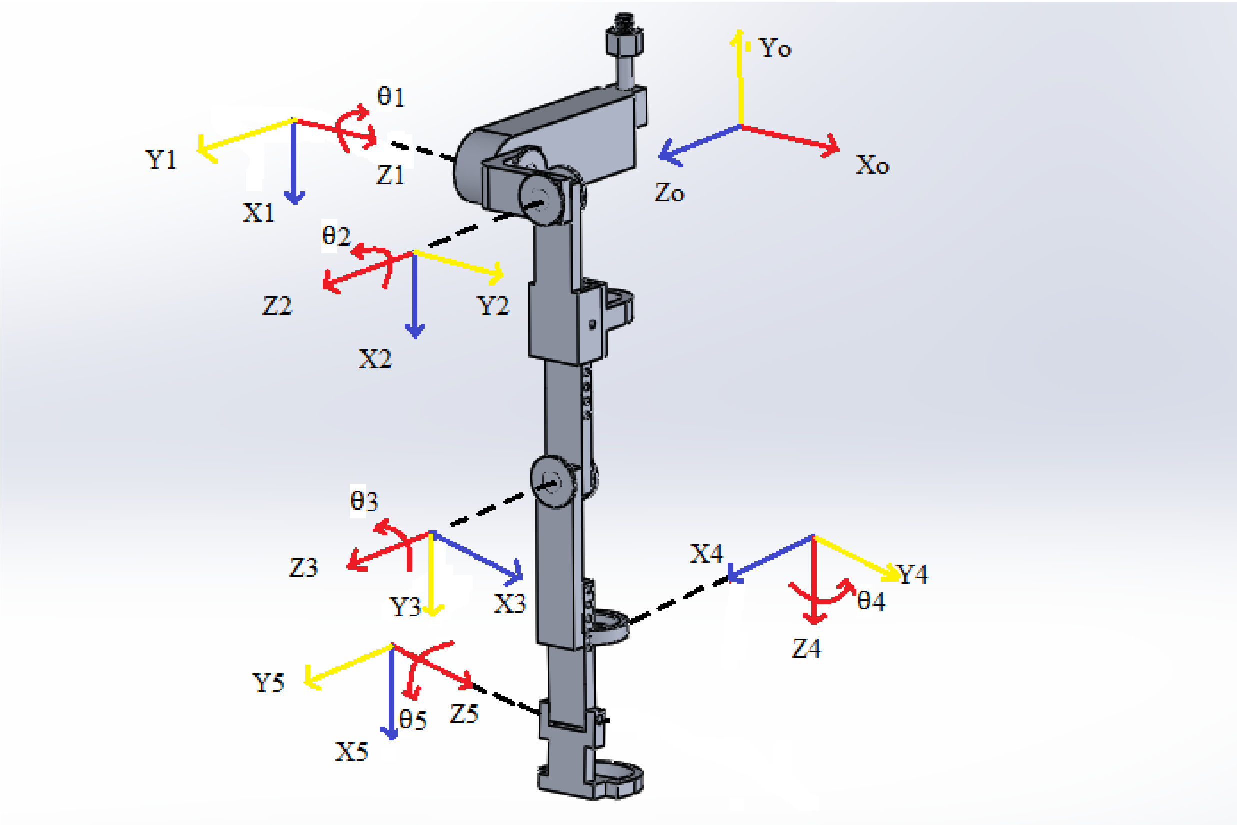


Figure 3.7: DOF upper limb exoskeleton.

Homogeneous Transformation matrix for n links is given by the equation below

$$n-1Tn = \begin{bmatrix} \cos(\theta_i^5) & -\cos(\alpha_i)\sin(\theta_i^5) & \sin(\alpha_i)\sin(\theta_i^5) & a_i\cos(\theta_i^5) \\ \sin(\theta_i^5) & \cos(\alpha_i)\cos(\theta_i^5) & \sin(\alpha_i)\cos(\theta_i^5) & a_i\sin(\theta_i^5 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- ✓ Let c1, c2, c3, c4, c5, s1, s2, s3, s4, s5 are given for the following values

c1=cos (θ_1^5) s1=sin (θ_1^5)

c2=cos (θ_2^5) s2=sin (θ_2^5)

c3=cos (θ_3^5) s3=sin (θ_3^5)

c4=cos (θ_4^5) s4=sin (θ_4^5)

c5=cos (θ_5^5) s5=sin (θ_5^5)

Putting first link parameters in homogeneous matrix:

$$0T1 = \begin{bmatrix} \cos(\theta_1^5) & -\cos(\alpha_i)\sin(\theta_i^5) & \sin(\alpha_i)\sin(\theta_i^5) & a_i\cos(\theta_i^5) \\ \sin(\theta_i^5) & \cos(\alpha_i)\cos(\theta_i^5) & \sin(\alpha_i)\cos(\theta_i^5) & a_i\sin(\theta_i^5 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$0T1 = \begin{bmatrix} c1 & -s1 & 00 \\ s1 & c1 & 00 \\ 0 & 0 & 10 \\ 0 & 0 & 01 \end{bmatrix}$$

Putting second link parameters in homogeneous matrix:

$$1T2 = \begin{bmatrix} \cos(\theta_1^5) & -\cos(\alpha_i)\sin(\theta_i^5) & \sin(\alpha_i)\sin(\theta_i^5) & a_i\cos(\theta_i^5) \\ \sin(\theta_i^5) & \cos(\alpha_i)\cos(\theta_i^5) & \sin(\alpha_i)\cos(\theta_i^5) & a_i\sin(\theta_i^5 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$1T2 = \begin{bmatrix} c2 & 0 & -s2 & a_2c2) \\ s2 & 0 & -c2 & a_2s2 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Putting third link parameters in homogeneous matrix:

$$2T3 = \begin{bmatrix} \cos(\theta_i^5) & -\cos(\alpha_i)\sin(\theta_i^5) & \sin(\alpha_i)\sin(\theta_i^5) & a_i\cos(\theta_i^5) \\ \sin(\theta_i^5) & \cos(\alpha_i)\cos(\theta_i^5) & \sin(\alpha_i)\cos(\theta_i^5) & a_i\sin(\theta_i^5 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$2T3 = \begin{bmatrix} c3 & -s3 & 0 & a_3c3) \\ s2 & c3 & -c1 & a_3s3 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Putting forth link parameters in homogeneous matrix:

$$3T4 = \begin{bmatrix} \cos(\theta_i^5) & -\cos(\alpha_i)\sin(\theta_i^5) & \sin(\alpha_i)\sin(\theta_i^5) & a_i\cos(\theta_i^5) \\ \sin(\theta_i^5) & \cos(\alpha_i)\cos(\theta_i^5) & \sin(\alpha_i)\cos(\theta_i^5) & a_i\sin(\theta_i^5 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$3T4 = \begin{bmatrix} c4 & 0 & -s4 & 0) \\ s4 & 0 & -c1 & 0 \\ 0 & -1 & 0 & d4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Putting fifth link parameters in homogeneous matrix:

$$4T5 = \begin{bmatrix} \cos(\theta_i^5) & -\cos(\alpha_i)\sin(\theta_i^5) & \sin(\alpha_i)\sin(\theta_i^5) & a_i\cos(\theta_i^5) \\ \sin(\theta_i^5) & \cos(\alpha_i)\cos(\theta_i^5) & \sin(\alpha_i)\cos(\theta_i^5) & a_i\sin(\theta_i^5 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$4T5 = \begin{bmatrix} c5 & 0 & -s5 & 0 \\ s5 & 0 & -c5 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Final transformation matrix (A) is the product of all the five transformation matrix;

$$A = 0T1.1T2.2T3.3T4.4T5.$$

$$A = \begin{bmatrix} Nx & Ox & Ax & X \\ Ny & Oy & Ay & Y \\ Nz & Oz & Az & Z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where;

$$Nx = c1c2(c3c4c5 - s3s4s5) - s1s2(s2c4c5 + c3s4c5 + c1s5)$$

$$Ny = s1c2(c3c4c5 - s3s4s5) + c1s2(s2c4c5 + c3s4c5 + c1s5)$$

$$Nz = -s2c4c5 - c3s4c5$$

$$Ox = c1c2(c3s4 - s3s1) - s1s2(c3s4 - s3c1)$$

$$Oy = s1c2(c3s4 - s3s1) + c1s2(c3s4 - s3c1)$$

$$Oz = -s2s4 - c1c3$$

$$Ax = c1c2(s3s4s5 - c3c4c5) - s1s2(s3s4s5 - c3c4c5)$$

$$Ay = s1c2(s3s4s5 - c3c4c5) - c1s2(s3s4s5 - c3c4c5)$$

$$Az = s2c5c4 + c3s4s5 + c1c5$$

$$X = c1(c2c3a3 + a2c2) - s1(s2c3a3 + a2s2)$$

$$Y = s1(c2s3a3 + a2c2) + c1(s2c3a3 + a2s2)$$

$$Z = s1(c2c3a3 + a2c2)$$

Final X, Y and Z coordinates of the end with respect to base frame can be obtained from x, y, z values and orientation of the end link is obtained from n, o, a values.

For:$\theta_5^5 = \theta_4^5 = \theta_3^5 = \theta_2^5 = \theta_1^5 = 0$

$$X = 1(1 * 1 * a3 + a2 * 1) - 0(0 * 1 * a3 + a2 * 0)$$

$$X = a3 + a2$$

Where: a2-length of upper arm and a3-length of forearm,

Upper arm length (u) of a human of height H and mass W can be calculated as;

$$u = 0.186\text{ H}$$

$$= 0.186 \text{ x } 1.75\text{m}$$

$$= 0.3255\text{ m}$$

Forearm length (l) can be calculated

$$l = 0.146\text{ H}$$

$$= 0.146 \text{ x } 1.75\text{m}$$

$$= 0.2555 \text{ m}$$

Total length of the arm (a) can be calculated

$$a = u + l$$

$$= 325.5 + 255.5 = 581.0 \text{ mm}$$

$$X = 2 * 581.0\text{mm} = 1162.0\text{mm}$$

$$Y = 0 * (1 * 1 * a3 + a2 * 1) + 1 * (0 * 1 * a3 + a2 * 0)$$

$$Y = 0$$

$$z = 0$$

For:$\theta_5^5 = \theta_4^5 = \theta_3^5 = \theta_2^5 = 0$ and $\theta_1^5 = 90$

$$X = 0(1 * 1 * a3 + a2 * 1) - 1(0 * 1 * a3 + a2 * 0)$$

$$X = 0$$

$$Y = 1(1 * 1 * a3 + a2 * 1) + 0(0 * 1 * a3 + a2 * 0)$$

$$Y = 581.0\text{mm}$$

$$z = 0$$

For:$\theta_5^5 = \theta_4^5 = \theta_3^5 = \theta_1^5 = 0$ and $\theta_2^5 = 90$

$$X = 0, Y = 0\text{mm}, z = 581.0\text{mm}$$

3.3 PART DESIGN

3.3.1 Power calculation

The average human weight is 80kg. But this machine will be designed for human weight up to 100kg in order to be functional for many peoples.

- ✓ For human weight up to 100kg.

Mass of the human arm is 5.7% of total mass [20].

$$m = \frac{5.7 * \text{total mass}}{100} = 5.7\text{kg}$$

Now, $W = m * g$

Where

- ✓ W is the weight of the arm
- ✓ G is gravitational acceleration (10 m/s^2)

$$W = 5.7\text{kg} * 10 \, {}^{m}/_{s^2} = 57\text{N}$$

Torque calculation for the exoskeleton is done by considering an average person of height 175cm.

- ✓ H = 175 cm

Upper arm length (u) of a human of height H and mass W can be calculated as;

$$u = 0.186\,H$$
$$= 0.186 \text{ x } 175$$
$$= 3255 \text{ mm}$$

Forearm length (l) can be calculated

$$l = 0.146\,H$$
$$= 0.146 \text{ x } 175$$
$$= 2555 \text{ mm}$$

Total length of the arm (a) can be calculated

$$a = u + l$$
$$= 3255 + 2555 = 5810 \text{ mm}$$

Wtp is the total mass of the arm;

$$W_{\ tp} = 5.7\text{Kg}$$

Assume, Wex is the total mass of the exoskeleton,

$$W_{eq} = 3\text{kg}$$

Wt is the total mass of the forearm and exoskeleton

$$W_{\ t} = W_{tp} + W_{ex} = 8 \text{ kg}$$

T is the torque require for the mass Wt

$$T = W_t \text{ x } a$$
$$= 8 \text{ x } 0.581$$
$$= 4.648 \text{ kg m}$$

Taking gravitational acceleration $= 10\,{}^{m}/_{s^2}$

$$= 4.648 * 10\text{Nm} = 46.48\text{Nm}$$

Power required:

By taking N=40rpm (recommended motor speed for upper limb robots) [].

$$P = \frac{2\pi NT}{60} = \frac{2 * \pi * 40 * 46.48}{60}$$
$$= 123\text{W}$$

3.3.2 Design of Spur Gears

Definition of gears

Gears are toothed members which transmit power motion between two shafts by meshing without any slip. Hence, gear drives are also called positive drives. In any pair of gears, the smaller one is called pinion and the larger one is called gear immaterial of which is driving the other.

The following are the advantages of the gear drive as compared to other drives, i.e. belt, rope and chain drives:

Advantages

1. It transmits exact velocity ratio.
2. It may be used for small center distances of shafts.
3. It has high efficiency.
4. It has reliable service.
5. It has compact layout.

Material Selection

The material on the criteria for supr gear is alloy steel which has the material strength for spur gears of the speed and load needs to be transferred.

In the design of spur gear the designer used spur gears because the axis of the two shafts is parallel and the speed of the shafts is very small. The other reason for selection is it is easy for manufacture.

Material properties:

- ✓ Alloy steel 1020: Hot rolled [21].
- ✓ Yield strength σ_{ut} = 200Mpa
- ✓ HBN = 285

Given conditions of the gear:

- ✓ System of the gear tooth: 20^0 full depth involute system
- ✓ Crushing speed = speed of rotation of the pinion gear ω_p= 40rpm = N
- ✓ Gear ratio G=1
- ✓ Tp = Number of teeth on pinion gear
- ✓ T_G= Number of teeth on gear
- ✓ L = the distance b/n the center of the two shafts

- ✓ D_G = Diameter of the gear
- ✓ M= module
- ✓ V= pitch line velocity
- ✓ W_t=Tangential load
- ✓ C_S= Service factor
- ✓ B= face width of the blade
- ✓ C = deformation facto
- ✓ BHN=285

Table 3.6: Standard Proportion of Gear System [23].

S. No.	Particulars	14.5° composite full depth involute system	20° full depth involute system	20°stub involute system
1	Addendum	1m	1m	0.8m
2	Deddendum	1.25m	1.25m	1m
3	Working depth	2m	2m	1.6m
4	Minimum depth	2.25m	2.25m	1.8m
5	Tooth thickness	1.5708m	1.5708m	1.5708m
6	Minimum clearance	0.25m	0.25m	0.25m
7	Fillet radius at root	0.4m	0.4m	0.4m
7	Fillet radius at root	0.4m	0.4m	0.4m

Calculating the minimum number of teeth on the pinion is given by:

$$T_p = \frac{2 * A_w}{G * [\sqrt{1 + \frac{1}{G}\left(\frac{1}{G} + 2\right) + \sin^2 \emptyset} - 1]}$$

Where A_W=1.

$$T_p = \frac{2 * 1}{1 * [\sqrt{1 + \frac{1}{1}\left(\frac{1}{1} + 2\right) + \sin^2 20} - 1]}$$

$$T_p = 12.32$$

Table 3.7: Systems of gear teeth [23].

S.NO.	Systems of gear teeth	Minimum number of teeth on the pinion
1.	$14\frac{1}{2}°$ composite	12
2.	$14\frac{1}{2}°$ full depth involute	32
3.	20° full depth involute	18
4.	20° Stub involute	14

From table the minimum number of teeth on the pinion for 20^0 full depth involute system is 18 but we take

$T_p = 20$

The gear ratio:

$$G = \frac{T_G}{T_P}$$

$$T_G = G * T_p = 20$$

The distance between the centers of the two shafts is given by:

$$L = \frac{D_P}{2} - \frac{D_G}{2}$$

$$G = \frac{D_G}{D_P}$$

$$D_G = D_p$$

$$D_p = 40\text{mm}$$

The module of the gear is:

$$m = \frac{D_G}{T_G} = \frac{D_P}{T_P}$$

$$m = \frac{60}{20} = 3\text{mm}$$

Pitch line velocity:

$$V = \frac{\pi DN}{60} = \frac{3.14 * 60 * 40}{60}$$

=125.6 mm/s =0.1256m/s

The design tangential load is obtained from the power transmitted and pitches line velocity

$$W_T = \frac{P * C_S}{V}$$

Table 3.8: Type of service.

Type of load	Type of service		
	Intermittent or 3 hours per day	8-10 hours per day	Continuous 24 hours per day
Steady	0.8	1.00	1.25
Light shock	1.00	1.25	1.54
Medium shock	1.25	1.54	1.80
Heavy shock	1.54	1.80	2.00

But C for light shock and 8-10 hrs. Per day from the above table C = 1.25

$$W_T = \frac{123 * 1.25}{0.0837} = 1230N$$

Applying the Lewis equation:

$$W_T = \sigma_O * C_V * b * \pi * m * Y$$

For pitch line velocity up to 12.5m/s, the velocity factor is;

$$c_v = \frac{3}{3 + v}$$

$$c_v = \frac{3}{3 + 0.1256} = 0.959$$

For 20^0 full depth involute system, the Lewis form factor or tooth form factor;

$$Y = 0.154 - \frac{0.912}{T_P} = 0.154 - \frac{0.912}{20}$$

$$Y = 0.1084$$

The allowable static stress (σ_o) for steel gears is approximately one-third of the ultimate tensile strength i.e.

$$\sigma_{o=} \frac{\sigma_{ult}}{3}$$

$$\sigma_o = \frac{\sigma_{ult}}{3} = \frac{200Mpa}{3}$$

$$\sigma_o = 66.66Mpa$$

The face width is given by:

$$b = \frac{W_T}{\sigma_O * C_S * \pi * m * Y}$$

$$b = \frac{1230N}{66.66Mpa * 1.25 * \pi * 3 * 0.1084}$$

$$b = \frac{1230\text{N}}{170.274\text{Mpa}} = 15\text{mm}$$

But we took the face width 15*3, b=45mm.

Dynamic tooth load:

$$W_D = W_T + \frac{21 * V(b * c + W_T)}{21 * V + \sqrt{b * c + W_T}}$$

The deformation factor, C

$$C = \frac{k * e}{\frac{1}{E_P} + \frac{1}{E_G}}$$

K=0.111, for 20^0 full depth involute system

$E_P = E_G$ (young's modulus) =210Gpa

Module(m) in mm	Tooth error in action(e) in mm		
	First class commercial gears	Carefully cut gears	Precision gears
Up to 4	0.051	0.025	0.0125
5	0.055	0.028	0.015
6	0.065	0.032	0.017
7	0.071	0.035	0.0186
8	0.078	0.0386	0.0198
9	0.085	0.042	0.021
10	0.089	0.0445	0.023
12	0.097	0.0487	0.0243
14	0.104	0.052	0.028
16	0.110	0.055	0.030
18	0.114	0.058	0.032
20	0.117	0.059	0.033

e=tooth error action is 0.065mm, for module up to 6mm.

$$c = \frac{0.111 * 0.065}{\frac{1}{210{,}000} + \frac{1}{210{,}000}} = \frac{7.88 * 900 * 10^3}{2}$$

$$c = 354.5\text{kpa}$$

$$W_D = 1230 + \frac{21 * 0.1256(15 * 354.5 + 1230)}{21 * 0.1256 + \sqrt{15 * 354.5 + 1230)}}$$

$$W_D = 1837 + 205 = 2042N$$

Calculating the static load:

$$W_S = \sigma_e * b * \pi * m * Y$$

For steel, the flexural endurance limit is given by

$$\sigma_e = 1.75 * BHN = 1.75 * 160 = 280Mpa$$

$$W_s = 280 * 45 * \pi * 6 * 0.1084 = 32.894KN$$

Calculate the wear load:

$$W_W = D_P * b * Q * k$$

The ratio factor, for external gears gained by;

$$Q = \frac{2 * T_G}{T_G + T_P} = \frac{2 * 20}{20 + 20}$$

$$Q = \frac{40}{40} = 1$$

The load stress factor (k) in N/mm^2

$$k = \frac{{\sigma_{es}}^2 * \sin\emptyset}{1.4}(\frac{1}{E_P} + \frac{1}{E_G})$$

The surface endurance limit for steel (σ_{es}) in N/mm^2 obtained from:

$$\sigma_{es} = 2.8 * 160 - 70 = 378Mpa$$

$$\text{so,} \quad k = \frac{378^2 \sin 20}{1.4}(\frac{1}{210{,}000} + \frac{1}{210{,}000}) = 1.587Mpa$$

$$\Longrightarrow \quad W_W = 60 * 45 * 1 * 1.587$$

$$W_W = 4284.9N$$

For safety against breakage W_s should be greater than W_D

$$W_S > W_D$$

$32.894KN > 1963N$: The gear is safe against breakage.

The maximum limiting wear load (W_W) must be greater than the dynamic load (W_D). Since the maximum wear load is much more than the tangential load on the tooth, therefore the Design is satisfactory from the standpoint of wear.

$$W_W > W_T$$

$$4284.9 > 1230N$$

Table 3.9: Result of spur gear analysis.

No	Parameters or Dimensions	General formula	Driver gear Dimensions	Driven gear Dimensions
1	Module (m)		3mm	3mm
2	Transverse pitch(P_t) = circular pitch	$P_t = \pi \times m$	9.42mm	9.42mm
3	Number of teeth(Z)		20	20
4	Diameter of the pitch circle(D)	$D = Z \times m$	60mm	60mm
5	Addendum(a)	$a = 1m$	3mm	3mm
6	Deddendum(d)	$d = 1.25 \times m$	3.75mm	3.75mm
7	Root circle diameter(D_r)	$D_r = D - 2 * d$	52.5mm	52.5mm
8	crown circle diameter(D_k)	$D_k = D + 2 * a$	66mm	66mm
9	Depth of tooth(h)	$h = a + d$	13.5mm	13.5mm
10	Depth of working tooth(h_w)	$h_w = 2 * m$	6mm	6mm
11	Tooth thickness(t)	$t = 1.5708m$	4.73mm	4.73mm
12	Filet radius at root	$0.4m$	1.2mm	1.2mm
13	Minimum clearance(c)	$c = 0.25m$	0.75mm	0.75mm
14	Face width(b)	b = 15m	45mm	45mm

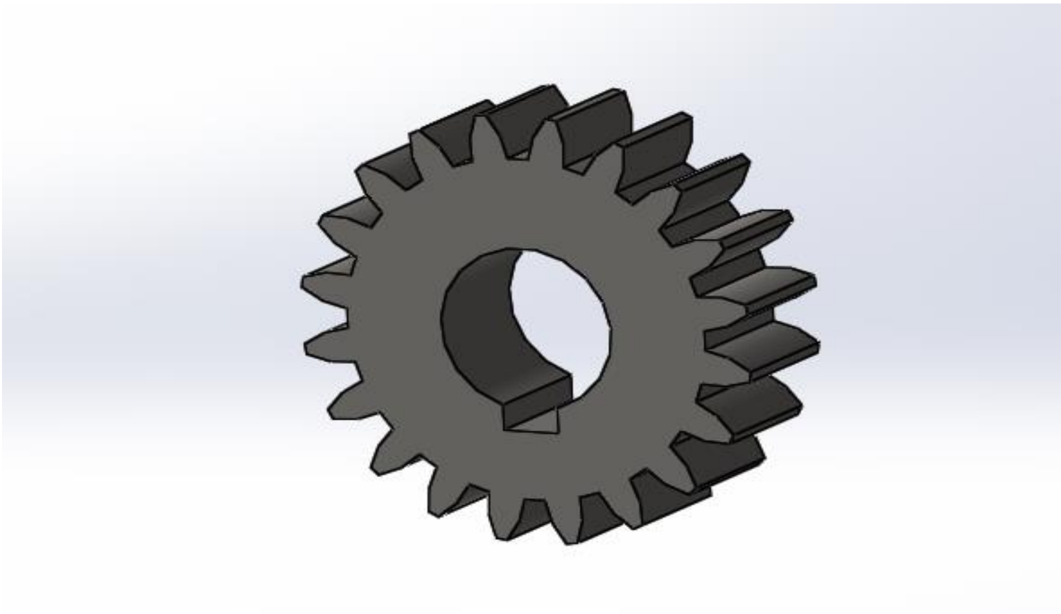


Figure 3.8: Spur Gear

3.3.3 Design of shaft

Material selection

Steel alloy 1040 cold drawn [21]:

- ✓ Ultimate tensile strength$\sigma_{ut} = 590$Mpa
- ✓ Yield strength $\sigma_y = 490$Mpa
- ✓ Modulus of elasticity E =210Gpa

Given parameters and assumptions

- ✓ Design power,$P = 123w$
- ✓ Output speed, $N = 40rpm$
- ✓ Safety factor, F.s=2 (assume)
- ✓ Number of teeth of the gear $Z = 20$
- ✓ Module m = 3mm

Analysis

Torque acting on the shaft:

$$T = \frac{60P}{2\pi N} = \frac{60 \times 123}{2\pi \times 40} = 117000Nmm$$

Radius of the gear:

$$R = \frac{Z * m}{2} = \frac{20 * 3}{2} = 30mm$$

Tangential force:

$$F_1 = \frac{T}{R} = \frac{117000Nmm}{30mm}$$

$$F_1 = 3900N$$

To find the reaction on the bearings we use the force and moment equilibrium equation:

$\sum F = 0$,

$$R_A = 3900N$$

$\sum M_A = 0$ we have

$$M = 3900 * 100 = 390000Nmm$$

Maximum bending moment:

$$M = 390000Nmm.$$

Equivalent twisting moment:

$$T_e = \sqrt{(K_m M^2 + K_t T^2)}$$

Where,

- ✓ K_m= Combined shock and fatigue factor for bending, and
- ✓ K_t= Combined shock and fatigue factor for torsion.

Now for suddenly applied load with minor shocks only we find from table:

$$K_m = 1.6 = K_t$$

$$T_e = \sqrt{(1.6 \times 390000\text{Nmm})^2 + (1.6 \times 117000\text{Nm})^2}$$

$$= 651475.12\text{Nmm}$$

Diameter of shaft:

$$d_s = \left(\frac{16T_e}{\pi\tau_{allow}}\right)^{\frac{1}{3}}$$

According to maximum shear stress theory,

$$\tau_{allow} = \frac{\sigma_y}{2.\text{Fs}} = \frac{490\text{Mpa}}{2 \times 2} = 122.5\text{Mpa}$$

Therefore

$$d_s = \left(\frac{16 \times 651475.\text{Nmm}}{\pi \times 122.5\frac{\text{N}}{\text{mm}^2}}\right)^{\frac{1}{3}}$$

$$d_s = 19.52\text{mm}$$

Equivalent bending moment

$$M_e = 0.5(K_m M + \sqrt{(K_m M^2 + K_t T^2})$$

$$M_e = 0.5(1.6 \times 390000\text{Nmm.} + \sqrt{(1.6 \times 390000\text{Nmm.} + 1.6 \times 117000\text{Nmm}^2})$$

$$= 312450\text{Nmm}$$

$$d_s = \sqrt[3]{\frac{32M_e}{\pi\sigma_b}}$$

According maximum normal stress theory,

$$\sigma_b = \frac{\sigma_y}{\text{FS}} = \frac{490}{2}\frac{\text{N}}{\text{mm}^2} = 245\frac{\text{N}}{\text{mm}^2}$$

$$d_s = \sqrt[3]{\frac{32 \times 312450}{\pi \times 245}} = 23.5\text{mm}$$

Now taking the maximum

$$d_s = 23.5\text{mm say } \mathbf{25mm}$$

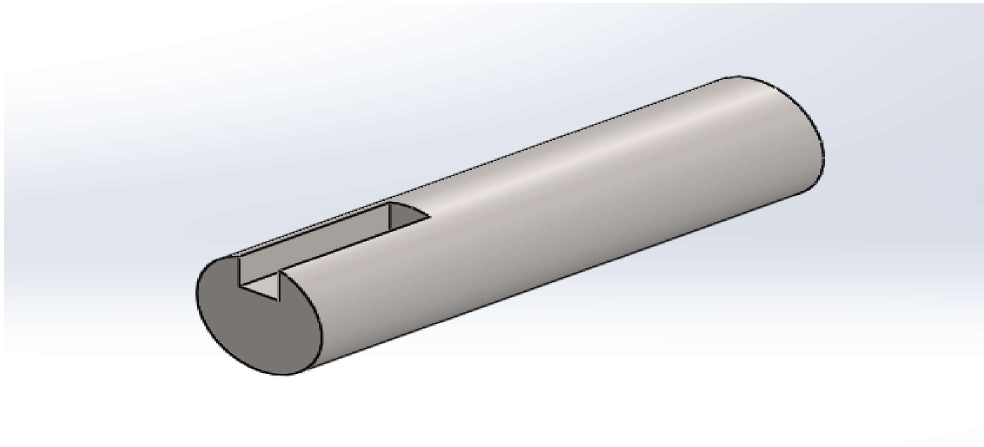


Figure 3.9: shaft.

3.3.4 Design and selection of contact ball bearing for first shaft

A bearing is a machine element which supports another moving machine element (known as journal). It permits are relative motion between the contact surfaces of the members, while carrying the load.

Rating life:

Rating life is defined as the life of a group of apparently identical ball or roller bearings, in number of revolutions or hours, rotating at a given speed, so that 90% of the bearings will complete or exceed before any indication of failure occur.

Given parameters and assumptions

- ✓ Shaft speed, $\mathbf{N_2 = 40rpm}$
- ✓ The shaft diameter is 25mm
- ✓ The bearing is subjected to radial load,
- ✓ The bearing is subjected to radial load,

$$\mathrm{F_r = R_A = 3900kN}$$

- ✓ The machine is to be used approximately 8 hrs. Per day
- ✓ The average service life of 5 years
- ✓ 240 working day per year

Analysis

Total working hours of the machine = 5×240×8= 9600hrs

Life in millions of revolution for the bearing

$$\mathrm{L} = \frac{\mathrm{N \times total\ service\ hrs}}{10^6} = \frac{40 \times 60 \times 9600}{10^6} = 8.64$$

Most manufacturers specifies dynamic load rating C which is load that results in 10^6 cycle (one million cycles).

Equivalent radial load:

$$F_e = XVF_r + YF_a$$

- ✓ X and Y are factors determined from table
- ✓ V = 1, when inner ring rotates

=1.2, when outer ring rotates

F_aIs axial component of the force acting on the bearing = 0 in this case.

Table 3.10: Equivalent radial load factors for all bearings.

		$F_a/(VF_r) \leq e$		$F_a/(VF_r) > e$	
F_a/C_o	e	X_1	Y_1	X_2	Y_2
0.014	0.19	1.00	0	0.56	2.30
0.021	0.21	1.00	0	0.56	2.15
0.028	0.22	1.00	0	0.56	1.99
0.042	0.24	1.00	0	0.56	1.85

$$F_e = F_r = 3900\text{N}$$

Basic or dynamic load rating:

$$C = F_e \times (L)^{\frac{1}{a}}$$

L: life in millions of revolution or life in hours.

a =constant which is 3 for ball bearings.

= 10/3 for roller bearings.

$$C = F_e \times (L)^{\frac{1}{a}}$$

$$C = 3900 \times (8.64)^{\frac{1}{3}}$$

$$C = 8.002\text{kN}$$

Now, the table 4.8 below for single row deep groove ball bearing of series- 02 shows that for a 25mm inner diameter, the value of$C = 14\text{kN}$.

Therefore, this bearing may be selected safely for the given requirement without increasing the shaft size. A possible bearing could be SKF 6210.

Table 3.11: Dimensions load rating for Single-Row 02-Series Deep-Groove and Angular contact Ball Bearing.

				shoulder diameter, mm		Load ratings, KN			
						Deep groove		Angular contact	
Bore, Mm	OD, mm	Width, Mm	Fillet radius, mm	d_s	d_h	C_{10}	C_o	C_{10}	C_o
25	52	15	1.5	30	47	14	6.95	14.8	7.65
30	62	16	1.0	35	55	19.5	10.0	20.3	11.0
35	72	17	1.0	41	65	25.5	13.7	27.0	15.0
40	80	18	1.0	46	72	30.7	16.6	31.9	18.6
45	85	19	1.0	52	77	33.2	18.6	35.8	21.2

We shall denote the catalog load rating as C_{10}.

- ✓ Bore =25mm
- ✓ Outside diameter =52mm
- ✓ Width=15mm

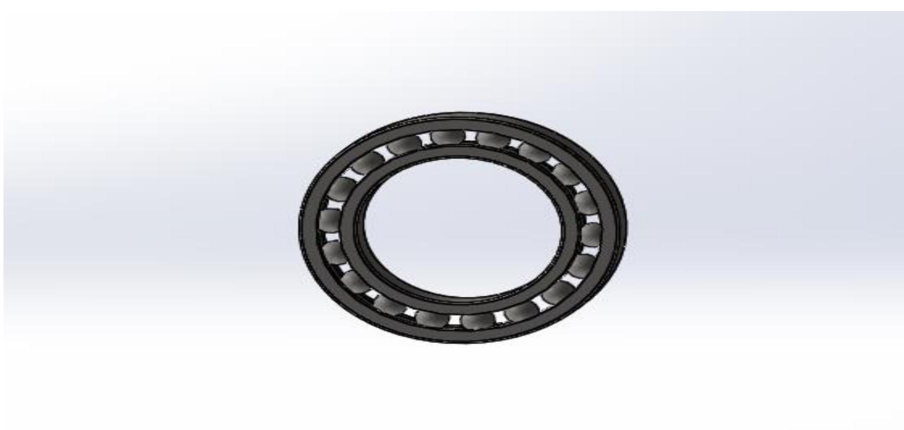


Figure 3.10: Contact Ball Bearing.

3.3.5 Selection of key for the shaft

Material selection

Mild steel

Given parameters and assumptions

- ✓ Torque provided by shaft $T = 117000\text{Nmm}$
- ✓ Factor of safety =2 (assume)
- ✓ Diameter of shaft d=25mm
- ✓ Allowable shear stress

$$\tau_{all} = \frac{\sigma_y}{2Fs} = 55\frac{N}{mm^2}$$

- ✓ Allowable crushing stress

$$\sigma_c = 110\frac{N}{mm^2} = \frac{\sigma_y}{Fs}$$

Analysis

Table 3.12: Proportions of standard parallel tapered and gib head keys.

Shaft diameter(mm) up to and including	Key cross-section		Shaft diameter(mm) up to and including	Key cross-section	
	Width (mm)	Thickness(mm)		Width (mm)	Thickness(mm)
22	8	7	170	45	25
30	10	8	200	50	28
38	12	8	230	56	32
44	14	9	260	63	32
50	16	10	290	70	36

From tableof standards we find that for a shaft of 25 mm diameter,

Width of key, w = 10mmand thickness of key, t = 8mm.

The length of key can be taken the same as the length of shaft holding the gear, L =45 mm

Considering shearing of the key, we know that shearing strength of the key,

$$T = L \times w \times \tau_{all} \times \frac{d}{2}$$

$$\tau_{all} = \frac{2T}{w \times l \times d} = \frac{2 \times 117000}{10 \times 45 \times 25} = 20.8\text{Mpa}$$

$20.8\text{Mpa} < 55Mpa$ Then design is safe

Considering the failure of key due to crushing,

$$T = L \times \frac{t}{2} \times \sigma_c \times \frac{d}{2}$$

$$\sigma_c = \frac{4T}{t \times L \times d} = \frac{4 \times 117000}{8 \times 45 \times 25} = 52\text{Mpa}$$

$52\text{Mpa} < 110Mpa$ Then design is safe.

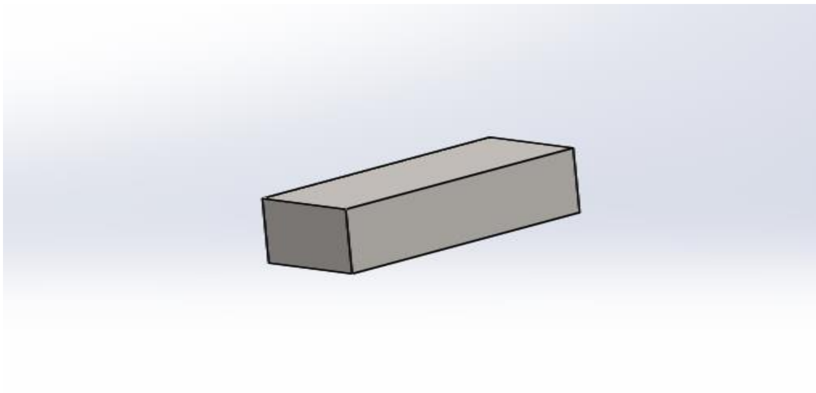


Figure 3.11: Key.

3.3.6 Design of forearm link

Assumption

- ✓ The link has rectangular shape and circular at the end.
- ✓ Thickness of the leg is 5 cm.
- ✓ Factor of safety to be 4.
- ✓ Dynamic load factor to be 1.5

Stress on the link

Bending stress- due to the weight of the forearm at the center of the link the horizontal link is subjected to bending stress during flexion and extension.

Analysis

Appling the dynamic load factor of 1.5, $W = 1.5 * 57N = 85.5N$

Before proceeding to the force analysis we need to calculate length of the forearm.

Length of the forearm

L=0.146H

Where, H is the height human.

The forearm link is adjustable link since the length of humans defer from one person to another.Then, the link will be designed by taking the range that consists most peoples that is height of human from 1.35m – 1.90m.

L_1=0.146*1350mm=197mm≅200mm.

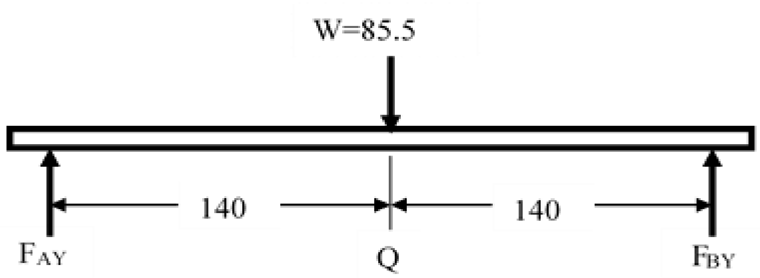
L_2=0.146*1900mm=270mm.

Where;

- ✓ L_1=Minimum length of the forearm.
- ✓ $L_{2=}$ Maximum length of the forearm.

The highest bending moment occurs on the largest length when they are under the same amount of load at center.

Then, the loading condition will be as follows



$\Sigma F_x = 0$

$\Sigma F_y = 0$

$$F_{Ay} + F_{By} - W = 0$$

$F_{Ay} + F_{By} = W$ ………………….. (1)

$\Sigma M_A = 0$

$$-140(W) + 280(F_{By}) = 0$$

$$F_{By} = {}^{140W}/_{280}$$

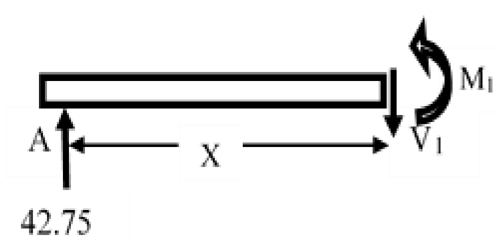
$$F_{By} = {}^{W}/_{2} = 42.75 \text{ N}$$

From equation (1)

$$F_{Ay} = 42.75\text{N}$$

To find the maximum bending moment

- ➢ Sectioning between points A and Q



For $0 < X < 140$

$\Sigma F_y = 0$

$$V_1 - 42.75N = 0$$

$$V_1 = 42.75N$$

$\Sigma M_A = 0$

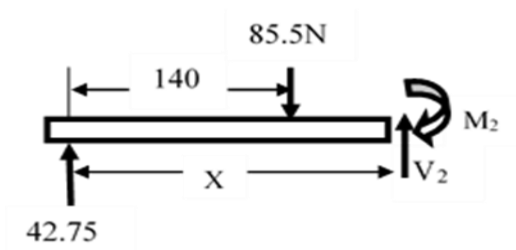
$$M_1(X) - 42.75N(X)$$

$$M_1(X) = 42.75(X)\ Nm$$

$M_1(0) = 0\ Nm$

$M_1(140) = 42.75(140)Nmm = 5985Nmm$

- Sectioning between points Q and B



$$140 < X < 280$$

$\Sigma F_y = 0$

$$V_2 - 42.75N + 85.5N = -42.75N$$

$\Sigma M_A = 0$

$$M_2(X) + 42.75N(X) - 85.5N(140)$$

$$M_2(X) = (-42.75(X) + 11970)Nmm$$

$$140 < X < 280$$

$M_2(140) = (-42.75(140) + 11970)Nmm = 5985Nmm$

$M_2(240) = (-42.75(240) + 11970)Nmm = 0Nmm$

From the calculations

- **The max bending moment=5985Nmm**
- **The maximum shear force=42.75N**

Material selection

The suitable material for this is aluminum alloy because aluminum alloys are light weight, their resistance to corrosion, most versatile materials.

Al alloy 1100(0 temper)

- ✓ $\sigma_t = 90 \text{ Mpa}$
- ✓ $\sigma_y = 34\text{Mpa}$
- ✓ $E = 71.7\text{Gpa}$
- ➢ Factor of safety is taken as 4 according to the safety standard ANSI MH29.1

$$\sigma_{all} = \frac{\sigma_y}{N} = \frac{34\text{Mpa}}{4} = 8.5\text{Mpa}$$

The bending stress is given by;

$$\sigma_b = \frac{My}{I}$$

$$I = \frac{bh^3}{12}$$

$$h^2 = \frac{6M}{b\sigma} = \frac{6 * 5985\text{Nmm}}{10\text{mm} * 8.5 \, {}^{N}/_{mm^2}}$$

$$h = 20\text{mm}$$

For better safety and to hold the motors let's take h=60mm.

Checking for tensile stress

$$\sigma_t = \frac{P}{A}$$

Where

- ✓ P is the tensile load= weight of the arm(85.5N)
- ✓ A=Cross section area=h*t=60*10=600mm^2

$$\sigma_t = \frac{P}{A} = \frac{85.5\text{N}}{600\text{mm}^2} = 0.14\text{Mpa}$$

$\sigma_t < \sigma_{all}$, therefore the design is safe.

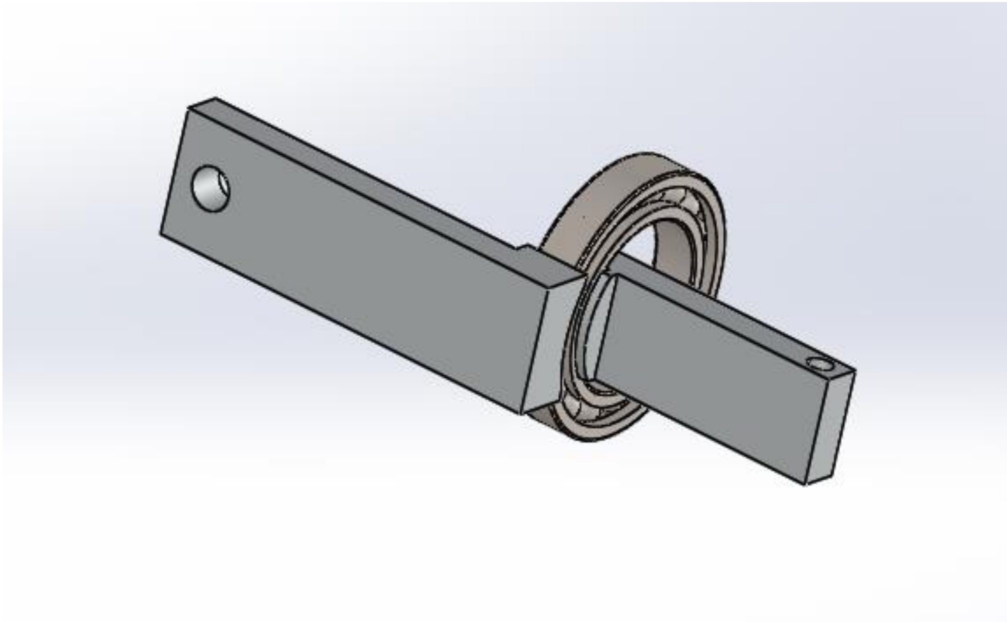


Figure 3.12: Forearm kink.

3.3.7 Design of upper arm link

Assumption

- ✓ The link has rectangular shape and circular at one end.
- ✓ Thickness of the upper arm is 5 cm.
- ✓ Factor of safety to be 4
- ✓ Dynamic load factor to be 1.5

Stress on the link

The upper link is design for bending stress during the abduction/adduction and for tensile stress during flexion/extension.

Appling the dynamic load factor of 1.5, $W = 1.5 * 57N = 85.5N$

Length of the upper arm

L=0.186H

Where, H is the height human

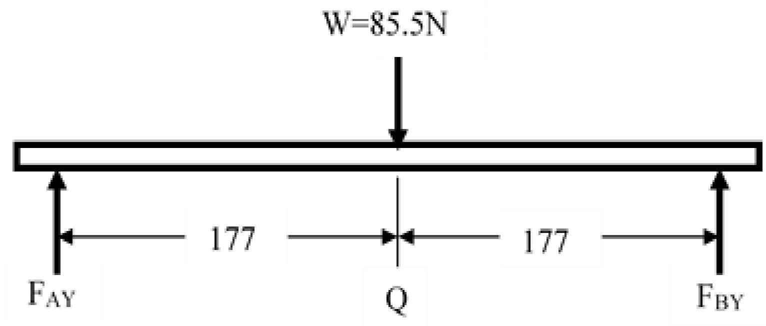
The upper arm link is also adjustable same as the forearm link Then, the link will be designed by taking the range that consists most peoples.That is height of human from 1.35m – 1.90m.

L_1=0.186*1350mm=251mm

L_2=0.186*1900mm=354mm

During the abduction/adduction

The loading condition will be as follows.



$\Sigma F_x = 0$

$\Sigma F_y = 0$

$$F_{Ay} + F_{By} - W = 0$$

$$F_{Ay} + F_{By} = W$$

$$F_{Ay} = W - F_{By} \ldots\ldots.. (1)$$

$\Sigma M_A = 0$

$$-177(W) + 354(F_{By}) = 0$$

$$F_{By} = {}^{177W}/_{354}$$

$$w = 85.5 \text{ N}$$

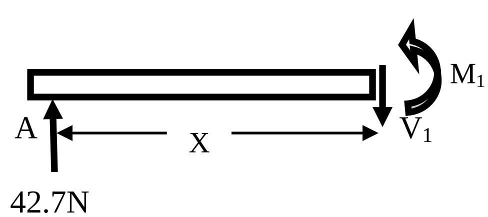
$$F_{By} = {}^{W}/_{2} = 42.75 \text{ N}$$

From equation (1)

$$F_{Ay} = 42.75\text{N}$$

To find the maximum bending moment

- Sectioning between points A and Q



For $0 < X < 177$

$\Sigma F_y = 0$

$$V_1 = 42.75\text{N}$$

$\Sigma M_A = 0$

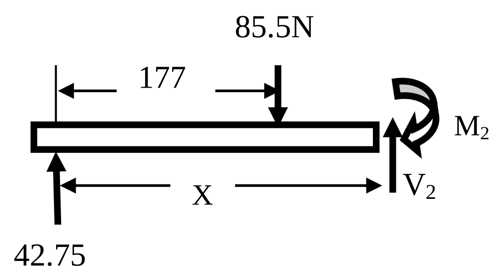
$$M_1(X) - 42.75N(X)$$

$$M_1(X) = 42.75(X)\ Nm$$

$M_1(0) = 0\ Nm$

$M_1(177) = 42.75(177)Nmm = 7566.75Nmm$

- Sectioning between points Q and B



$$177 < X < 354$$

$\Sigma F_y = 0$

$$V_2 - 42.75N + 85.5 = -42.75N$$

$\Sigma M_A = 0$

$$M_2(X) + 42.75N(X) - 85.5N(177)$$

$$M_2(X) = (-42.75(X) + 15133.5)Nmm$$

$$177 < X < 354$$

$M_2(177) = (-42.75(177) + 15133.5)Nmm = 7566.75Nmm$

$M_2(354) = (-42.75(354) + 15133.5)Nmm = 0Nmm$

From the calculations

- **The max bending moment=7566.75Nmm**
- **The maximum shear force=42.75N**

Material selection

The selected material is the same as the forearm link.

Al alloy 1100(0 temper)

- ✓ $\sigma_t = 90$ Mpa
- ✓ $\sigma_y = 34$Mpa
- ✓ $E = 69$Gpa

- ✓ Factor of safety is taken as 4 according to the safety standard.

$$\sigma_{all} = \frac{\sigma_y}{N} = \frac{34\text{Mpa}}{4}$$

$$= 8.5\text{Mpa}$$

The bending stress is given by;

$$\sigma_b = \frac{My}{I}$$

$$I = \frac{bh^3}{12}$$

$$h^2 = \frac{6M}{b\sigma}$$

$$h^2 = \frac{6 * 7566.75\text{Nmm}}{10\text{mm} * 8.5\,{}^{\text{N}}\!/_{\text{mm}^2}}$$

$$h = 23\text{mm}$$

For better safety and to hold the motors let's take h=60mm.

Checking for tensile stress

$$\sigma_t = \frac{P}{A}$$

Where

- ✓ P is the tensile load= weight of the arm(85.5N)
- ✓ A=Cross section area=h*t=60*10=600mm^2

$$\sigma_t = \frac{P}{A} = \frac{85.5\text{N}}{600\text{mm}^2}$$

$$= 0.14\text{Mpa}$$

$\sigma_t < \sigma_{all}$, therefore the design is safe.

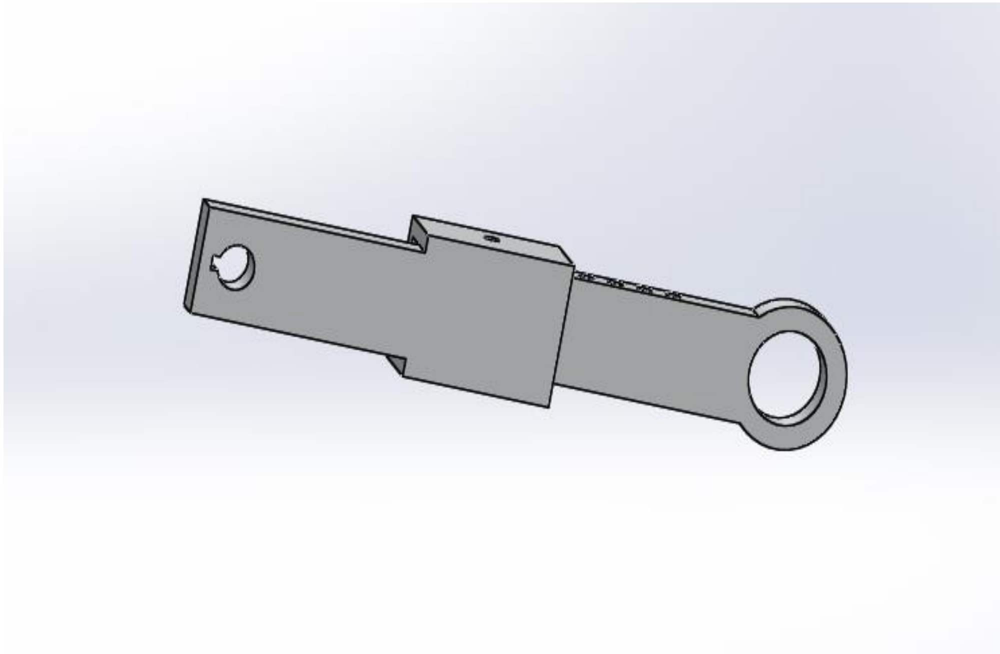


Figure 3.13: Upper-arm link.

3.3.8 Design of the shoulder and palm links

Material selection

The material for the shoulder link and palm link is the same as the upper and forearm link that is aluminum alloy.

Analysis

The palm link is under smaller force then the calculated force.Therefore thethickness for the link is taken the same as the forearm link. Detail dimension of this link can be found on the appendices A.

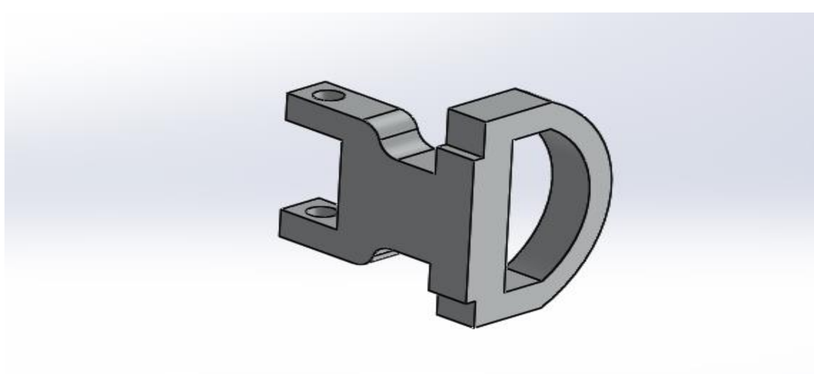


Figure 3.14: Palm link.

The shoulder link is subjected to a force same as the calculated force, which is the total weight of the arm hence, due its short length it is under the stress less than the upper arm link. Then height and thickness of the link is taken the same as the calculated parameter for upper link. Draft drawing with Detail dimension of the link is prepared.

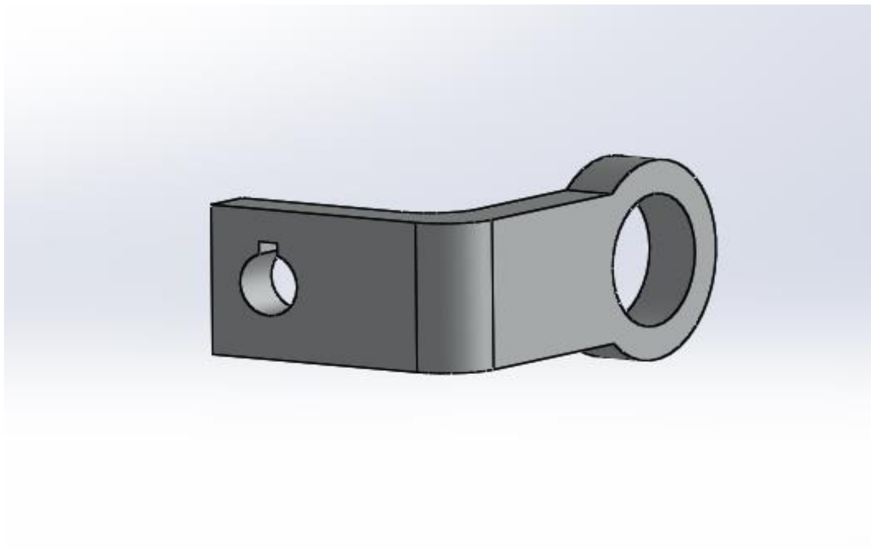


Figure 3.15: Shoulder link.

3.3.9 Design of the hollow rectangular bars 1

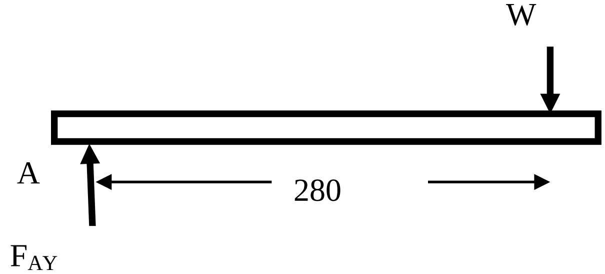
Assumption

- ✓ Assume thickness, t=4cm.
- ✓ H_1=7cm
- ✓ Assuming the cross-section of the bar to be rectangular and its length to be, L =280mm

Stress occurred on the bar

The stress occurred on the bar is Bending stress. Because a vertical force is applied at the end of a horizontal bar hinged at one end and free at the other end.

Free body diagram



$\Sigma F_y = 0$

$F_{AY} - W = 0$

Where;

$$W\ (\text{total weight}) = \text{weight of the human arm} + \text{weight of the designed exoskeleton arm}$$

$$W\ (\text{total weight}) = 80.5N + 10N = 90.05$$

$$F_{AY} = W$$

$$F_{AY} = 10N$$

The maximum bending moment occurs at point a

$$M = W * L = 90.05 * 280 = 25214Nmm$$

Material selection

Material needed

- ✓ Low cost
- ✓ Easily available

The selected material Steel alloy A36

- ✓ $\sigma_t = 400$ Mpa
- ✓ $\sigma_y = 220$Mpa
- ✓ $E = 200$ Gpa
- ✓ FS=4

Taking a factor of safety of 4 the allowable stress will be:

$$\sigma_{all} = \frac{\sigma_y}{N} = \frac{220Mpa}{4}$$

$$= 55Mpa$$

The bending stress is given by;

$$\sigma_b = \frac{My}{I}$$

Where;

$$y = \text{the centroid of object} = \frac{h - h1}{2}$$

$$M = \text{the maximum moment} = 2544Nmm$$

$$I = \text{moment of inertia} = \frac{b(h^3 - {h_1}^3)}{12}$$

$$I = \frac{40(h^3 - 70^3)}{12} = 3.33h^3 - 343000$$

$$\sigma_b = \frac{My}{I}$$

$$55\text{MPa} = \frac{25214\text{Nmm} * (h - h1)}{2(3.33h^3 - 343000)}$$

$$2(3.33h^3 - 343000) * 55 = 25214h$$

$$h = 78.\text{mm} \cong 80\text{mm}$$

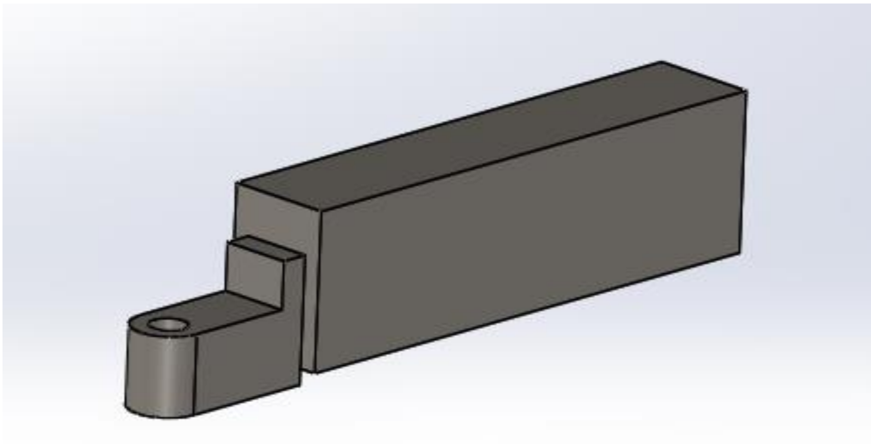


Figure 3.16: Hollow rectangular bar.

3.3.10 Design of the hollow square stand

Material selection

Material needed

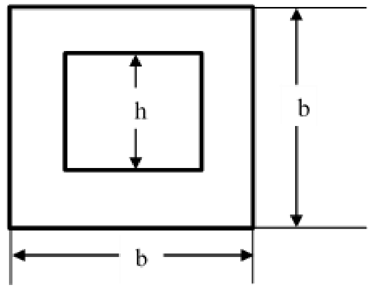
- ✓ Low cost
- ✓ Easily available

The selected material is Steel alloy A36

- ✓ $\sigma_t = 400$ Mpa
- ✓ $\sigma_y = 220$Mpa
- ✓ $E = 200$ Gpa

Assumption

- ✓ Factor of safety to be 4.
- ✓ It is adjustable to fit individual people constraint, range from 1.40m-1.90m so it has one fixed and one movable hollow square bar. But for the design case let's consider as one.
- ✓ Assume the cross-section of the stand to be hollow square h=5cm and b=6cm



Analysis

This part is design for buckling.

Length

Average height of chair =50cm

Height human

L= 1.2m

The slenderness ratio can be calculated as

$$\text{Slenderness ratio} = \frac{l}{k} = \frac{l}{\sqrt{\frac{I}{A}}}$$

Moment of inertia for Hollow Square

$$I = \frac{b^4 - h^4}{12} = \frac{(60\text{mm})^4 - (50\text{mm})^4}{12} = 559166.67\text{mm}^4$$

Cross sectional area

$$A = A1 - A2$$

$$A = b^2 - h^2 = (60\text{mm})^2 - (50\text{mm})^2$$

$$A = 1100\text{mm}^2$$

Therefore,

$$\text{Slenderness ratio} = \frac{l}{\sqrt{\frac{I}{A}}} = \frac{1200\text{mm}}{\sqrt{\frac{559166.67\text{mm}^4}{1100\text{mm}^2}}} = \frac{1200\text{mm}}{22.55\text{mm}}$$

$$\text{Sladness ratio} = 53.2$$

The columns whose slenderness ratio is more than 80, are known as **long columns,** and those whose slenderness ratio is less than 80 are known as **short columns.**Prof. J.B. Johnson proposed the following formula for short columns.

Table 3.13: Relation between equivalent length (L) and actual length (l).

No.	End connection	Relation between equivalent length(L) and actual length (l)
1	Both ends hinged	$L = l$
2	Both ends fixed	$L = l/2$
3	One end fixed and other end hinged	$L = l/\sqrt{2}$
4	One end fixed and other end free	$L = 2l$

The bar is one end fixed and other end hinged then the equivalent length,

$$L = \frac{l}{\sqrt{2}} = \frac{1200\text{mm}}{\sqrt{2}} = 848.5\text{mm}$$

Table 3.14: End fixity coefficient (C).

No.	End connections	End fixity coefficient (C)
1	Both ends hinged	1
2	Both ends fixed	4
3	One end fixed and other end hinged	2
4	One end fixed and other end free	0.25

End fixity coefficient, C=2

Allowable stress

$$\sigma_{all} = \frac{\sigma_y}{N} = \frac{220}{4}\text{Mpa}$$

$$= 55\text{Mpa}$$

$$Pcr = A \times \sigma_\gamma[1 - \frac{\sigma_\gamma}{4 \times c \times \pi^2 \times E}(\frac{L}{K})^2]$$

$$Pcr = 1100\text{mm}^2 \times 55\text{Mpa}[1 - \frac{55\text{Mpa}}{4 \times 2 * \pi^2 \times 200\text{Gpa}}\left(\frac{1200}{22.55}\right)^2]$$

$$Pcr = 74.673\text{N}$$

Therefore, the design is safe according to Prof. Johnson’s Formulae for Columns because the stand can resist about a load of 74.673N.

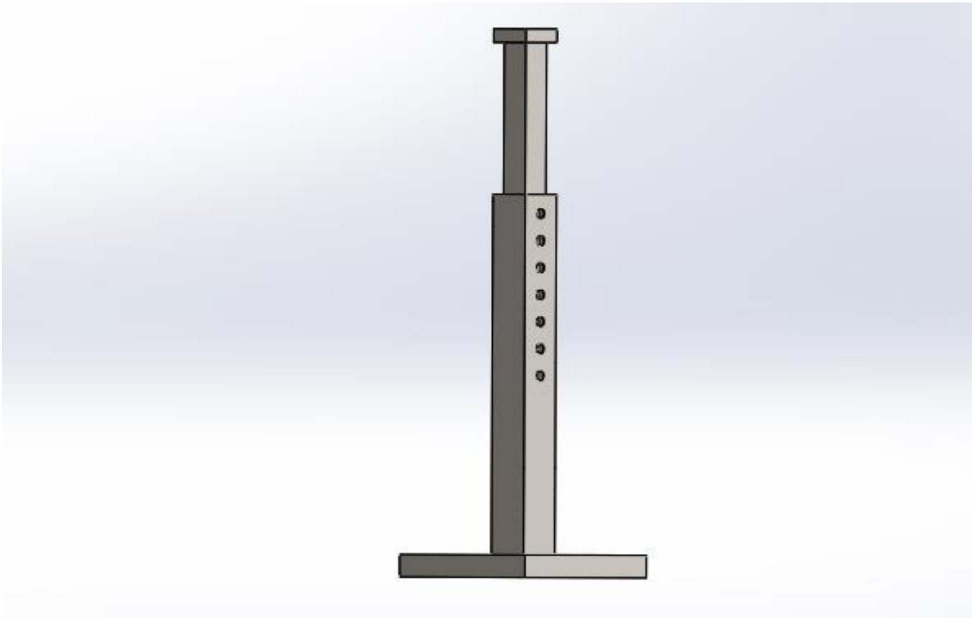


Figure 4.1: Vertical stand.

3.3.11 Design of pins

This pin is used to connect the 2 vertical beams (stand) and also used for adjusting the length of the stand.

The pin will typically be in direct shear.

Material selection

Material needed

- ✓ Good strength
- ✓ Low cost
- ✓ Available

The selected material is Steel alloy A36 (Hot rolled)

- ✓ Yield strength=220 Mpa
- ✓ Tensile strength=400Mpa

Assumption

- ✓ Factor of safety=4
- ✓ The pins have threaded and unthreaded parts.

Analysis

$F_y = 85.5\text{N}$

$$\sigma_{all=}\frac{\sigma_y}{4} = \frac{220\text{ Mpa}}{4} = 55\text{Mpa}$$

The shear stress can be calculated as;

$$\tau = \frac{\sigma_{all}}{2} = \frac{55 \text{ Mpa}}{2} = 27.5\text{Mpa}$$

$$\tau = \frac{F}{A}$$

Where;

- τ, is the shear stress
- F, Force act on the pin
- A, Area of the pin

$$27.5\text{Mpa} = \frac{85.5\text{N}}{A}$$

$$A = 3.1\text{mm}^2$$

$$A = \frac{\pi * d^2}{4}$$

$$d^2 = \frac{4A}{\pi} = \frac{4 * 3.1\text{mm}^2}{3.14} = 4\text{mm}$$

$$d = 2\text{mm}$$

Let’s take d = 10 mm.

- for the threaded part of the pin, using a standard thread of fine series (according to IS: 4694 – 1968) with d = 10 mm
  - ✓ Major diameter for bolt and nut, 10mm and 10.5mm respectively.
  - ✓ Depth of thread for bolt and nut, 1mm and 1.25 mm respectively.
  - ✓ Minor diameter = 8mm
  - ✓ Pitch = 2mm

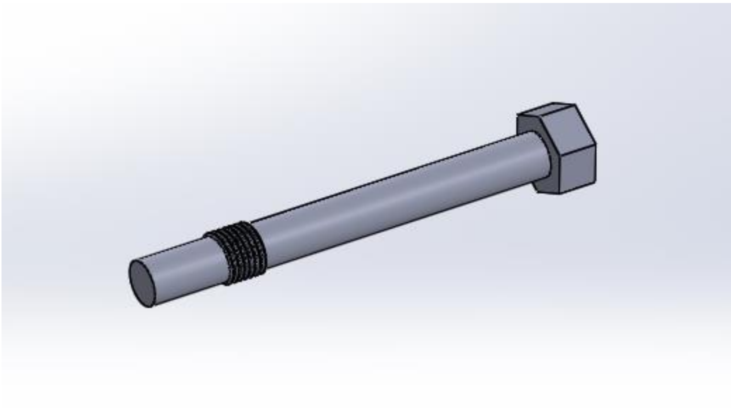


Figure 3.17: Pin.

3.4 Material needed

3.4.1 Motor

Selection of electrical motors requires several parameters to take account for arm control, position, angular and linear movements.

Servo motors

Servo motor is a rotary actuator that allows for precise control of angular or linear position, velocity and acceleration. It consists of a suitable motor coupled to a sensor for position feedback. Servomotor is not a specified class of motor although the term servomotor is often used to refer to a motor suitable use in a closed-loop control system. Servo drives that tune themselves automatically adapt to the given motor drive-mechanism, without a decrease in performance and with little need for further fine tuning of the control loops.

Figure 3.18: DC Servo Motor.

Servo motors are controlled by a signal (data) better known as a pulse-width modulator (PWM). There are two types of servo motors. Those are DC servo motors and AC servo motors. There are various voltage input for servo motor and the common voltage input for servo motor are 4.8V, 6V, 12V.

Specification

The selected motor is DC Servo Motor of type RHS series.

- ✓ Model No.: RHS-25-3012
- ✓ Rated output power: 123W
- ✓ Max. continuous torque: 48Nm
- ✓ Max. output speed: 40
- ✓ Peak current: 8.8A
- ✓ Rated voltage: 75V

3.4.2 Force torque sensor

A force torque sensor detects the different forces that are applied on the robot in the 3 geometric axes (X-Y-Z) the sensor also detects the torque applied around the 3 different axes. Which basically means the sensor feels what is going on in all axes. By doing so, the sensor gives feedback to the robot.

Typical specifications for force torque sensors are the number of measured axes, physical dimension and force range.

In this project force torque sensor used to detect force applied by the patient that can’t be enough to move his/her arm during the patient active assisted phase. After the sensor detect the force it gives a signal to the microcontroller and the microcontroller execute the command that is to move the link in the direction of the detected force or torque.

Specification

- ✓ Model No.: PD3-32-05-080
- ✓ Input voltage: DC 3-5V
- ✓ Weight: 18g

Figure 3.19: Force sensor.

3.4.3 Liquid-crystal display (LCD)

LCD module is a ready-made circuit module from a company. It function is to display number and character on screen. The LCD module uses serial communication to communicate between a microcontroller and the LCD module. There are various size such as 8x2, 16x2, 20x4 character display. All size of LCD module have the same function and depend on the user requirement of display. [15] Figure below shows the dimension and pin number function for the LCD module.

There were 16 pins and only 12 pins were used and shows the actual look of the LCD module. A liquid-crystal display (LCD) is a flat-panel display or other electronic visual display that uses the light-modulating properties of liquid crystals. Liquid crystals do not emit light directly. LCDs are available to display arbitrary images (as in a general-purpose computer display) or fixed images with low information content, which can be displayed or hidden, such as preset words, digits, and 7-segment displays, as in a digital clock.

LCDs are used in a wide range of applications including computer monitors, televisions, instrument panels, aircraft cockpit displays, and indoor and outdoor signage. Small LCD screens are common in portable consumer devices such as digital cameras, watches, calculators, and mobile telephones, including smartphones. LCDs are, however, susceptible to image persistence.

The LCD screen is more energy-efficient and can be disposed of more safely than a CRT can. Its low electrical power consumption enables it to be used in battery-powered electronic equipment more efficiently than CRTs can be. It is an electronically modulated optical device made up of any number of segments controlling a layer of liquid crystals and arrayed in front of a light source (backlight) or reflector to produce images in color or monochrome.

Figure 3.20: LCD Display.

3.4.4 ARDUINO

Arduino is a prototype platform (open-source) based on an easy-to-use hardware and software. An Arduino board consists of an Atmel 8-bit AVR microcontroller with complementary components to facilitate programming and incorporation into other circuits. The board contains everything that amid sized 8bit microcontroller project needs. The key point of the whole Arduino hype is the IDE (Integrated Development Environment) and loads of libraries available for an easy start and the boot loader. An important aspect of the Arduino is the standard way that connectors are exposed, allowing the CPU board to be connected to a variety of interchangeable add-on modules known as shields. Some shields communicate with the Arduino board directly over various pins, but many shields are individually addressable via an I²C serial bus, allowing many shields to be stacked and used in parallel.

Arduino Uno

Arduino UNO is a component on the shelf (COTS) circuit board which aim for the helping people on their project. It is based on ATmega328 microcontroller. Rather than making own circuit board from scratch, Arduino UNO provide a sufficient circuit board which able to program and contain most of the necessary pin function. Arduino UNO board consist of 14 input output pin whereby 6 of them can be used as PWM output. Besides that it contain also 6 analog to digital (ADC) pin. Basically, Arduino UNO operate at 5V and the input power source need to be a range of 7V to 12V. Table blow shows the summary of Arduino UNO microcontroller and Figure shows the Arduino UNO board. The Arduino Uno is a microcontroller board. It has 28 digital input/output pins, 12 PWM outputs, 16 analog inputs, 10 communication pins, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply it can be connected to a computer with a USB cable or powered it with an AC to-DC adapter or battery to get started. The UDP packets had to be processed by the Arduino to tell the motors how much speed to operate and in which direction the wheels should turn. There were PWM pins in the Arduino UNO R3 (3, 5, 6, 9, 10, and 11). Physical pins 9 and 3 were responsible for controlling the switches in the left motor's H-bridge and 10 and 11 were responsible for controlling the right motor. Since similar speeds were needed in both motors to move forward or backward, the left pins of each motor operated on the same timerfrequency while the right pins on another timer. Operating all the PWMs on the same timer was desirable, but not possible on the UNO. In the case of this microcontroller, pins 9 and 10 were on timer1 and, pins 3 and 11 are on timer2.This means that switching (from a HIGH signal to a LOW signal) for the PWMs was done at the same frequency for each pair of pins, which was necessary to move each wheel at a constant speed. For the motors to have changed speeds, the Arduino varied the duty cycle on the physical pins using analog Write. When the value of the write was 255, that means the duty cycle was 100% and 0 was 0%. The duty cycle ratio was thus x/255%, where x was the value of the write to the analog pin. For the purposes of this report, the physical pins 9 and 3 were referred to as the left switches of the left pins of the left and right motor, respectively. The physical pins 10 and 11 were referred to the right pins of the left and right motor, respectively. When the brakes on a motor were used, both pins on the motor were set to a 100% duty cycle, meaning 0 voltage was flowing through the motor. To go forward, both motors should have set the right pins to a 0% duty cycle and the left pins to a non-zero duty cycle (in the Arduino code, the values 178,193,208, 224, 239, and 255 were used for a range of 70% duty cycle ratio to 100% in steps of 6%).

Figure 3.21: ARDUINO UNO.

Specification

Table 3.15: ARDUINO UNO Specification.

Micro controller	ATmega168
Operating voltage	5V
Input voltage (recommended)	7-12V
Input voltage (limit)	6-20V
Digital I/O Pins	14
Analog Input Pins	6
Flash memory	32KB
Closed speed	16MHz

3.4.5 Momentary push button switch

Push buttons or switches connect two points in a circuit when they pressed. When the pushbutton is open (unpressed) there is no connection between the two legs of the push button, so the pin is connected to ground and it reads a LOW. When the button is closed (pressed), it makes a connection between the two legs, so it reads high.

Specification

Name: momentary push button switch- 12 mm square

Model: COM-09190

Figure 3.22: Momentary push button.

3.4.6 LED

Figure below shows the basic symbol of a common LED; when polarized, the current flowing through the LED is commonly called forward current and the voltage drop across it forward voltage. In the next paragraphs, the basic implications of these parameters in system behavior are described.

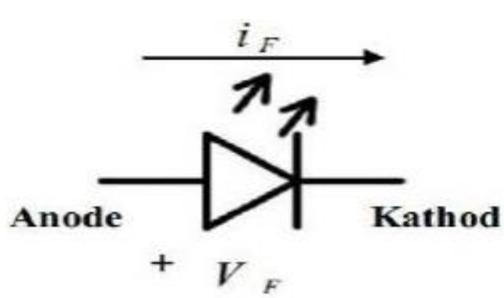


Figure 3.23: LED Symbol.

3.4.7 Motor Encoder

Encoder helps us to determine how much motor has moved from its original position. Encoders are of two types; incremental and absolute. Absolute encoders have an index channel to indicate the distance travelled from a fixed point. But in the incremental encoder, there is no such mechanism, we can find out the relative distance between the original position and current position. In this project we are using incremental magnetic encoder. Incremental magnetic encoders are designed with a diametrically magnetized code wheel which is pressed onto the motor shaft and provides the axial magnetic field to the encoder electronics. The electronics contain all the necessary functions of an encoder including hall sensors, interpolation, and driver.

Specification

- ✓ Model No.: E100DO
- ✓ Type: Open collector
- ✓ Resolution: 1000 P/r
- ✓ Input voltage: DC 5V-12V

3.5 DESIGN OF PROPORTIONALINTEGRALDERIVATIVE (PID) CONTROLLER

PID controller is considered the most widely used control technique in control applications. A high number of applications and control engineers had used the PID controller in daily life. PID control offers an easy method of controlling process by varying its parameters. It consists from Proportional (P) controller, Proportional-Integral (PI) controller, Proportional Derivative (PD) controller and Proportional-Integral-Derivative (PID) controller

P determines the reaction to current error, we determine reaction to the sum of recently appeared errors, and D determines reaction according to the rate off error changing. The sum of all three parts contribute the control mechanism such as speed control of a motor in which P value depends upon current error, I on the accumulation of previous error and D predict future error based on the current rate of change.Proportional-Integral-Derivative (PID) controller has the optimum control dynamics including zero steady state error, fast response (short rise time), no oscillations and higher stability. The necessity of using a derivative gain component in addition to the PI controller is to eliminate the overshoot and the oscillations occurring in the output response of the system. One of the main advantages of the PID controller is that it can be used with higher order processes including more than single energy storage.

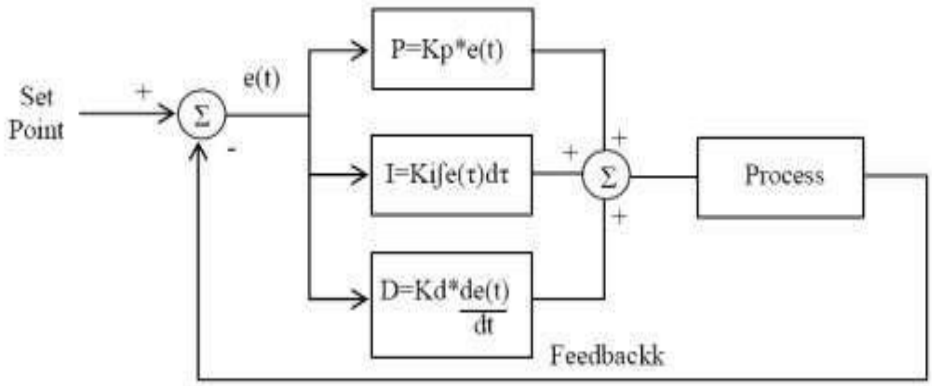


Figure 3.24: PID controller block diagram.

The control structure used was the PID as a base for software development. This type of controller was initially chosen, because it is generally applied to most of the control systems of continuous processes, proving its usefulness by providing a generally satisfactory control. Which can be found in various formats. Among the existing formats, the one chosen to be implemented in the experiment was parallel PID.Mathematical description of PID controller is:

$$U(t) = Kpe(t) + Ki\int_0^t kd\frac{de(t)}{dt}$$

Where;

- ✓ t = Time
- ✓ U (t) = Output, e (t) = Error = set point – process variable
- ✓ K_P = Proportional controller mode gain
- ✓ K_i = Integral controller mode gain
- ✓ K_d = Derivative controller mode gain

3.5.1 DC Servo motor control in feedback loop

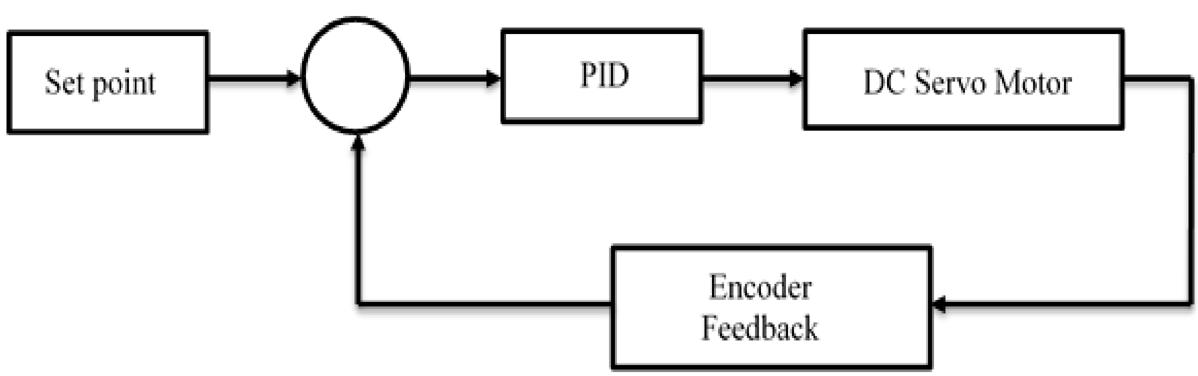


Figure 3.25: PID loop control system of DC Servo motor

Quick Details
Place of Origin:
    Henan, China (Mainland)
Brand Name:
    Xiangyu
Model Number:
    XYKSZFK-1
Instrument classification:
    Class II
Model number:
    XYKSZFK-1
Power:
    AC220V 50/60Hz
Sensitivity of sensor:
    1.1mv/N
Grip rangement:
    0~10kgs
Length of upper arm:
    20~30cm
Length of forearm:
    24~40cm
Height of arm:
    98~138cm
Horizontal of arm:
    0~55cm
Gravity compensation of upperarm:
    0~6kgs
Gravity compensation of forearm:
    0~4kgs

Supply Abilit

Now let's get the DC motor transfer function. Consider motor torque equation is given by,

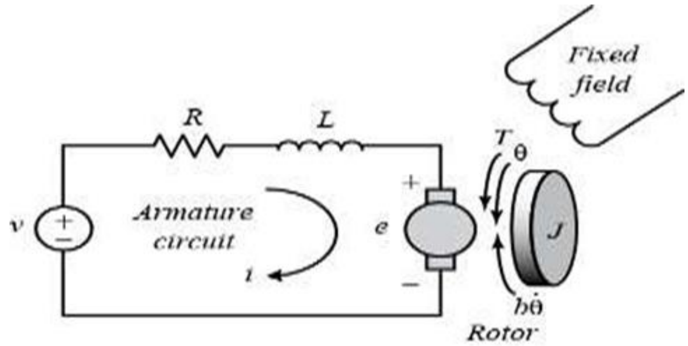


Figure 3.26: Electrical DC Servo motor.

$$\tau = Kt * I \quad (1)$$

Where Kt is torque constant and motor torque is directly relate to armature current. Back emf is related to rotational velocity and is given by

$$e = Ke * \Theta' \quad (2)$$

By Newton's 2nd law i.e. torque is the rate of change of angular momentum,

$$\tau = J\Theta'' + b\Theta$$

$$K * I = J\Theta'' + b\Theta$$

Laplace transform:

$$K * I(s) = Js^2\Theta(s) + bs\Theta(s) \quad (3)$$

ByKirchhoff's law we get,

$$I = \frac{va - vb}{L + R}$$

$$\frac{LdI}{dt} + RI = Va - Vb = Va - Ke * \Theta'$$

Laplace transform:

$$[Ls + R]I(s) = V(s) - Ke * s * \Theta(s) \quad (4)$$

From equation (3) & (4) we get:

$$\frac{Js^2\theta(s) + bs\theta(s)}{k} = \frac{V(s) - Ks\theta(s)}{Ls + R}$$

$$s(Js + b)\theta(s)(Lss + R) - k * V(s) + k^2 s\theta(s) = 0$$

So the DC Servo motor transfer function be;

$$\frac{\theta(s)}{V(s)} = \frac{K}{s[(Js+b)(Ls+R)+K^2]}$$

Which gives angle vs. voltage equation used for control of DC Servo motor.

Table 3.16: DC Servo motor specification

Nominalvoltage	75V
Armatureresistance(R)	1.2Ω
BackEMF(b)	2.15 V/rpm
Torqueconstant(Kt)	21 Nm/A
Armatureinductance(L)	0.01 H
Inertiaofthesystem(J)	2.1Kg.m^2

Transfer function of RHS-25-3012 DC Servo Motor.

$$G(s) = \frac{\theta(s)}{V(s)} = \frac{K}{s[(Js+b)(Ls+R)+K^2]}$$

$$G(s) = \frac{21}{0.00231S^3 + \ 2.522781S^2 + 443.58S}$$

$$T.F = \frac{G(s)Kc}{1 + G(s)H(s)Kc}$$

$$T.F = \frac{\frac{21}{0.00231S^3 + 2.522781S^2 + 443.58S}Kc}{1 + \frac{21}{0.00231S^3 + 2.522781S^2 + 443.58S} * 1 * Kc}$$

Where $H(s) = 1$

$$T.F = \frac{\frac{21Kc}{0.00231S^3 + 2.522781S^2 + 443.58S}}{\frac{0.00231S^3 + 2.522781S^2 + 443.58S + 21Kc}{0.00231S^3 + 2.522781S^2 + 443.58S}}$$

$$T.F = \frac{21Kc}{0.00231S^3 + \ 2.522781S^2 + 443.58S + 21Kc} = \frac{N(s)}{D(s)}$$

To find critical gain say

$$D(s) = 0.00231S^3 + \ 2.522781S^2 + 443.58S + 21Kc = 0$$

Then construct Routh –Hurwitze table to find the value of Kc.

Table 3.17: Routh-Hurwitze Table.

S^3	0.0231	443.58	0
S^2	2.5228	21Kc	0
S^1	$\frac{1119.063 - 0.4851\text{Kc}}{2.5228}$	0	0
S^0	21Kc	0	0

To make the system stable the coefficients on the first raw must be greater than 0,

$$\frac{1119.063 - 0.4851\text{Kc}}{2.5228} \geq 0$$

$\text{WhereKc} = \text{critical gain}$

$$1119.063 = 0.4851\text{Kc}$$

$$\text{Kc} = 2306.872$$

$\text{Then KP} = 0.6\text{Kc} = 0.6 * 2306.87203$

$\text{Kp} = 1384.12322$

$\text{Pcr} = \frac{2\pi}{\omega}$

Then to findω substitute in to the denominator assuming $S = j\omega$

$$D(s) = 0.00231(j\omega)^3 + 2.522781(j\omega)^2 + 443.58(j\omega) + 21\text{Kc} = 0$$

$$-0.00231\omega^3 + 2.522781\omega^2 - 443.58\omega + 21 * 2306.872 = 0$$

$$\omega^3 - 109.2121\omega^2 + 19202.5974\omega - 2097156.4 = 0$$

By trial and error the value of $\omega = 109.25$

Then $\text{Pcr} = \frac{2\pi}{\omega} = 0.057512$ $\quad$ $\text{Ki} = \frac{\text{Pcr}}{2} = 0.028756$ and $\text{Kd} = \frac{\text{Pcr}}{8} = 0.007189$

After estimating the continuous transfer function of DC Servo Motors and design PID controller using PID tune, to implement the controller on Arduino and see how the DC Servo Motors fares with controller. We receive desired motor position from serial port and compare it to the measured position from analog input .the position error goes through the PID block which generates a voltage to be sent to the motors.

By check on SIMULINK icon in command window, we opened the SIMULINK window in MATLAB program, we opened a new project and choose step signal block, PID block, and transfer function block and we connect this component together as follow Figure below.

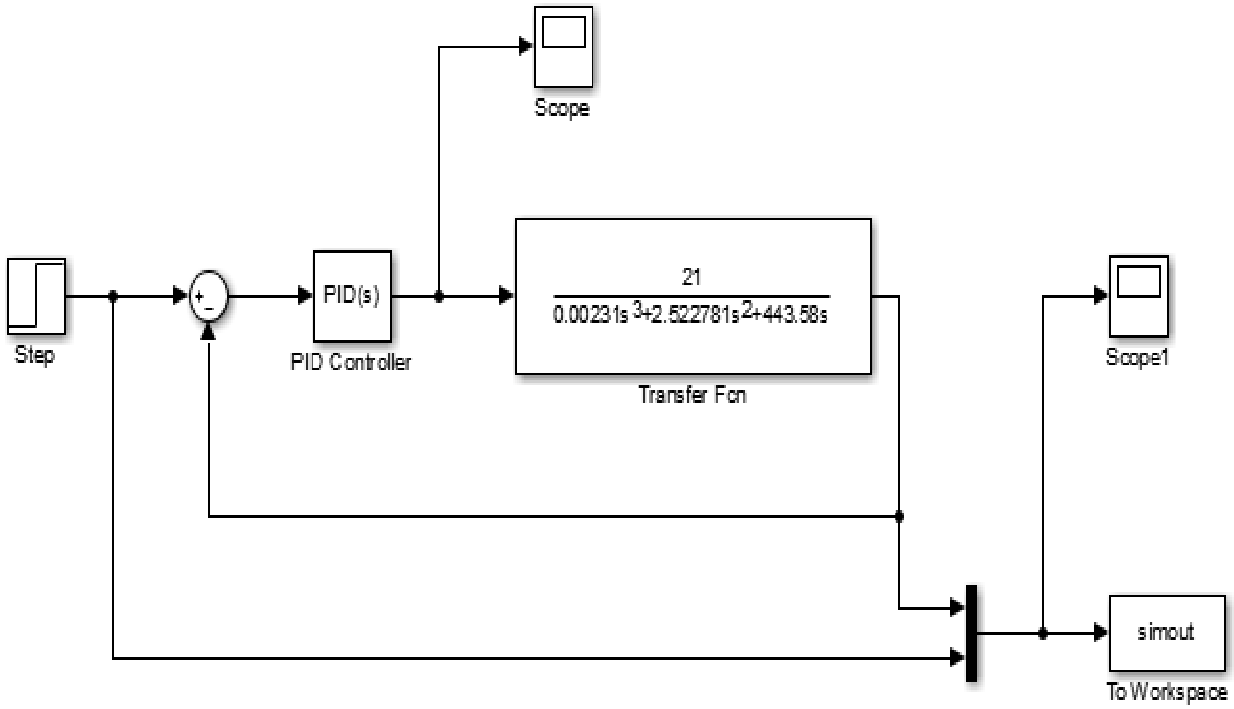


Figure 3.27: Simulink Model of PID controller.

To obtain optimum PID controller parameters the Simulink model is tuned to linearization plant (transfer function) and obtain figure the figure below.

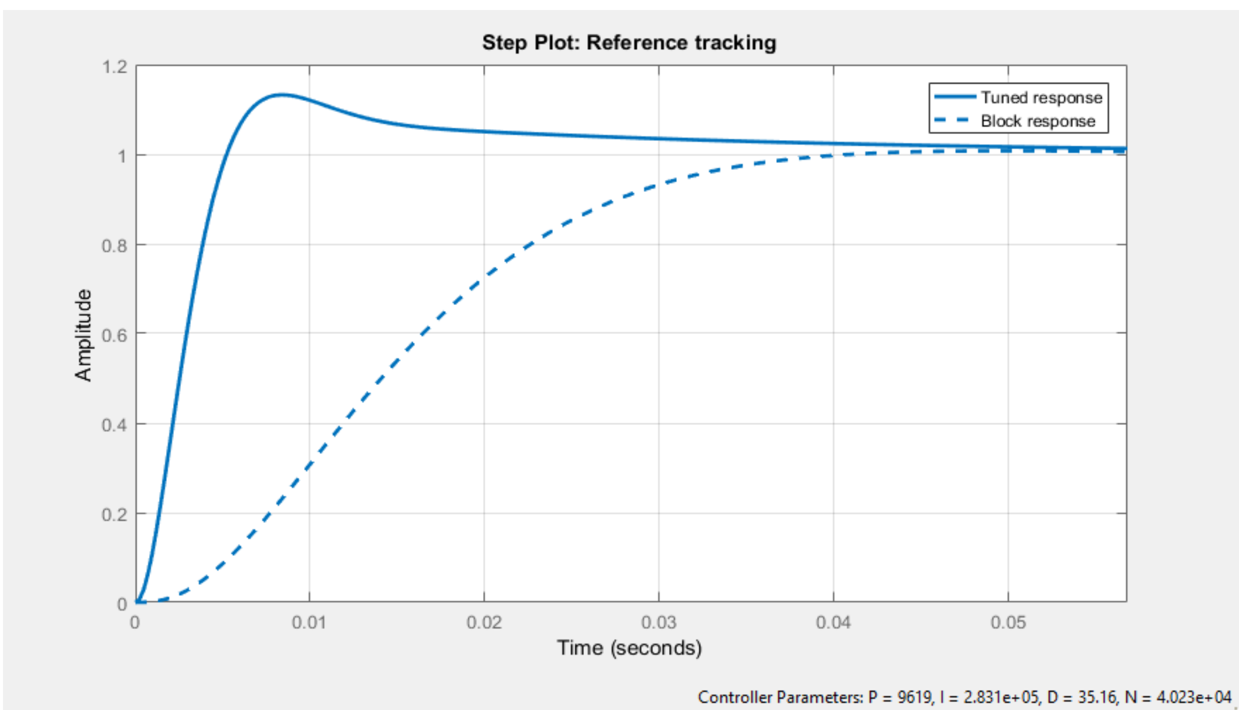


Figure 3.28: Amplitude vs. time graph of the DC Servo motor.

Controller Parameters

	Tuned	Block
P	9618.5858	1384.1232
I	283143.0651	0.028756
D	35.1632	0.007189
N	40228.1806	100

Performance and Robustness

	Tuned	Block
Rise time	0.00353 seconds	0.0223 seconds
Settling time	0.0449 seconds	0.0357 seconds
Overshoot	3.3 %	0.767 %
Peak	1.13	1.01
Gain margin	40.4 dB @ 5.74e+03 ra...	24.4 dB @ 438 rad/s
Phase margin	60 deg @ 352 rad/s	70 deg @ 62.9 rad/s
Closed-loop stability	Stable	Stable

Table 3.18: Result of PID Controller suitable values.

Controller	Values
Proportional gain(KP)	9618.5858
Integral gain(KI)	283143.0651
Derivative gain(KD)	35.1632

Simulation

The goal of the PID controller is to show how each of Kp, Ki and Kd contributes to obtain Fast rise time, Minimum overshoot, and No steady-state error for systemof DC servo motor that drive the robot arm. Figure below shows DC servo motor response without PID controller.

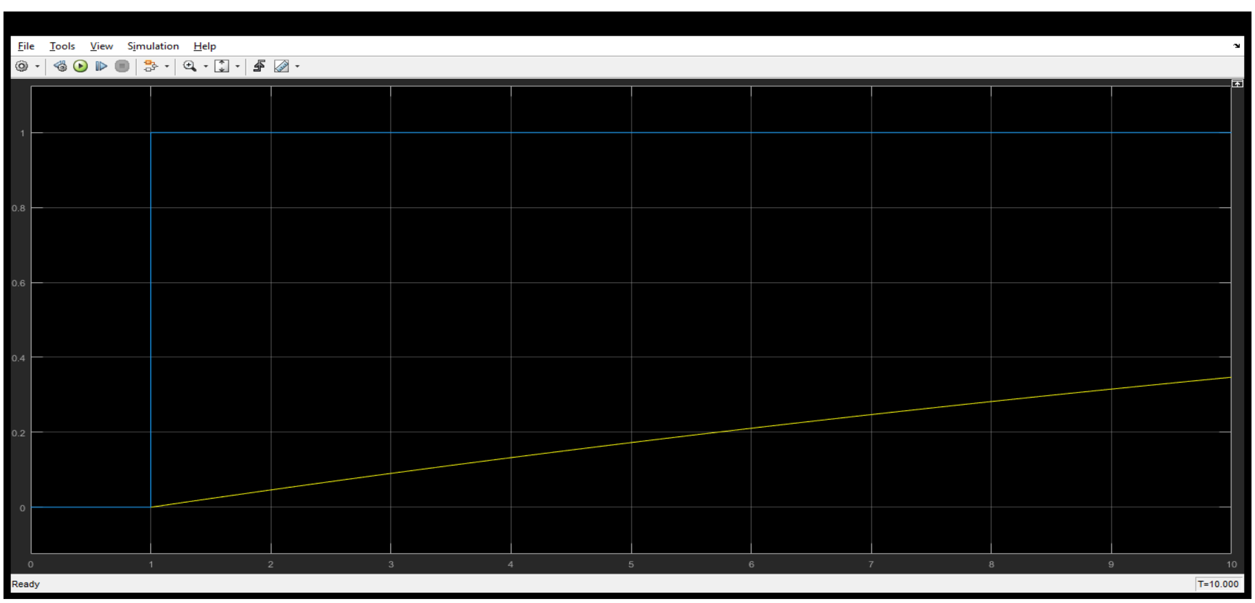


Figure 3.29: DC Servo Motor Response without PID controller.

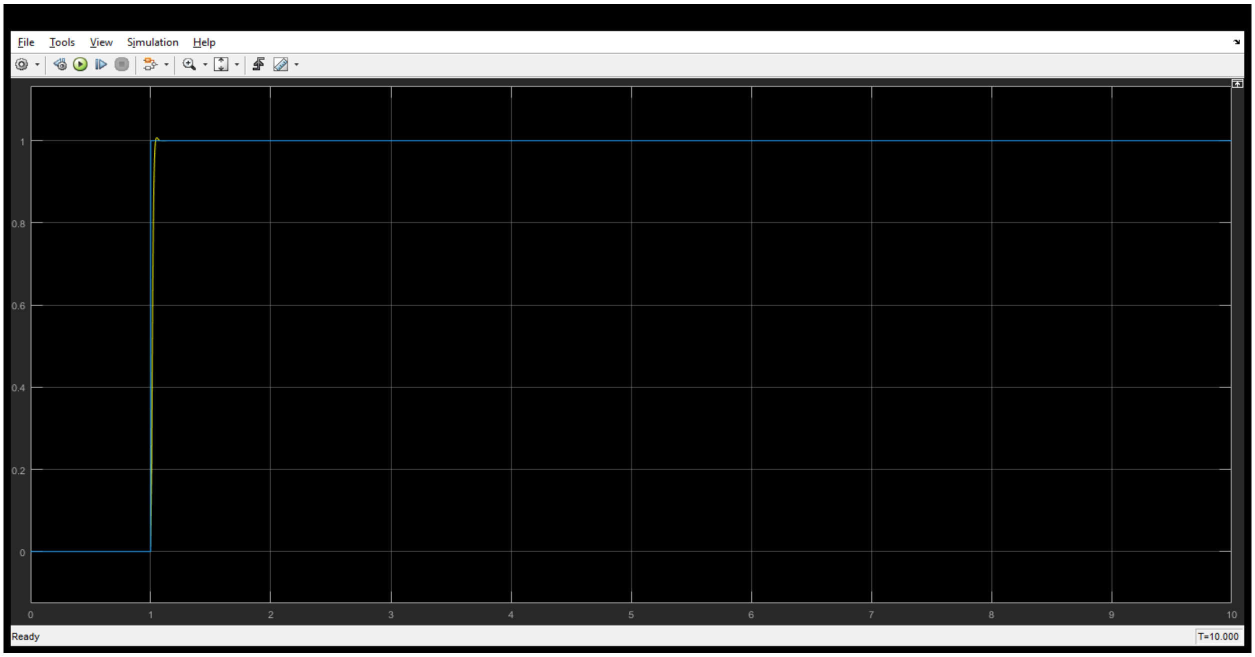


Figure 3.30: DC Servo Motor Response with PID controller.

3.6 SOFTWARE DEVELOPMENT

The entire control algorithm developed for this robot is run on the Arduino Uno. To enable the robot to move or operate, a microcontroller is needed in order to allow the robot to function by itself. Arduino UNO is used as the microcontroller for this project. The movement and the path of the therapy robot is programmed into the microcontroller. An algorithm need to be develop to ensure the microcontroller can perform desire output depending on the input.

The flow chart will then turn into c programming and compiled into the Arduino UNO using Arduino 1.0.6 IDE complier. The microcontroller required a program to operate and execute the process associated with the proposed design. Arduino programming has been used to construct the program for the proposed design. Program execution starts with initializing all the memory location and pointers.

The basic flow of the therapy robot

The basic flow of the therapy robot is that first the therapist attaché the arm of the patient to the exoskeleton robot after the carefully attachment of human arm to the robot, the therapist himself will press one of the four BUTTONs according to patient performance, the four buttons represent a full of 1 month rehabilitation training one button for one week (five days per week). As the therapist pressed the button all the robot system initialized, then microcontroller will control the action of the robot. After initialization, the robot will startmoving the patient’s arm. The movement differ from one button to another on the degree at which the motors rotate and the time that takes the motors to rotate the given amount of degree for each joints. Along the path, if there is something uncomfortable to the patient the therapist can press the emergency button to stop it. Those four buttons are used in the patient passive assisted. For the patient active assisted rehabilitation there is an active button. If the active button pressed, the 3 axis force sensor reads any force on the arm of the patient with its direction and if there the sensor send a signal to the microcontroller. Then the motor will rotate the appropriate range of motion on the axis and direction of the sensed force.

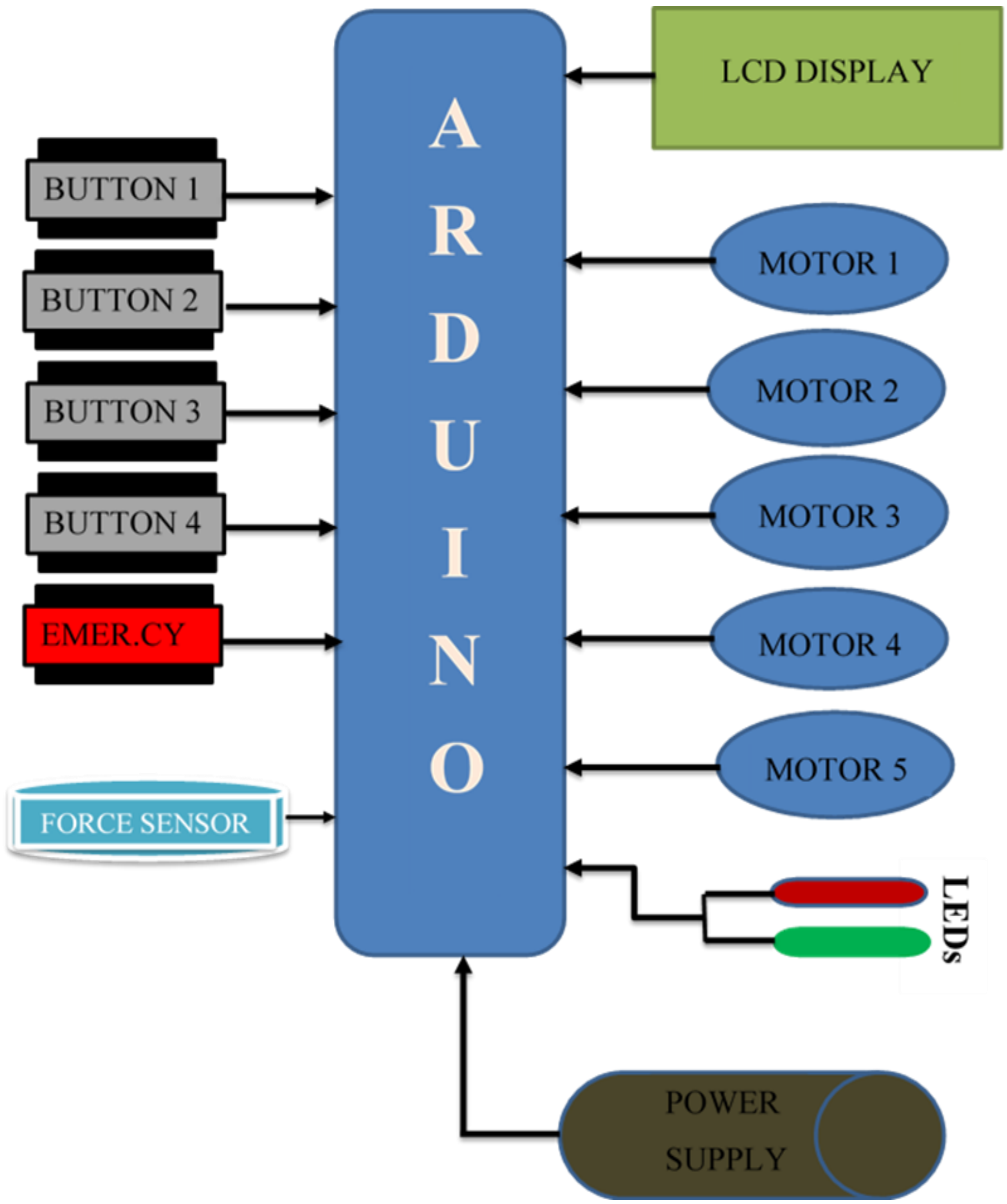


Figure 3.31: Block diagram of Arduino connection with sensors and motors.

3.7 PROTEUS SIMULATION

Simulation for this project is done on "Proteus". On this simulation we have used an ARDUINO UNO microcontroller to control the functionality of the robot, four push buttons used to give the patient one full month rehabilitation training (Each push button represent one week rehabilitation training), force sensor used after the patient starts to move his arm by himself, an emergency button to stop the rehabilitation phase if something not good is happen or felt by the patient, 5 Servo motor for the movement of the 5 DOF of the upper limb and controlled by PID, two LED (Light Emitting Diode, one Liquid crystal Display (LCD) to display condition of the robot. The robot movement should be safe, vibration free and with precise control of the rotation angle.

Over all PROTEUS simulation of our project

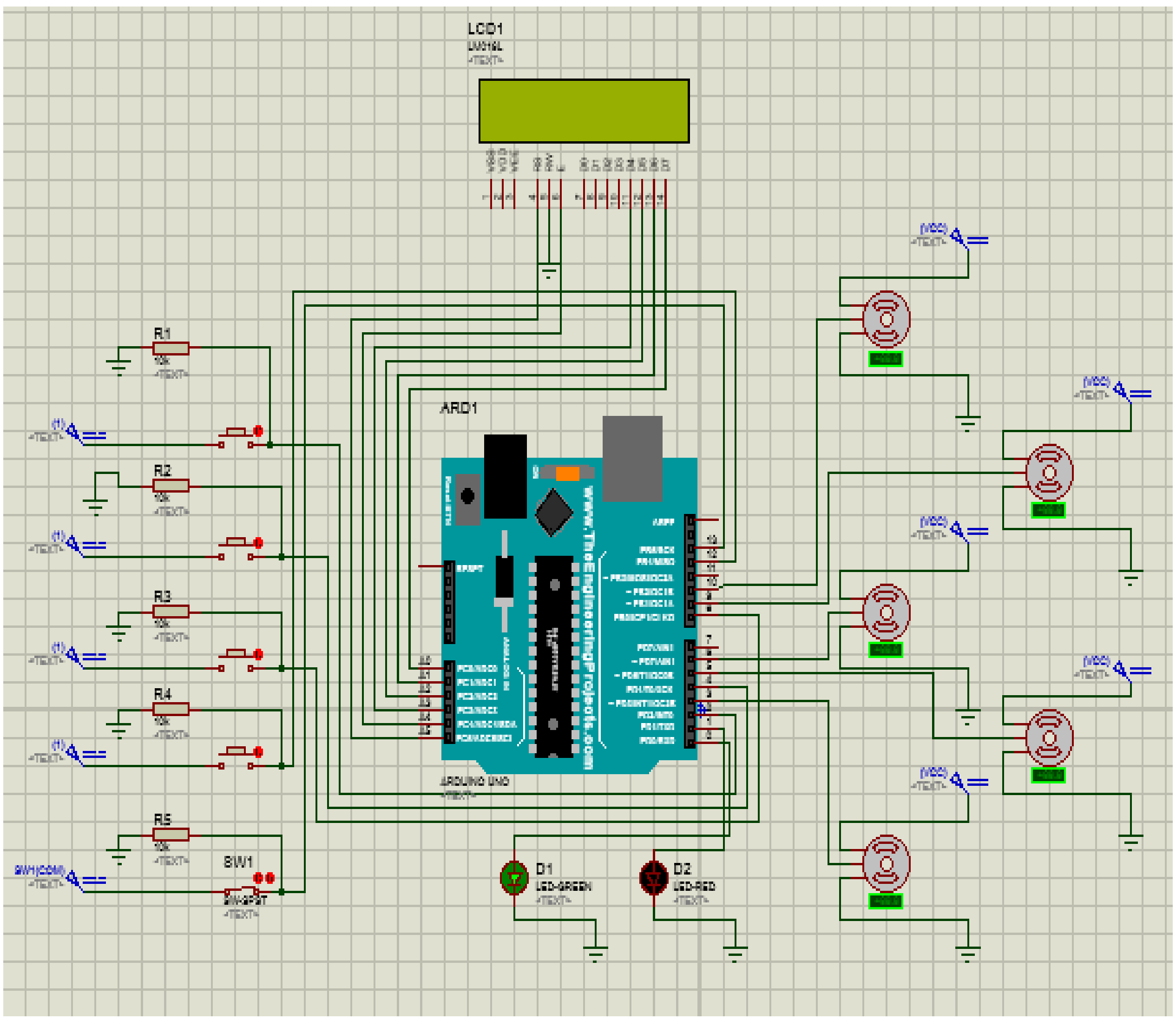


Figure 3.32: PROTEUS Simulation of Robotic arm for physiotherapy.

3.8 COST ANALYSIS

Evaluating a set of feasible alternatives requires that costs should be analysed so that we can estimate the cost of a product.

Cost estimation of a machine includes

- ✓ Material cost
- ✓ Direct labor cost
- ✓ Overhead cost and others (machine cost and transportation cost)

Note: Manufacturing overhead costs include indirect materials and indirect labor costs like materials used to support the production process and wages paid not directly involved in production work.

Now we can calculate the cost of the machine components as follows;

3.8.1 The cost estimation of selected components

Component type	Model	Quantity	Unit price(ETB)	Total Cost(ETB)
Dc servo motor	RHS-25-3012	5	2800	14000
Force torque sensor	PD3-32-05-080	3	5400	16200
push button switch	COM-09190	5	80	400
Incremental encoder	E100DO	5	1250	6250
PID controller	--------	1	200	200
Arduino Microcontroller	ATmega168	1	500	500
LED	-------	2	75	150
Liquid crystal display	--------	1	250	250
Programing development	-------	------	12000	12000
Total cost = 49950 ETB				

3.8.2 The cost estimation of designed components

1) Forearm link

Material; Al alloy 1100(0 temper)

Quantity = 1

$$\text{Volume } = \text{l} \times \text{w} \times \text{t} = 255.5 * 60 * 25 = \ 383250 \text{ mm3}$$

$$\text{Unit mass } = \ \rho * \text{V} = 383250 * 2.71 * 10^{\wedge} - 6 \text{ Kg/mm3} = \ 1.0386 \text{ Kg}$$

Unit price = 900 birr/kg

$$\text{Material cost } = \text{quantity} \times \text{unit mass} \times \text{unit price} = 1 * 1.0386 * 900$$
$$= 934.74 \text{ Birr}$$

Manufacturing process; Casting & machining

Direct labor cost/hour = 12 birr

Total hours required = 42 hours

$$\text{Total labor cost } = \text{quantity} \times \text{total hours required} \times \text{Direct labor} \frac{\text{cost}}{\text{hour}}$$
$$= 1 * 42 * 12 = 504\text{Birr}$$

Overhead cost/hour = 75 birr

$$\text{Total overhead cost } = \text{ quantity} \times \text{total hours required} \times \text{Overhead} \frac{\text{cost}}{\text{hour}}$$
$$= 1 \times 42 \times 75 = 3150 \text{ Birr}$$
$$\text{Total cost } = \text{ Material cost } + \text{ Total labor cost } + \text{ total overhead cost}$$
$$= 934.74 * 504 * 3150 = 4588.74 \text{ Birr}$$

2) Upper arm link

Material; Al alloy 1100(0 temper)

Quantity = 1

$$\text{Volume } = L * W * t = 325.5 * 60 * 25 = 488250 \text{ mm3}$$
$$\text{Unit mass } = \rho * V = 488250 * 2.71 * 10\text{\^{}} - 6 \text{ Kg/mm3} = 1.323 \text{ Kg}$$

Unit price = 900 Birr/kg

$$\text{Material cost } = \text{quantity} \times \text{unit mass} \times \text{unit price} = 1 * 900 * 1.323 = 1190.7 \text{ Birr}$$

Manufacturing process; Casting & machining

Direct labor cost/hour = 12 birr

Total hours required = 42 hours

$$\text{Total labor cost } = \text{quantity} \times \text{total hours required} \times \text{Direct labor} \frac{\text{cost}}{\text{hour}}$$
$$= 1 * 42 * 12$$
$$\text{Total labor cost } = 504 \text{ Birr}$$

Overhead cost/hour = 75 birr

$$\text{Total overhead cost } = \text{ quantity} \times \text{total hours required} \times \text{Overhead} \frac{\text{cost}}{\text{hour}}$$
$$= 75 \times 1 \times 42 = 3150 \text{ Birr}$$

$$\text{Total cost} = \text{Material cost} + \text{Total labor cost} + \text{total overhead cost}$$

$$= 1190.7 + 504 + 3150 = 4844.7 \text{ Birr}$$

3) Hollow rectangular bar

Material; Steel alloy A36

Quantity = 2

Volume = 280 * 70 * 70 – 280 * 40 * 40 = 924000 mm3

Unit mass = $\rho * V = 7.85 * 10$ ^ $- 6$ * 924000 = 7.25 kg

Unit price = 40 Birr

$$\text{Material cost} = \text{quantity} \times \text{unit mass} \times \text{unit price} = 2 * 7.25 * 40 = 580 \text{ Birr}$$

Manufacturing process; Casting & machining

Direct labor cost/hour = 20 birr

Total hours required = 26 hours

$$\text{Total labor cost} = \text{quantity} \times \text{total hours required} \times \text{Direct labor cost/hour}$$

$$= 2 * 26 * 20 = 1040 \text{ Birr}$$

Overhead cost/hour = 40 birr

$$\text{Total overhead cost} = \text{quantity} \times \text{total hours required} \times \text{Overhead} \frac{\text{cost}}{\text{hour}}$$

$$= 2 * 26 * 40 = 2080 \text{ Birr}$$

$$\text{Total cost} = \text{Material cost} + \text{Total labor cost} + \text{total overhead cost}$$

$$= 290 + 2080 + 1040 = 3700 \text{ Birr}$$

4) Shoulder link and palm link

Material; Al alloy 1100(0 temper)

Quantity = 1

$$\text{Volume} = l \times w \times t = 255.5 * 60 * 25 = 383250 \text{ mm3}$$

$$\text{Unit mass} = \rho * V = 383250 * 2.71 * 10\text{^} - 6 \text{ Kg/mm3} = 1.0386 \text{ Kg}$$

Unit price = 900 birr/kg

$$\text{Material cost} = \text{quantity} \times \text{unit mass} \times \text{unit price} = 1 * 1.0386 * 900$$

$$= 934.74 \text{ Birr}$$

Manufacturing process; Casting & machining

Direct labor cost/hour = 15 birr

Total hours required = 42 hours

$$\text{Total labor cost} \ = \text{quantity} \times \text{total hours required} \times \text{Direct labor} \frac{\text{cost}}{\text{hour}}$$

$$= 1 * 42 * 15 = 630 \text{ Birr}$$

Overhead cost/hour = 75 birr

$$\text{Total overhead cost} \ = \ \text{quantity} \times \text{total hours required} \times \text{Overhead} \frac{\text{cost}}{\text{hour}}$$

$$= 1 \times 42 \times 75 = 3150 \text{ Birr}$$

$$\text{Total cost} \ = \ \text{Material cost} \ + \ \text{Total labor cost} \ + \ \text{total overhead cost}$$

$$= \ 934.74 \ * \ 630 \ * \ 3150 \ = \ 4714.74 \text{ Birr}$$

5) hollow square stand

Material; Steel alloy A36

Quantity = 1

$$\text{Volume} \ = \ 1200 \ * \ 60 \ * \ 60 - 1200 \ * \ 50 \ * \ 50 \ = \ 1320000 \text{ mm3}$$

$$\text{Unit mass} \ = \ \rho \ * \text{V} = 7.85 * 10 \wedge - 6 \ * \ 1320000 \ = \ 10.362 \text{ kg}$$

Unit price = 40 Birr

$$\text{Material cost} \ = \text{quantity} \times \text{unit mass} \times \text{unit price} = 1 * 10.362 * 40 = \ 414.48 \text{ Birr}$$

Manufacturing process; Casting & machining

Direct labor cost/hour = 20 birr

Total hours required = 28 hours

$$\text{Total labor cost} \ = \text{quantity} \times \text{total hours required} \times \text{Direct labor} \frac{\text{cost}}{\text{hour}}$$

$$= \ 1 \ * \ 28 \ * \ 20 \ = \ 560 \text{ Birr}$$

Overhead cost/hour = 40 birr

$$\text{Total overhead cost} \ = \ \text{quantity} \times \text{total hours required} \times \text{Overhead} \frac{\text{cost}}{\text{hour}}$$

$$= 1 * \ 28 * \ 40 = 1120 \ Birr$$

$$\text{Total cost} \ = \ \text{Material cost} \ + \ \text{Total labor cost} \ + \ \text{total overhead cost}$$

$$= \ 414.48 \ + \ 560 \ + \ 1120 \ = \ 2094.48 \text{ Birr}$$

6) pins

Material; Steel alloy A36 (Hot rolled)

Quantity = 3

$$\text{Volume} \ = \ \pi r^2 \ * \text{l} \ = \ \pi * 10^2 * 70 = \ 21980 \text{ mm3}$$

$$\text{Unit mass} \ = \ \rho \ * \text{V} = 7.85 * 10 \wedge - 6 \ * \ 21980 \ = \ 0.173 \text{ g}$$

Unit price = 40 Birr

$$\text{Material cost} = \text{quantity} \times \text{unit mass} \times \text{unit price} = 3 * 0.173 * 40 = 20.76 \text{ Birr}$$

Manufacturing process; Casting & machining

Direct labor cost/hour = 20 birr

Total hours required = 3 hours

$$\text{Total labor cost} = \text{quantity} \times \text{total hours required} \times \text{Direct labor} \frac{\text{cost}}{\text{hour}} = 3 * 20 * 3$$

$$= 120 \text{ Birr}$$

Overhead cost/hour = 40 birr

$$\text{Total overhead cost} = \text{quantity} \times \text{total hours required} \times \text{Overhead} \frac{\text{cost}}{\text{hour}}$$

$$= 3 * 3 * 40 = 240 \text{ BIrr}$$

$$\text{Total cost} = \text{Material cost} + \text{Total labor cost} + \text{total overhead cost}$$

$$= 20.76 + 120 + 240 = 380.76 \text{ Birr}$$

7) Spur gear

Material; alloy steel 1020: Hot rolled

Quantity = 10

Pressure angle on gear φ =20°

Number of teeth of the gear $Z = 20$

Face width $b = 45\text{mm}$

Module $m = 3\text{mm}$

Number of gears $n = 1$

Weight of the gears

$$W_1 = 0.00118 n.Z.b.m^2$$

$$= 0.00118 \times 1 \times 20 \times 45 \times 3^2 = 9.56\, N$$

Unit mass = 0.956 kg

Unit price = 40

$$\text{Material cost} = \text{quantity} \times \text{unit mass} \times \text{unit price} = 10 * 0.956 * 40 = 382.4 \text{ Birr}$$

Manufacturing process; Casting & Finishing process

Direct labor cost/hour = 20 birr

Total hours required = 7hours

$$\text{Total labor cost} = \text{quantity} \times \text{total hours required} \times \text{Direct labor} \frac{\text{cost}}{\text{hour}}$$

$$= 10 * 7 * 20 = 1400$$

Overhead cost/hour = 40 birr

$$\text{Total overhead cost} = \text{quantity} \times \text{total hours required} \times \text{Overhead} \frac{\text{cost}}{\text{hour}}$$

$$= 10 * 7 * 40 = 2800$$

$$\text{Total cost} = \text{Material cost} + \text{Total labor cost} + \text{total overhead cost}$$

$$= 382.4 + 1400 + 2800 = 3182.4 \text{ Birr}$$

8) Contact Ball Bearing

Quantity = 5

Unit price = 120 Birr

$$\text{Total cost} = \text{quantity} * \text{unit price} = 5 * 120 = 600 \text{ birr}$$

9) Key for shaft

Material; alloy steel 1020: Hot rolled

Quantity = 1

$$\text{Volume} = L * W * t = 45 * 10 * 8 = = \pi * 10^2 * 70 = 3600 \text{ mm3}$$

$$\text{Unit mass} = \rho * V = 7.85 * 10 \wedge -6 * 3600 = 0.02826 \text{ Kg}$$

Unit price = 40 birr /kg

$$\text{Material cost} = \text{quantity} \times \text{unit mass} \times \text{unit price} = 11.304 \text{ birr}$$

Manufacturing process; Cutting and milling operations

Direct labor cost/hour = 20 birr

Overhead cost/hour = 40 birr

Total hours required = 0.5 hours

$$\text{Total labor cost} = 1 \times 0.5 \times 20 = 10 \text{ birr}$$

$$\text{Total overhead cost} = \text{quantity} \times \text{total hours required} \times \text{Overhead} \frac{\text{cost}}{\text{hour}}$$

$$= 1 \times 0.5 \times 40 = 20 \text{ birr}$$

$$\text{Total cost} = \text{Material cost} + \text{Total labor cost} + \text{Overhead cost} =$$

$$= 11.304 + 10 + 20 = 41.304 \text{ Birr}$$

Total cost of the Designed robot arm parts = 20447.124 ETB

Total cost of the proposed robot arm = 49950+20447.124 = 70397.124 ETB

CHAPTER FOUR

4 RESULT AND DISCUSSION

4.1 RESULT

Part no.	Components	Qty.	Result	Function and Assembly Procedure
1.	Microcontroller (Arduino Uno)	1	Operating voltage=5V	Used to control the whole operation of the robot using the code programmed. Connected to the battery to get power and all motors, sensors and LCD connected with it.
2.	Liquid crystal display(LCD)	1	size =16×2 (columns×row)	Uses to display the status of the robot in order to understand the programming well for the user.
3	Dc servo motors	5	123 watt RHS-25-3012 servo motors	The motorsare to rotate the shaft.The motors are electrically connected with Arduino to run automatically based on the programming.
4	Force torque sensor	3	PD3-32-05-080 Input voltage[V]=3-5	The force torque sensor used to detect force and torque applied by the patient so that the sensor detect the force and it gives a signal to the microcontroller

5	Motor Encoder	1	E100DO incremental encoder with Input voltage: DC 5V-12V	Encoder helps us to determine how much motor has moved from its original position.
6	PID CONTROLLER	1	Kp=9618.5858 Ki=283143.0651 Kd=35.1632	PID used to precisely control the DC Servo motors.
7	Shaft	5	d_s= 25 mm L =100 mm	Used to transfer power from servo motor to links
8	Contact ball bearing	5	Do = 52 mm bore = 25 mm W = 15 mm	Force fitted to the shaft and used to rotate the shaft
9	Key	5	W = 10 mm t = 8 mm	used to connect the shaft with the motor
10	Forearm link	1	h = 20mm b = 10 mm	Force fitted to the shaft and enable for flexion/extension of the forearm
11	Upper arm link	1	b = 140mm h = 23 mm	Mounted with the shoulder link enables for adduction/abduction of the upper arm
12	hollow rectangular bars 1	1	t = 5cm H = 7cm	Mounted with the Hollow rectangular bar
13	hollow square stand	1	h 1= 5 cm b = 6 cm	Welded with the hollow square stand
14	Pins	3	Di = 8 mm Do = 10 mm Pitch = 2 mm	This pin is used to connect the 2 vertical beams (stand) and also used for adjusting the length of the stand.

4.2 DISCUSSION

The expected result (output) is a fully functional, compact, safe and economical robot arm for physiotherapy. Hence it is important what the results of the analysis really are.The above results show the mechanical design analysis and software development of PID based robot arm for physiotherapy. In each case the output is shown. The result of each case can be described as follows.

- ✓ A forward kinematic analysis was conducted to describe the position and orientation of a link in space. Finally, the robotic arm requires a space 1162 mm, 581 mm and 581 mm in x, y and z-direction respectively.
- ✓ Analysis of the design proofs that every component is safe from failure and the indication that we can proceed to testing and manufacturing.
- ✓ The motor selection is based on the maximum power and torque required to move the links to the required angle and the selected motor have T = 46.48 Nm, p = 123 W.
- ✓ The designed PID controller has a great role in enhance the system performance by reducing step response, over shoot error of each DC Servo motors as we can see on the graph simulated using Mat-lab.
- ✓ Total cost estimation of the designed robot is 80347.124 ETB. The current cost of the other 5 DOF robot arm that are available in the market is estimated from $4,000 - $6,000 (excluding tax). So compared to other 5DOF robots this robot have a low cost.

CHAPTERFIVE

5 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The main goal of this thesis is to model, design and analysis of a 5 DOF robotic arm for rehabilitation purpose. The robotic arm structure, designed as a rectangular link made of an aluminum metal. The position and orientation of the robotic arm obtained with the help of forward kinematic analysis. Mechanical design performed to analysis and verify the ability of the mechanical parts whether or not withstand the loads applied on the system.

Having the design completed, the whole project report shall be concluded by forwarding the following points.

- ✓ Project Objectives and literature review are discussed clearly; which means one can get all the input and subordinate things to PID based Robot arm for physiotherapy.
- ✓ Design of the robot was fully explained including the mechanism and mechanical design of each parts, material needed like actuators and sensors, the control mechanism using PID and the appropriate C++ Arduino program.
- ✓ One surely can say that the design outputs have generally been illustrated more after having investigation on the different part drawings of each component.
- ✓ As long as the machine is able to treat the patients by itself after it has been switched on, the doctor will have much extra time to complete other tasks. Furthermore, using this machine an increased number of patients will be treated in a short period of time.
- ✓ Understanding the basic concepts on design of this PID based Robot arm for physiotherapy allows to manufacture the machine locally with a low cost of production and to extend development of new system.

5.2 RECOMMENDATION

Finally the following points are found remarkable to be recommended.

- ✓ Only a physiotherapist can use this machine to treat patients to turn on and to receive the patient response during the training and it requires carefully attachment of patient arm with the robot.
- ✓ The patient who take the rehabilitation using this machine should be within the range of the assumed parameters that is:

- Weight: Up 100Kg andHeight: 1.35m-190m

- ✓ The robot is 5-DOF but in the daily activities of upper-limb, shoulder supination/pronation and wrist ulnar deviation/radial devotionare very important. Therefore, it is vital to add those motion assist mechanism for the robot. However, when adding another several DOF for the robot the mechanical design will be more complex. Therefore, with the increasing of DOF, design optimization should also be carried out carefully.
- ✓ This system need more advance software to perform and to be more enjoyable by the patients like developing a human-machine interface for the control system.
- ✓ Considering the need of the machine in our country locality the machine should be manufactured for further studies.

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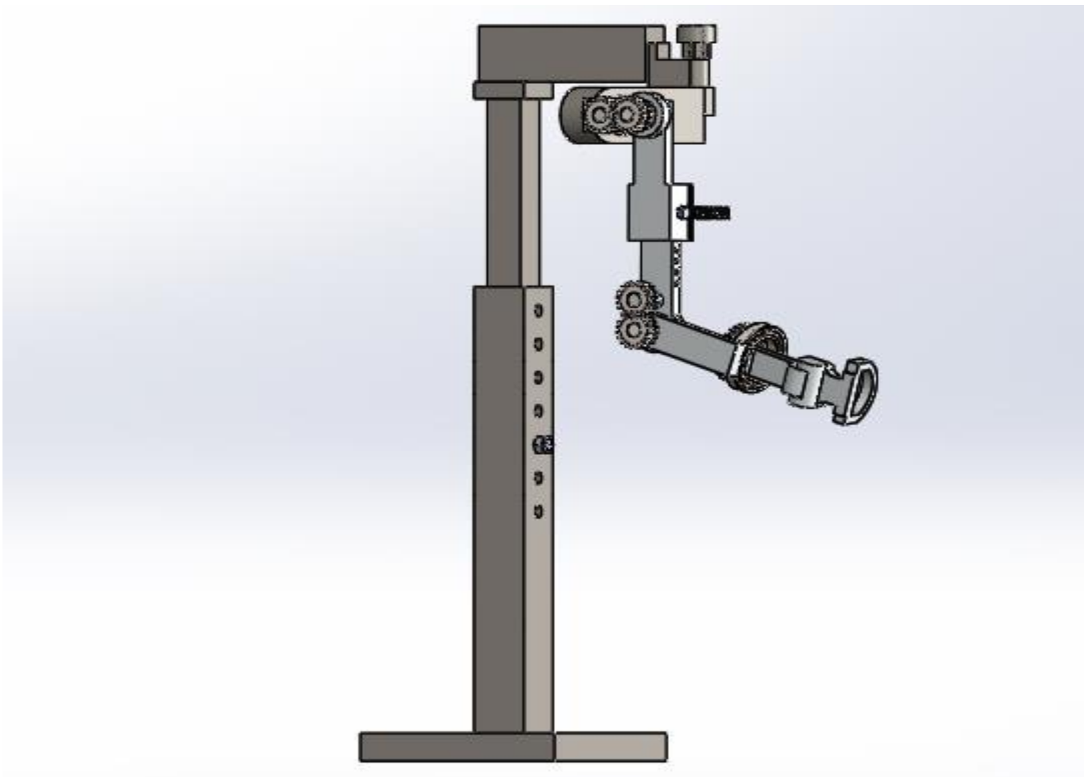
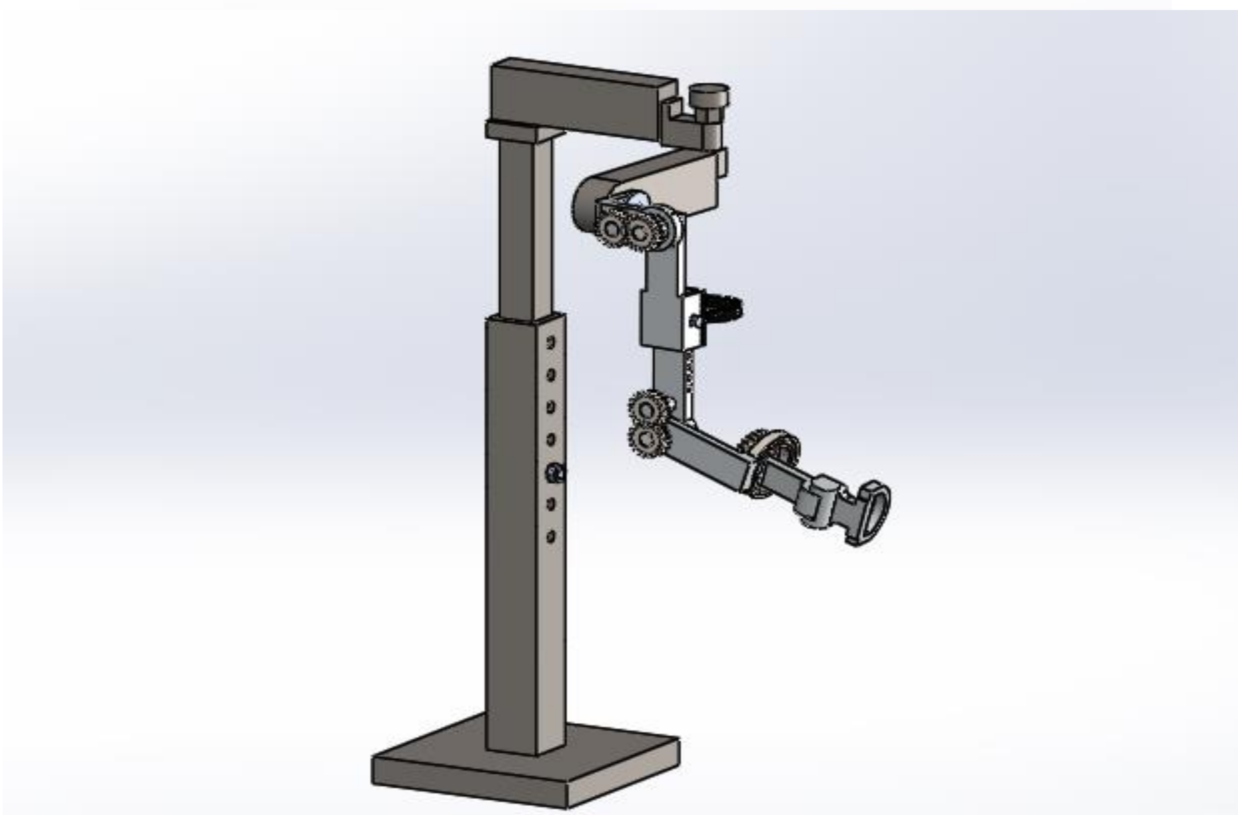
APPENDICES

APPENDIX A: 3D MODEL OF THE ROBOT ARM





APPENDIX B: Arduino code for controlling robot arm for physiotherapy.

THERAPY | Arduino 1.8.5

File Edit Sketch Tools Help

THERAPY

```
/*
*******************************************************************
               ----------MEKELLE UNIVERSITY------------
                              EiT-M

           SCHOOLL OF MECHAICAL AND INDUSTRIAL ENGINEERING
                DEPARTMENT OF MECHANICAL ENGINEERING

          TITLE: PID CONTROLLED ROBOTIC ARM FOR PHYSIOTHERAPY

PRPAIRED BY: 1.FISEHA YISAK
             2.NATNAEL H/MESSKEL
             3.SAMUEL H/MARIAM

                           ADVISOR:INS. SIRAK A.(MSc)
*******************************************************************
 */

#include <Servo.h>

Servo myservo1;  // create servo object to control a servo
Servo myservo2;
Servo myservo3;
Servo myservo4;
Servo myservo5;
// twelve servo objects can be created on most boards
int red = 1;
int green = 0;
int pos = 0;    // variable to store the servo position
const int buttonPin1 = 2;     // the number of the pushbutton pin
const int buttonPin2 = 4;
const int buttonPin3 = 8;
const int buttonPin4 = 12;
const int buttonPinE = 13;

int buttonState1 = 0;         // variable for reading the pushbutton-1 status
int buttonState2 = 0;         // variable for reading the pushbutton-2 status
int buttonState3 = 0;         // variable for reading the pushbutton-3 status
int buttonState4 = 0;         // variable for reading the pushbutton-4 status
int buttonStateE = 0; // variable for reading the emergency pushbutton status
#include <LiquidCrystal.h> //including Liquid crystal library
```

Done compiling.

THERAPY | Arduino 1.8.5

File Edit Sketch Tools Help

THERAPY §

```
LiquidCrystal lcd(A5,A4,A3,A2,A1,A0); //Pin onnection of LCD microcontroller

void setup() {
        lcd.begin(16,2);
    lcd.print("Robotict arm for"); //dispalaying on LCD"1st Week Th
    lcd.setCursor(0,1);
    lcd.print("-Physiotherapy-");

  myservo1.attach(3);  // attaches the servo on pin 9 to the servo object
  myservo2.attach(5);
  myservo3.attach(6);
  myservo4.attach(9);
  myservo5.attach(10);
 // initialize the pushbutton pin as an input:
  pinMode(buttonPin1, INPUT);
  pinMode(buttonPin2, INPUT);
  pinMode(buttonPin3, INPUT);
  pinMode(buttonPin4, INPUT);
  pinMode(buttonPinE, INPUT);
  pinMode(red, OUTPUT);
  pinMode(green, OUTPUT);
}

void loop() {
   // read the state of the pushbutton value:
  buttonState1 = digitalRead(buttonPin1);
  buttonState2 = digitalRead(buttonPin2);
  buttonState3 = digitalRead(buttonPin3);
  buttonState4 = digitalRead(buttonPin4);
  buttonStateE = digitalRead(buttonPinE);

  // check if the pushbutton is pressed. If it is, the buttonState is HIGH:
  if (buttonState1 == HIGH && buttonState2 == LOW && buttonState3 == LOW &&
  buttonState4 == LOW && buttonStateE == LOW) {
    lcd.begin(16,2);
    lcd.print("1st Week Therapy"); //dispalaying on LCD"1st Week Therapy"
    digitalWrite(green,HIGH);
    digitalWrite(red,LOW);
 for (int i = 0; i <= 3; i+=1){
    if (buttonStateE == LOW){   lcd.begin(16,2);
    lcd.print("1st Week Therapy");
```

Done compiling.

THERAPY | Arduino 1.8.5

File Edit Sketch Tools Help

THERAPY §

```
    lcd.setCursor(0,1);
    lcd.print("Palm flexion");
    }
  for (pos = 0; pos <= 115; pos += 1) { //goes from 0 degrees to 115 degrees
    // in steps of 1 degree

     buttonStateE = digitalRead(buttonPinE);
    if (buttonStateE == LOW){
    myservo1.write(pos);    //tell servo to go to position in variable 'pos'
    delay(5);               // waits 5ms for the servo to reach the position
   }
  }
  if (buttonStateE == LOW){
            lcd.begin(16,2);
    lcd.print("1st Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Palm extension");
  }
  for (pos = 115; pos >= 0; pos -= 1) { // goes from 115 degrees to 0 degrees
    buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){

    myservo1.write(pos);      // tell servo to go to position in variable 'pos'
    delay(5);                // waits 5ms for the servo to reach the position
  }
 }
 }
     for (int i = 0; i <= 3; i+=1){
   if (buttonStateE == LOW){
            lcd.begin(16,2);
    lcd.print("1st Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Elbow Pronatin");
   }
  for (pos = 0; pos <= 130; pos += 1) { // goes from 0 degrees to 130 degrees
    // in steps of 1 degree
     buttonStateE = digitalRead(buttonPinE);
    if (buttonStateE == LOW){
    myservo2.write(pos);       // tell servo to go to position in variable 'pos'
    delay(5);                  // waits 5ms for the servo to reach the position
   }
```

Done compiling.

THERAPY | Arduino 1.8.5

File Edit Sketch Tools Help

THERAPY §

```
    }
  }
    if (buttonStateE == LOW){
            lcd.begin(16,2);
    lcd.print("1st Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Elbow Supination");
    }
  for (pos = 130; pos >= 0; pos -= 1) { // goes from 130 degrees to 0 degrees
    buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
    myservo2.write(pos);      // tell servo to go to position in variable 'pos'
    delay(5);                 // waits 5ms for the servo to reach the position
  }
 }
 }
      for (int i = 0; i <= 3; i+=1){
    if (buttonStateE == LOW){
    lcd.begin(16,2);
    lcd.print("1st Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Elbow flexion");
    }
  for (pos = 0; pos <= 90; pos += 1) { // goes from 0 degrees to 90 degrees
    // in steps of 1 degree
     buttonStateE = digitalRead(buttonPinE);
    if (buttonStateE == LOW){
    myservo3.write(pos);     // tell servo to go to position in variable 'pos'
    delay(5);               // waits 55ms for the servo to reach the position
   }
  }
  if (buttonStateE == LOW){
    lcd.begin(16,2);
    lcd.print("1st Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Elbow Extension");
  }
  for (pos = 90; pos >= 0; pos -= 1) { // goes from 90 degrees to 0 degrees
    buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
    myservo3.write(pos);     // tell servo to go to position in variable 'pos'
```

Done compiling.

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File Edit Sketch Tools Help

THERAPY §

```
     delay(5);           // waits 5ms for the servo to reach the position
   }
  }
  }
       for (int i = 0; i <= 3; i+=1){
                   lcd.begin(16,2);
    if (buttonStateE == LOW){
     lcd.print("1st Week Therapy");
     lcd.setCursor(0,1);
     lcd.print("Shoulder flexion");
    }
   for (pos = 0; pos <= 110; pos += 1) { //goes from 0 degrees to 110 degrees
     // in steps of 1 degree
      buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
     myservo4.write(pos);    // tell servo to go to position in variable 'pos'
     delay(5);               // waits 5ms for the servo to reach the position
    }
   }
   if (buttonStateE == LOW){
   lcd.begin(16,2);
     lcd.print("1st Week Therapy");
     lcd.setCursor(0,1);
     lcd.print("Shoulder extension");
   }
   for (pos = 110; pos >= 0; pos -= 1) {//goes from 110 degrees to 0 degrees
     buttonStateE = digitalRead(buttonPinE);
      if (buttonStateE == LOW){
     myservo4.write(pos);     //tell servo to go to position in variable 'pos'
     delay(5);               // waits 5ms for the servo to reach the position
   }
  }
  }
  for (int i = 0; i <= 3; i+=1){
   if (buttonStateE == LOW){
     lcd.begin(16,2);
     lcd.print("1st Week Therapy");
     lcd.setCursor(0,1);
     lcd.print("Shoulder adduction");
   }
   for (pos = 0; pos <= 60; pos += 1) {//goes from 0 degrees to 60 degrees
```

Done compiling.

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THERAPY §

```
    // in steps of 1 degree
     buttonStateE = digitalRead(buttonPinE);
    if (buttonStateE == LOW){
    myservo5.write(pos);   // tell servo to go to position in variable 'pos'
    delay(5);             // waits 5ms for the servo to reach the position
   }
  }
   if (buttonStateE == LOW){
    lcd.begin(16,2);
    lcd.print("1st Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Shoulder abduction");
    }
  for (pos = 60; pos >= 0; pos -= 1) { // goes from 60 degrees to 0 degrees
    buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
    myservo5.write(pos);   // tell servo to go to position in variable 'pos'
    delay(5);              // waits 5ms for the servo to reach the position
  }
 }
 }
   }
  buttonState1 = digitalRead(buttonPin1);
  buttonState2 = digitalRead(buttonPin2);
  buttonState3 = digitalRead(buttonPin3);
  buttonState4 = digitalRead(buttonPin4);
  buttonStateE = digitalRead(buttonPinE);
 if (buttonState2 == HIGH && buttonState1 == LOW && buttonState3 == LOW &&
 buttonState4 == LOW && buttonStateE == LOW) {
    digitalWrite(green,HIGH);
    digitalWrite(red,LOW);
    for (int i = 0; i <= 3; i+=1){
    if (buttonStateE == LOW){
    lcd.begin(16,2);
    lcd.print("2nd Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Palm flexion");
    }
  for (pos = 0; pos <= 125; pos += 1) { //goes from 0 degrees to 125 degrees
    // in steps of 1 degree
     buttonStateE = digitalRead(buttonPinE);
```

Done compiling.

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THERAPY §

```
    if (buttonStateE == LOW){
    myservo1.write(pos);  // tell servo to go to position in variable 'pos'
    delay(4);             // waits 4ms for the servo to reach the position
   }
  }
  if (buttonStateE == LOW){
    lcd.begin(16,2);
    lcd.print("2nd Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Palm extension");
  }
  for (pos = 125; pos >= 0; pos -= 1) {//goes from 125 degrees to 0 degrees
    buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
    myservo1.write(pos);   // tell servo to go to position in variable 'pos'
    delay(4);             // waits 4ms for the servo to reach the position
  }
 }
 }
  for (int i = 0; i <= 3; i+=1){
   if (buttonStateE == LOW){
    lcd.begin(16,2);
    lcd.print("2nd Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Elbow pronation ");
   }
  for (pos = 0; pos <= 145; pos += 1) {//goes from 0 degrees to 145 degrees
    // in steps of 1 degree
     buttonStateE = digitalRead(buttonPinE);
    if (buttonStateE == LOW){
    myservo2.write(pos);  // tell servo to go to position in variable 'pos'
    delay(4);              // waits 4ms for the servo to reach the position
   }
  }
  if (buttonStateE == LOW){
          lcd.begin(16,2);
        lcd.print("2nd Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Elbow supination ");
  }
  for (pos = 145; pos >= 0; pos -= 1) {//goes from 145 degrees to 0 degrees
```

Done compiling.

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THERAPY §

```
    buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
    myservo2.write(pos);   // tell servo to go to position in variable 'pos'
    delay(4);              // waits 4ms for the servo to reach the position
  }
 }
 }
 for (int i = 0; i <= 3; i+=1){
   if (buttonStateE == LOW){
    lcd.begin(16,2);
    lcd.print("2nd Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Elbow flexion ");
     }
  for (pos = 0; pos <= 100; pos += 1) {//goes from 0 degrees to 100 degrees
    // in steps of 1 degree
     buttonStateE = digitalRead(buttonPinE);
    if (buttonStateE == LOW){
    myservo3.write(pos);   // tell servo to go to position in variable 'pos'
    delay(4);              // waits 4ms for the servo to reach the position
   }
  }
      if (buttonStateE == LOW){
          lcd.begin(16,2);
        lcd.print("2nd Week Therapy");
    lcd.setCursor(0,1);
    lcd.print("Elbow extension ");
      }
  for (pos = 100; pos >= 0; pos -= 1) {//goes from 100 degrees to 0 degrees
    buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
    myservo3.write(pos);  // tell servo to go to position in variable 'pos'
    delay(4);             // waits 4ms for the servo to reach the position
  }
 }
 }
      for (int i = 0; i <= 3; i+=1){
       if (buttonStateE == LOW){
              lcd.begin(16,2);
        lcd.print("2nd Week Therapy");
    lcd.setCursor(0,1);
```

Done compiling.

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THERAPY §

```
    ;
  }
   for (int i = 0; i <= 3; i+=1){
    if (buttonStateE == LOW){
     lcd.begin(16,2);
     lcd.print("3rd Week Therapy");
     lcd.setCursor(0,1);
     lcd.print("Elbow Pronation");
    }
   for (pos = 0; pos <= 155; pos += 1) {//goes from 0 degrees to 155 degrees
     // in steps of 1 degree
      buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
     myservo2.write(pos);  // tell servo to go to position in variable 'pos'
     delay(3);             // waits 3ms for the servo to reach the position
    }
   }
   if (buttonStateE == LOW){
     lcd.begin(16,2);
     lcd.print("3rd Week Therapy");
     lcd.setCursor(0,1);
     lcd.print("Elbow Supination");
   }
   for (pos = 155; pos >= 0; pos -= 1) {//goes from 155 degrees to 0 degrees
     buttonStateE = digitalRead(buttonPinE);
      if (buttonStateE == LOW){
     myservo2.write(pos);   // tell servo to go to position in variable 'pos'
     delay(3);              // waits 3ms for the servo to reach the position
    }
   }
  }
   for (int i = 0; i <= 3; i+=1){
     if (buttonStateE == LOW){
     lcd.begin(16,2);
     lcd.print("3rd Week Therapy");
     lcd.setCursor(0,1);
     lcd.print("Elbow flexion");
     }
   for (pos = 0; pos <= 110; pos += 1) {//goes from 0 degrees to 110 degrees
     // in steps of 1 degree
      buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
```

Done compiling.

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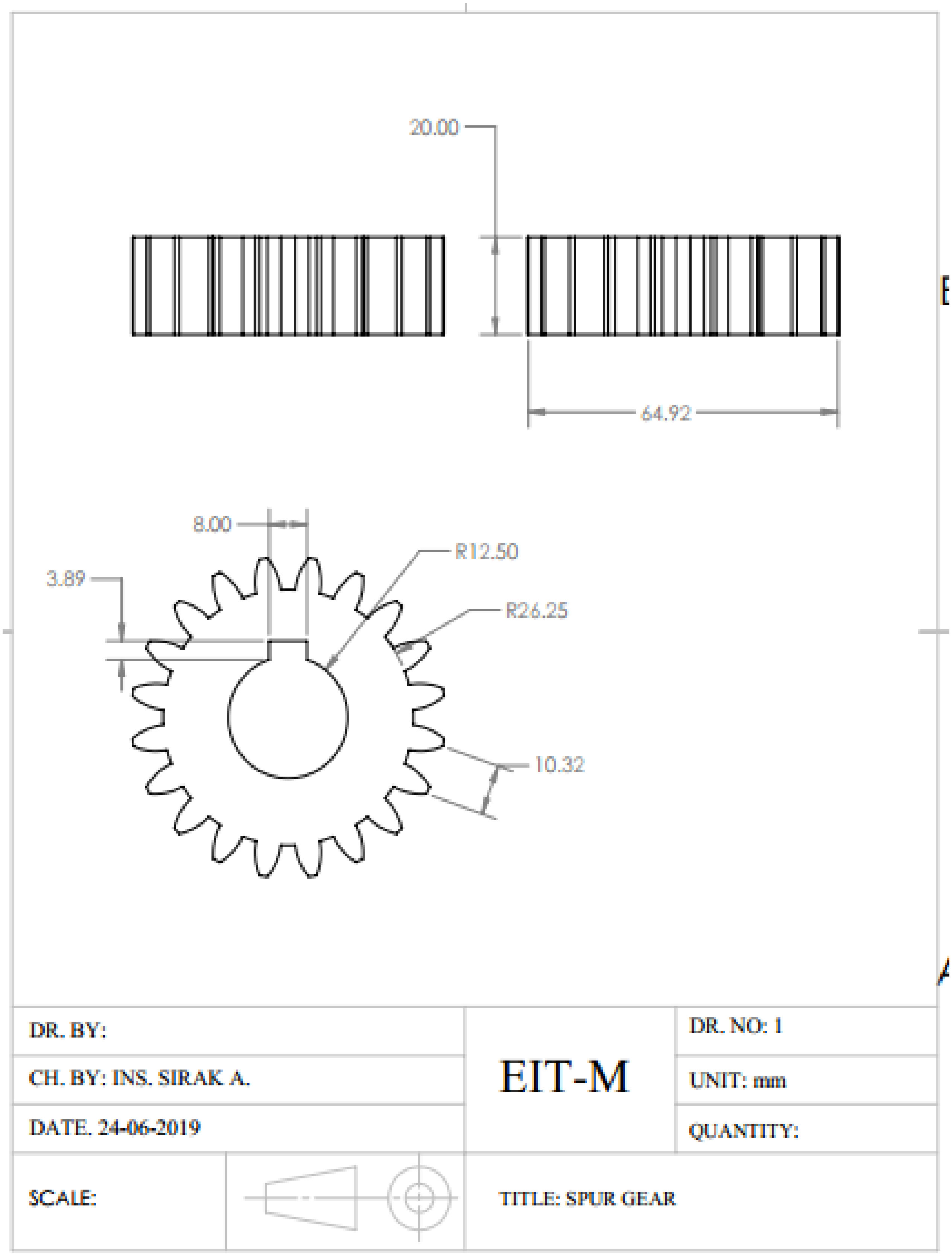
File Edit Sketch Tools Help

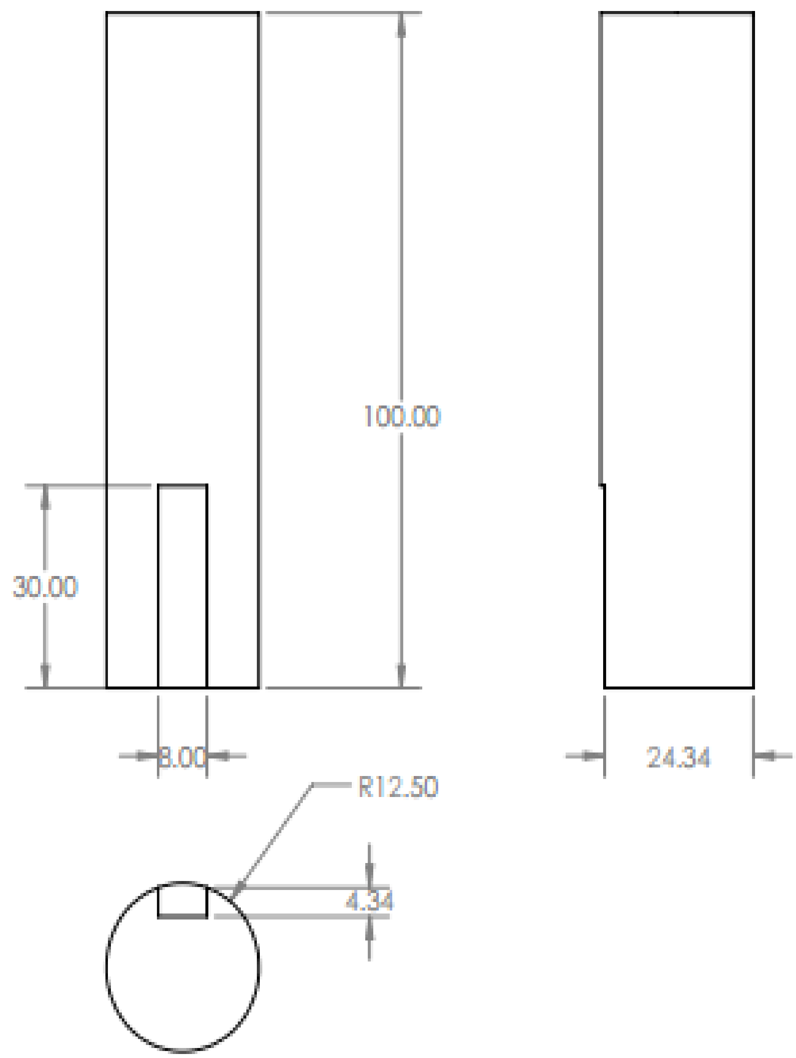
THERAPY §

```
     lcd.print("Shoulder adduction");
    }
   for (pos = 0; pos <= 90; pos += 1) {//goes from 0 degrees to 90 degrees
     // in steps of 1 degree
      buttonStateE = digitalRead(buttonPinE);
     if (buttonStateE == LOW){
     myservo5.write(pos); // tell servo to go to position in variable 'pos'
     delay(2);            // waits 2ms for the servo to reach the position
    }
   }
   if (buttonStateE == LOW){
     lcd.begin(16,2);
     lcd.print("4th Week Therapy");
     lcd.setCursor(0,1);
     lcd.print("Shoulder abduction");
   }
   for (pos = 90; pos >= 0; pos -= 1) {//goes from 90 degrees to 0 degrees
     buttonStateE = digitalRead(buttonPinE);
      if (buttonStateE == LOW){
     myservo5.write(pos);  // tell servo to go to position in variable 'pos'
     delay(2);              // waits 2ms for the servo to reach the position
     }
    }
   }
 }
    else{
         digitalWrite(green,LOW);
          }
  if (buttonStateE == HIGH){
       digitalWrite(red,HIGH);
         lcd.begin(16,2);
         lcd.print("----stopped----");
   delay(15);
       digitalWrite(red,HIGH);
    }
   else {
    digitalWrite(green,LOW);
    digitalWrite(red,LOW);
   }
 }
```

Done compiling.

APPENDIX C:Draft Drawing





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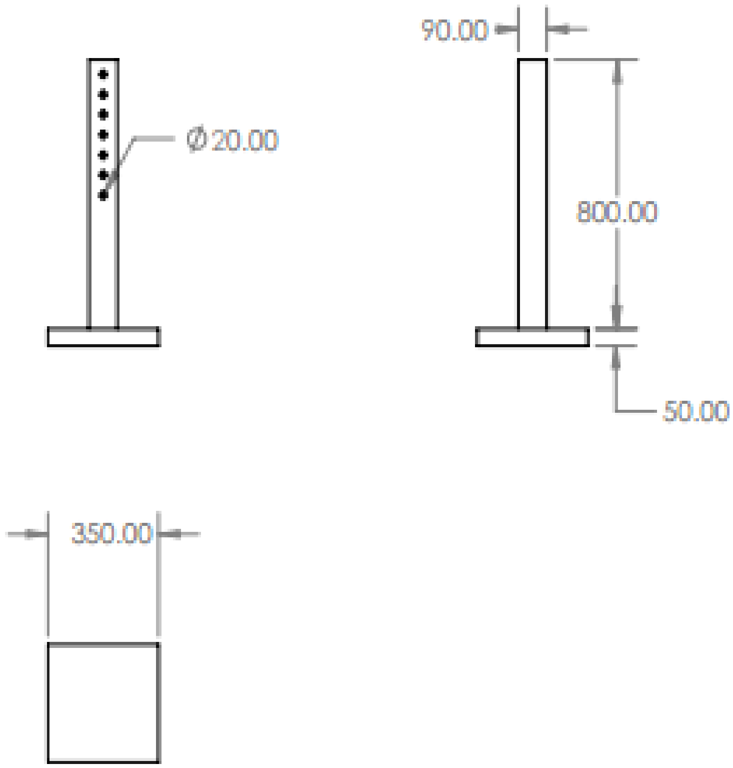
CH. BY: INS. SIRAK A.		UNIT: mm
DATE. 24-06-2019		QUANTITY:
SCALE:		TITLE: SHAFT



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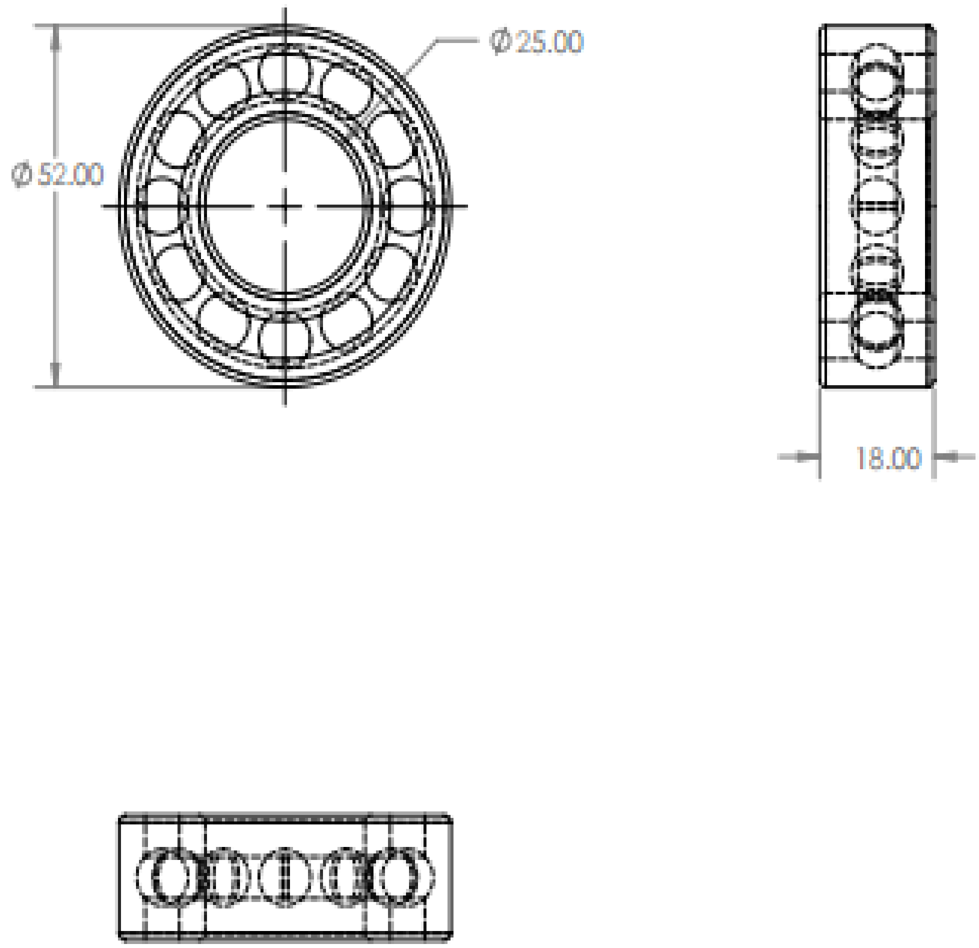
DATE. 24-06-2019		QUANTITY:
SCALE: 1:6		TITLE: LOWER PART OF STAND



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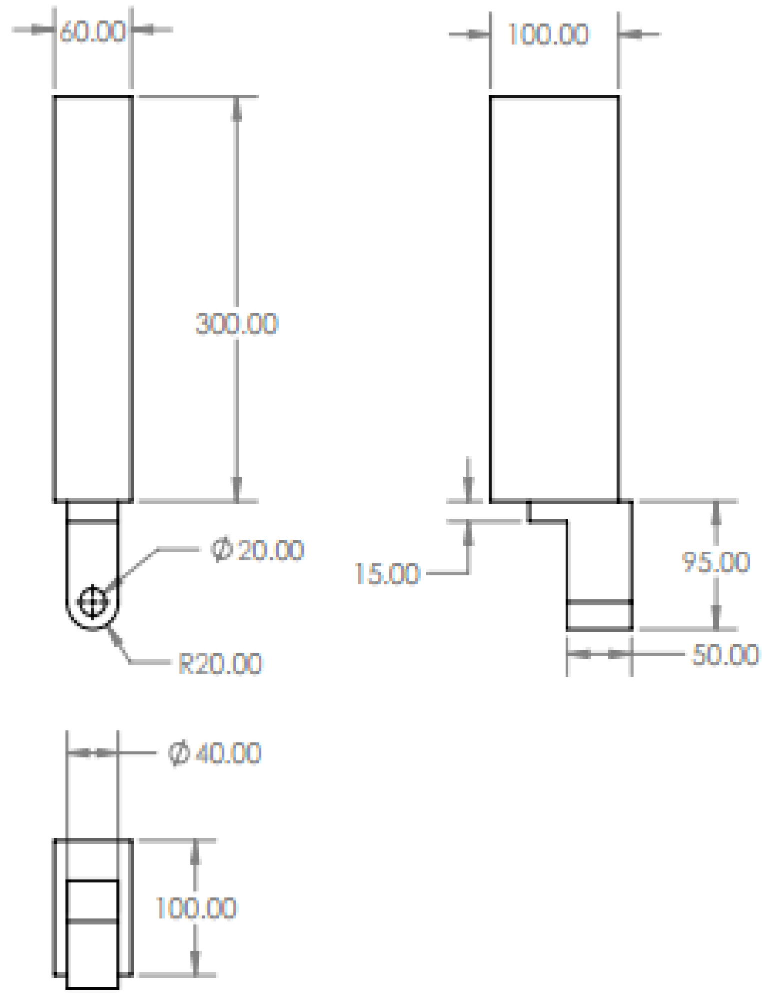

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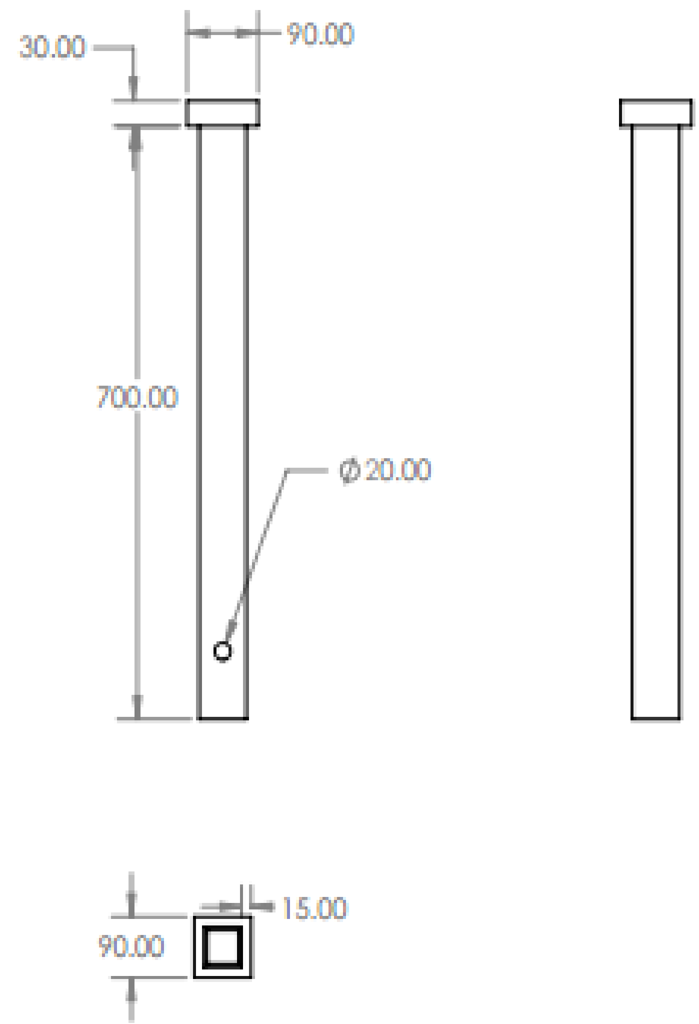
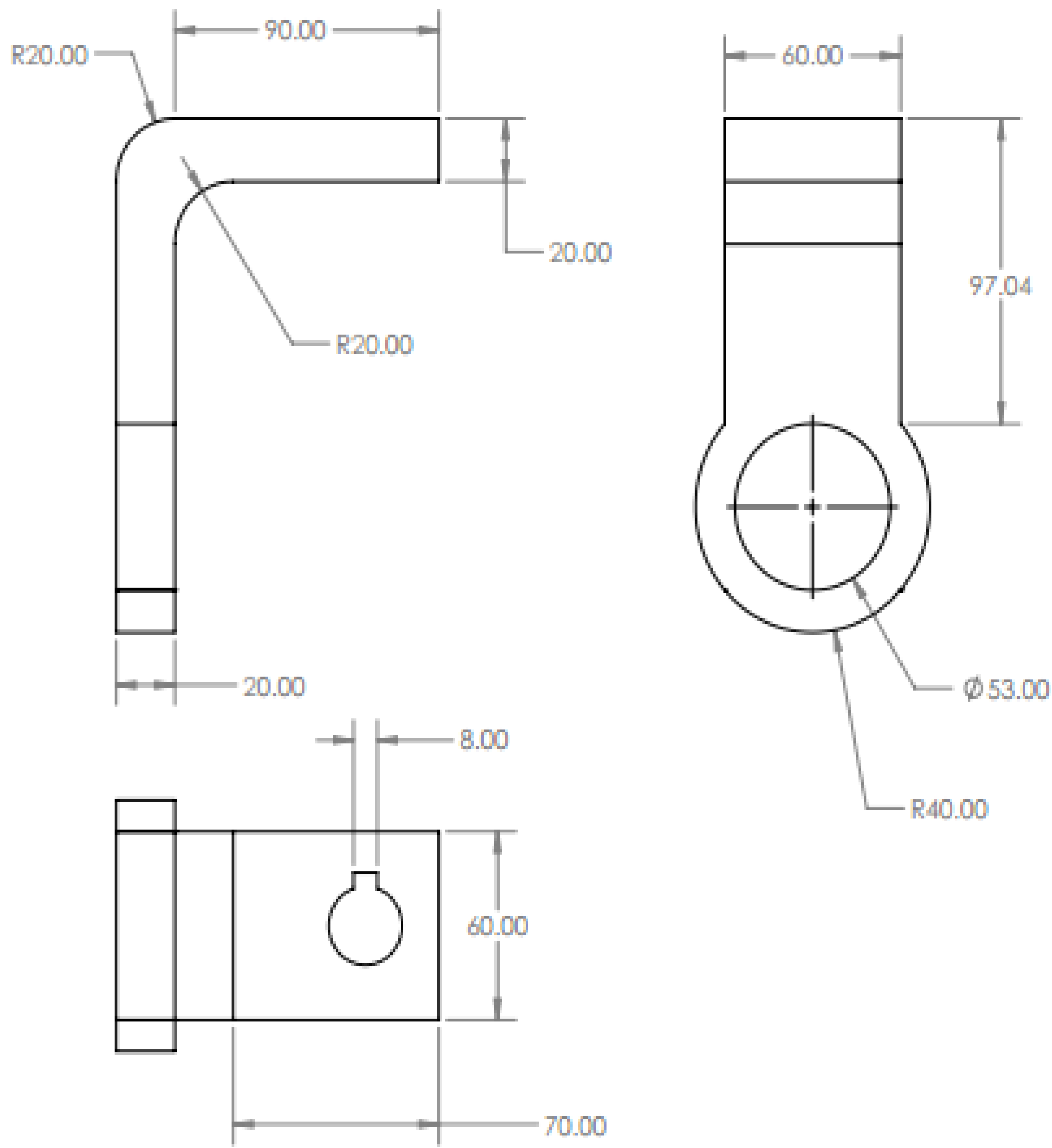
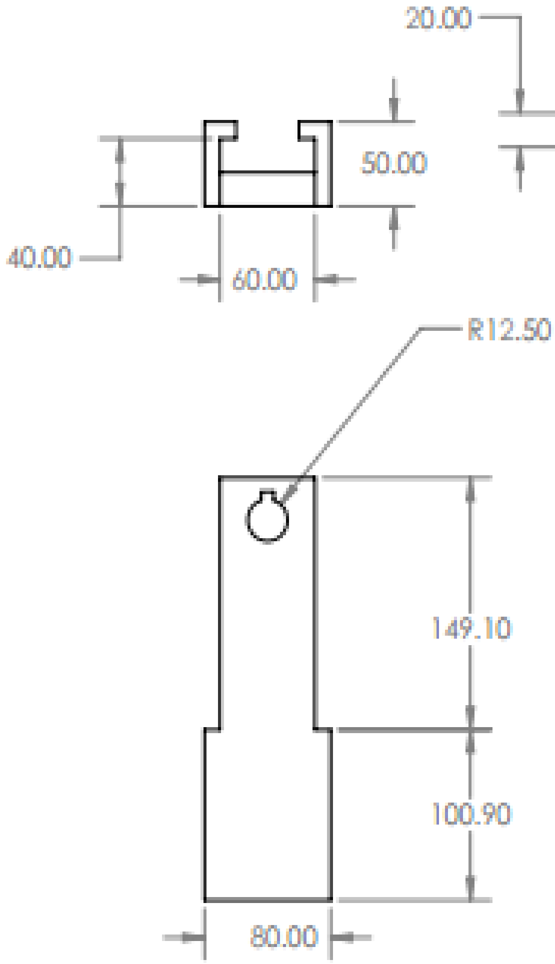
DATE. 24-06-2019		QUANTITY:
SCALE:	TITLE: HOLLOW RECTANGULAR BAR 1	



DR. BY:	EIT-M	DR. NO: 1
CH. BY: INS. SIRAK A.		UNIT: mm
DATE. 24-06-2019		QUANTITY:
SCALE: 1:6	TITLE: UPPER PART OF STAND	



DR. BY:		EIT-M	DR. NO: 1
CH. BY: INS. SIRAK A.			UNIT: mm
DATE. 24-06-2019			QUANTITY:
SCALE:		TITLE: PALM LINK	



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CH. BY: INS. SIRAK A.		UNIT: mm
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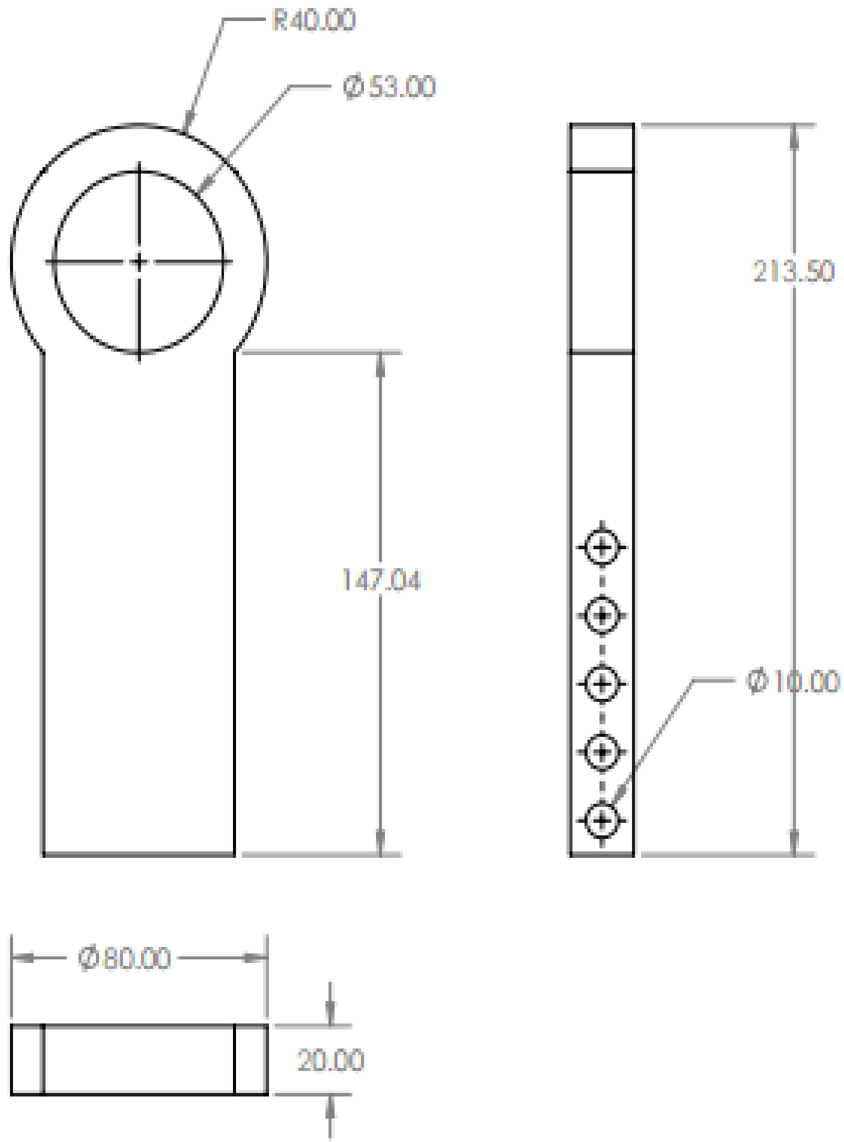

DR. BY:	EIT-M	DR. NO: 1
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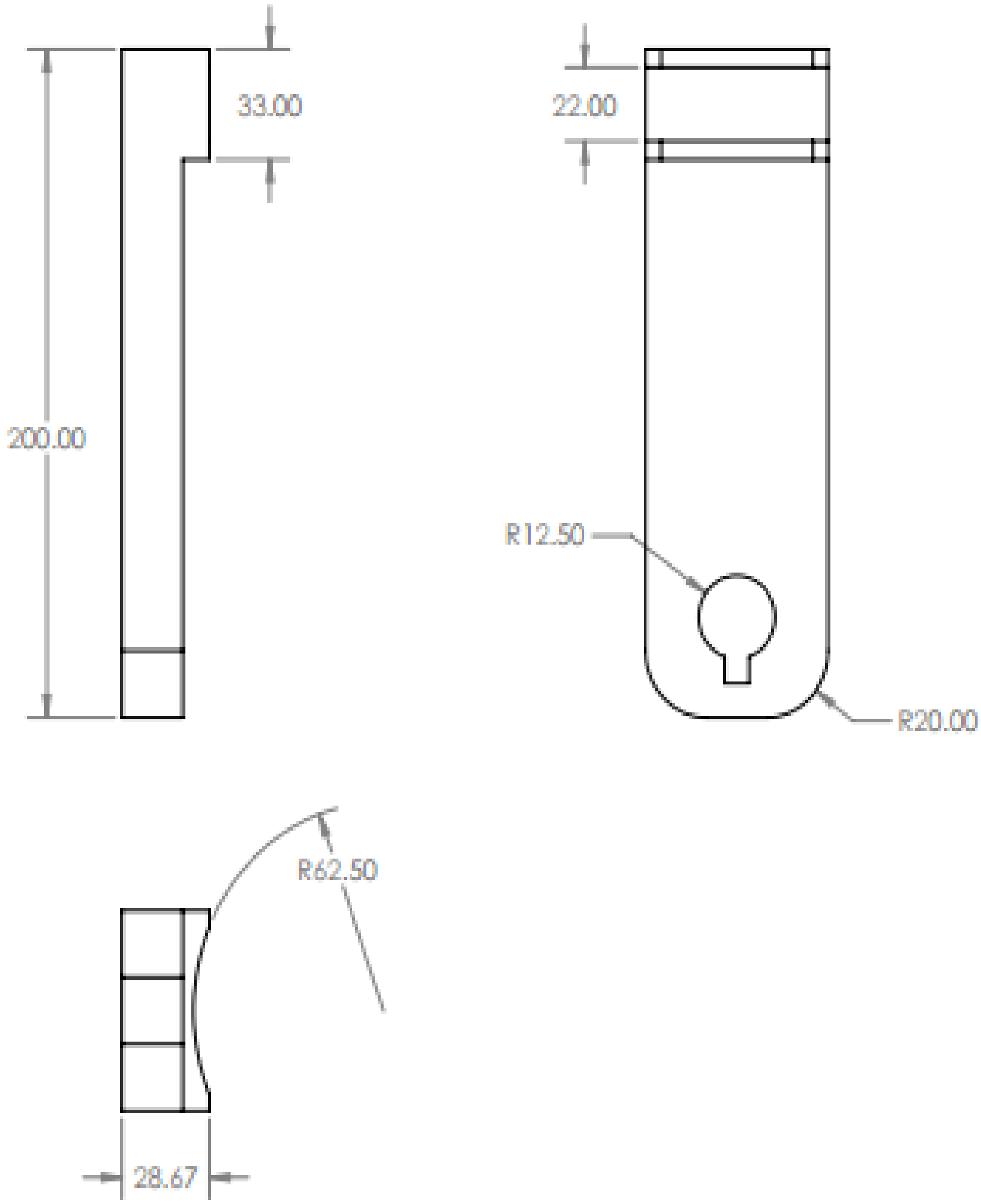
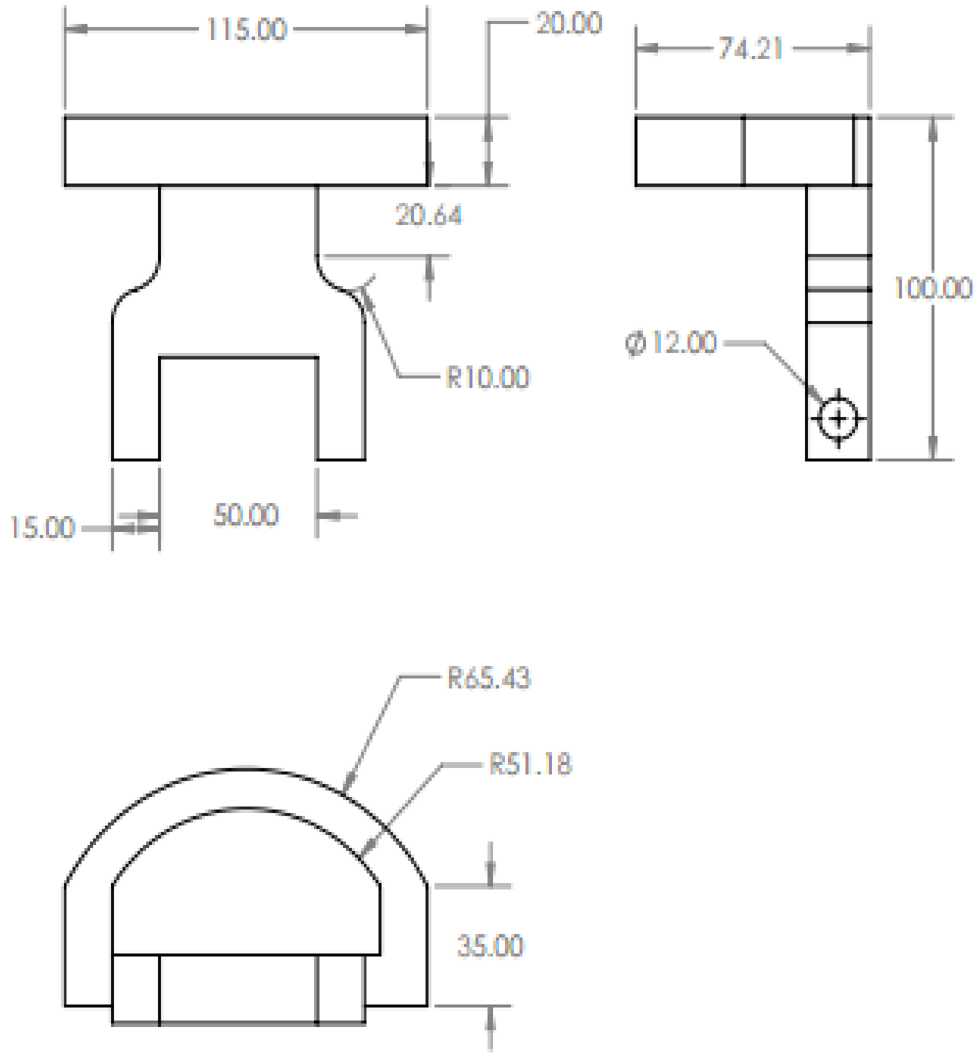
DATE. 24-06-2019		QUANTITY:
SCALE:		TITLE: UPEER LINK2



DR. BY:		EIT-M	DR. NO: 1
CH. BY: INS. SIRAK A.			UNIT: mm
DATE. 24-06-2019			QUANTITY:
SCALE:		TITLE: FORE ARM LINK	



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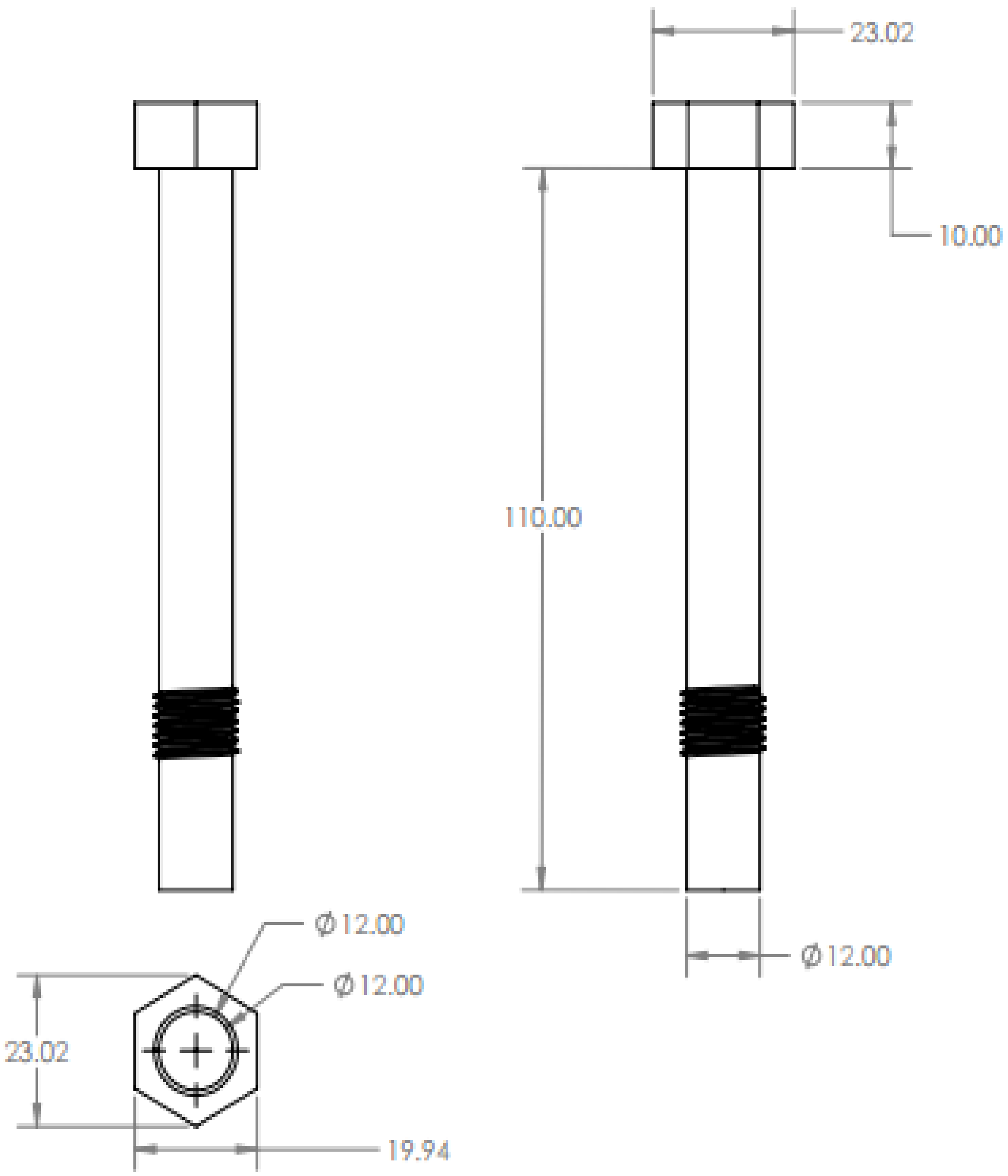
DATE. 24-06-2019		QUANTITY:
SCALE:		TITLE: SHOULDER LINK



DR. BY:	EIT-M	DR. NO: 1
CH. BY: INS. SIRAK A.		UNIT: mm
DATE. 24-06-2019		QUANTITY:
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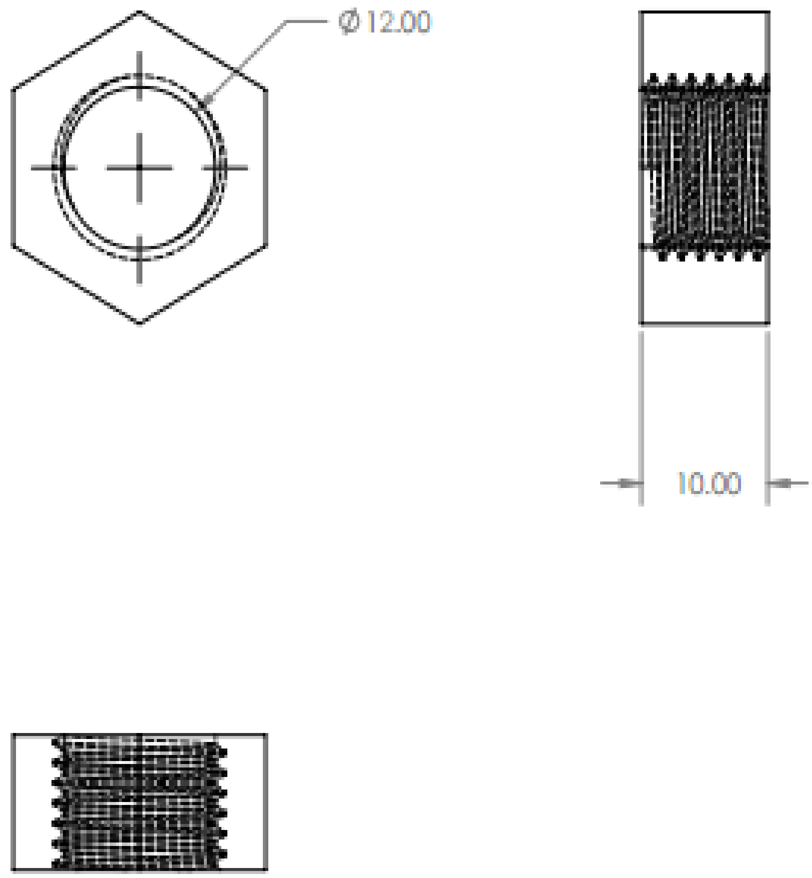

DR. BY:		EIT-M	DR. NO: 1
CH. BY: INS. SIRAK A.			UNIT: mm
DATE. 24-06-2019			QUANTITY:
SCALE: 1: 1		TITLE: NUT	