DESIGN AND ANALYSIS OF FUZZY BASED PID CONTROLLER FOR ELBOW-FOREARM REHABILITATION ROBOT

By

ALEME ADDISIE

A Thesis submitted to The department of Electromechanical Engineering For partial fulfillment of the Requirements for the degree of

Master of Science in Electromechanical Engineering

(Mechatronics Engineering)

ADDIS ABABA SCIENCE AND TECHNOLOGY UNIVERSITY

OCTOBER 2019

Certificate

This is to certify that the thesis prepared by **Mr. Aleme Addisie** entitled **"Design and Analysis of Fuzzy Based PID Controller for Elbow-Forearm Rehabilitation Robot"** and submitted as a partial fulfillment for the Degree of Master of Science complies with the regulations of the University and meets the accepted standards with respect to originality, content and quality

Signed By Examining Board:

External Examiner: Signature, Date

....

Internal Examiner: Signature, Date

....

Chairperson: Signature, Date

....

DGC Chairperson: Signature,Date

....

College Dean/Associate Dean for DP: Signature,Date

....

Declaration

I hereby declare that this thesis entitled **"Design and Analysis of Fuzzy Based PID Controller for Elbow-Forearm Rehabilitation Robot"** was prepared by me, with the guidance of my advisor. The work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted, in whole or in part, for any other degree or professional qualification.

Author: Signature,Date

....

Witnessed By:

Name of Student Advisor: Signature,Date

....

Name of Student Co-advisor: Signature,Date

....

Abstract

Nowadays, the use of Rehabilitation Robots for stroke patients has been growing rapidly. However, there was a limited scope of using such Rehabilitation Robots for patients suffer from accidental physical fracture. Since the pain condition of such accidents need a critical treatment, Precise control of such robotic manipulator is mandatory.

This thesis presents the design of Elbow-forearm rehabilitation robot by considering the pain level of the patient. It Includes the mechatronic design processes such as mechanical design, controller design, and Vertual prototyping using ADAMS-MATLAB Co-simulation. By reviewing different literature, the mechanical model is designed using concept generation by considering the Ergonomics and other aspects of the patient. Then the model is developed using Solidwork 2018. The pain level is estimated using three parameters i.e the patient general condition, the muscle strain, and the duration of exercise from the beginning of rehabilitation. Using these three input parameters, the manipulator's desired range of motion has been determined using Fuzzy Logic System. The output of this fuzzy logic system would be an input to the main control system.

The vertual prototype is realized by the ADAMS-MATLAB Co-simulation using the developed PID control block on simulink. The Co-simulation is carried out using three reference inputs i.e Step, sinusoidal and the proposed fuzzy reference input. Using step input, we have discussed the step response characteristics of the developed system. The Co-simulation of the ADAMS dynamic model is realized with a 30 degree oscillating motion by providing a sinusoidal input. Finally, using the developed fuzzy reference input, we have done a Co-simulation of ADAMS plant. The simulation result demonstrates that the proposed PID controller with gains Kp=0.001 and Ki=0.01 yields 99.6% of accuracy in the tracking of the reference input as compared to the simulation without introducing controller which has an accuracy of 94.9%. The simulation also shows that derivative gain (Kd) of the PID controller has no effect on the system so that it is over damping system. This shows that the Elbow-Forearm rehabilitation robot could be smoothly controlled as per the pain level of the patient.

Keywords: Rehabilitation Robot, Fuzzy Logic System, ADAMS-MATLAB Co-simulation, PID Controller, Virtual Prototype, Elbow-Forearm.

”Acknowledgements”

First of all, I would like to thank Almighty GOD, the lord of the world, for giving me the strength, ability, knowledge and opportunity to undertake this research study and to persevere and complete it satisfactorily. Without his blessings, this achievement would not have been possible.

I am very grateful to my Advisor Riessom W/Giorgis (Assoc. Professor) for his Continuous assisting and collaboration for this thesis work. He was an encouraging companion in my research activities and has always provided me with lots of support in Technical Knowledge and materials, given me great enthusiasm and a lot of inspiration in many aspects. I appreciate the latitude and confidence he gave me along the thesis journey, his knowledgeable advice, our positive interactions and his persistent commitment to high-quality research.

It is my great pleasure to be thankful to my Co-advisor Mr. Tamru H/Silassie, who gave me the a great support to do this research paper and advised me with very useful suggestions and motivating comments.

I am interested to express my great thanks to Mr. Yemane G/Meskel Head of the Department for his continuous motivation and support for the accomplishment of this thesis.

I would like to express my deep appreciation to Dr. Samson and Dr. Gebremichael for their critical consultation and technical advice to enhance the progress accomplishment of this thesis.

I will express my Great gratitude to Therapists and Doctors found in Tirunesh Bejing General Hospital and Abet General Hospitals for their positive attitude and collaboration for my data Collection. At every part of my need and request, they have been fully interested to support me.

Abbreviations and Acronyms

ADAMS	Automatic Dynamic Analysis of Mechanical Sytems
ADC	Analog to Digital Converter
DALY	Disablity Adjusted Life Year
DAQ	Data Acquisition
DH	Denavit Hartenberg
DOF	Degree of Freedom
EMG	Electromyography
MARSE	Exoskeleton-Motion Assistive Robot for Superior Extremity
FIS	Fuzzy Inference System
FLC	Fuzzy Logic Controller
GF	Gage Factor
HMI	Human Machine Interface
K	Kinetic Energy
L	Lagrange
l_e	Length of Elbow connecting link
l_f	Length of Forearm twisting link
LI	Linguistic Input
LO	Linguistic Output
MAV	Mean Absolute Value
MC	Muscle Contraction
MF	Membership Function
MTB	Multi Body model
NTUH	National Taiwan University Hospital

P	Potential Energy
PID	Proportional-Integral-Derivative
ROM	Range of Motion
sEMG	Surface Electromyography
SMC	Sliding Mode Control
SRS	Shoulder Rehabilitation System
SSI	Simple Square Integral
θ_e	Angle of Elbow joint
θ_f	Angle of Forearm twisting joint
X_e, Y_e, Z_e	X-Y-Z axis of Elbow Joint
X_f, Y_f, Z_f	X-Y-Z axis of Forearm twisting Joint

Contents

Tables

List of Figures

Chapter 1

Introduction

1.1 Background

The upper limp is a complex neuro-mechanical system that occupies a central role in our daily activities including interacting and communicating with our environment, manipulating objects and other activities [1]. The versatility of the upper limp which has 7 DOF enables us to perform different activities. The upper arm, the forearm and the hand with joints at the shoulder, elbow and wrist can achieve a wide range of motion.

This upper limp may suffer from a neurological injury such as stroke or physical fracture. Fractures may occur from small to big bones of the upper limp due to the crushing or twisting injuries from sport or fall injury. In most upper and lower limp fractures, the bones can be realigned and treated without surgery. Sometimes, surgery may be required when the bones are unstable, shattered or crushed. After surgery, joint stiffness will happen due to long immobilization time. During this time, Recovery exercises will help to restore strength and motion of the injured body part. To do this, conventional clinical physiotherapy is needed to rehabilitate the injured body part to be restored to its normal function. A physiotherapist can make the patient perform the therapeutic exercises, which consist of passive and active exercises, or the patient can perform by himself or herself depending on his or her physical condition.

In the previous 15 years, many efforts have been devoted to developing systems that can help people with limited movement or rehabilitate injuries and disabilities and also replaces the conventional physiotherapists. In this area, many technologies are introduced through robotic devices that are attached to the upper and lower limbs of the human body to maintain and improve their movement in a constrained environment. However, the large majority of these devices have hardly been validated in studies with end-users for feasibility and even less for clinical efficacy. Generally, there are three types of robotic approaches for hand rehabilitation [1]: (i) Hand exoskeletons (ii) end-effector-based manipulators for hand and (iii) the whole upper-limb solutions as seen in Fig.1.1.

1.2 Motivation and Problem Justification

The shortage of therapists assisting physically injured patients at hospitals and individual homes has been increased and was going to be a serious problem [1]. Especially, in populous countries, the number of physiotherapists per patient is not enough. The transportation problems of the patients are also challenging. For these reasons, researches are growing on the use of robotic manipulators for the rehabilitation process. However, most proposed

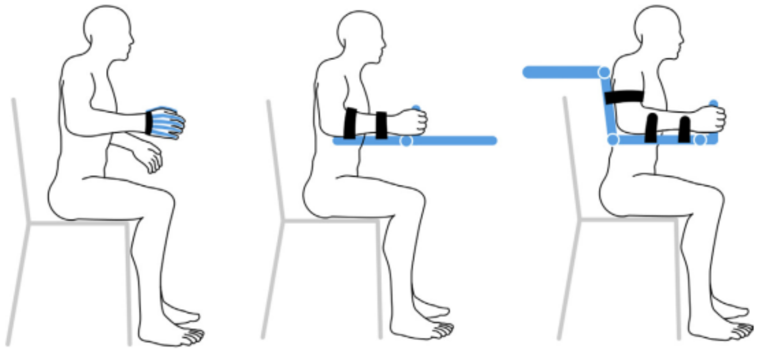


Fig. 1.1: Different approaches of robot-assisted rehabilitation[1]

and developed rehabilitation manipulator systems are concerned only on injuries caused by stroke (mostly long term injuries). There is a limited scope of research on accidental physical injuries such as breakage or fracture of hand which have highly sensitive pain. Here, precisely controlled (with pain level) rehabilitation robot is needed. Consequently, fuzzy based PID controlled rehabilitation robot is proposed to eliminate the stated problems.

1.3 Objectives of the Thesis

1.3.1 General Objective

The general objective of this thesis is to design and analyze the fuzzy-based PID controller for Elbow-Forearm Rehabilitation Robot.

1.3.2 Specific Objectives

The specific objective of the research has been stated as follows:

- To develop the mechanical design of a two degree of a freedom robot manipulator for the rehabilitation of broken/fractured hand of a patient.
- To develop the kinematical and dynamical model of the proposed robot manipulator.
- To collect strain-gauge based data from patients.
- To design the fuzzy-based PID control algorithm for the system.
- To do the ADAMS-MATLAB Co-simulation with graphs and analyze the results

1.4 Thesis Contribution

Most researches are concentrating on injuries that are caused by strokes. It is known that stroke is the most serious issue in the world. It has different pain conditions from that of the injuries caused by accidents such as fracture, elbow dislocation, and other breakages. Since the pain is different and due to scares of research on accidental injuries, we are forced to study in this area.

Since the type of pain experienced in this type of accident is very sensitive, precise control of a range of motion for a rehabilitation robot is mandatory. To achieve this, this research has a great contribution by introducing fuzzy logic system for determining the desired range of motion of the manipulator. The pain level of the patient is purely fuzzy in nature. So, the use of fuzzy logic for the determination of the desired range of motion could be one contribution for the state of art. Furthermore, the strain gauge which is simple and low cost with low sampling frequency is proposed to detect the muscle contraction. By using the data obtained using strain gauge and by considering different conditions of the patients, the controller is designed to control the manipulator with the pain level of the patient. Generally, unlike other researches, this paper concentrates on the pain level of the patients and gives a significant contribution in the area of accidental physical fractures and joint dislocations.

1.5 Outline of the Thesis

Since this thesis covers the whole mechatronic design of the Elbow-Forearm rehabilitation robot, it is outlined sequentially start from the mechanical design and go through the data acquisition and control design and simulation. It is stated briefly as follows:

The first chapter introduces the general background of the thesis idea. This includes introducing the nature of the human upper limp specifically around the elbow and forearm of the human body. The statement of the problem for the proposed idea and the objectives of the thesis is stated here. Finally, the contribution of the thesis and the outline of the paper are summarized.

The second chapter states the reviewed literature by categorizing them depending on the type of pain and the type of sensor used. Here different literature which uses surface electromyography are reviewed. Most researches that are done by considering stroke patients are illustrated and discussed. The mechanism they are following and results what they achieve are briefly discussed.

The third chapter presents the overall mechanical design of the system (the elbow-forearm rehabilitation robot). This section starts with concept generation and selection of the mechanical structure. Four design concepts are proposed and selected using pugh's concept selection method. Then the final selected design concept is developed using Solid work 2018. Here the mathematical model is also presented.

The fourth chapter presents the data acquisition system. Here the instrumentation circuit using a wheatstone bridge is designed, the experimental setup is prepared. The data acquisition mechanism from the patient is also presented and finally, the recorded data is tabulated for further investigation.

Fifth chapter deals with control design of the system. Here two parts of the control schemes are presented. The first one is Fuzzy logic system for determining the desired range of motion and speed of the manipulator. And the second one is the main controller of the plant that is the PID controller to achieve this desired position.

The final chapter presents the simulation and discussion of the results. This part is the main part of the whole thesis that shows the feasibility of the work. Here the mechanical model designed using solid work is imported to MSC ADAMS to do the ADAMS-MATLAB co-simulation. It also presents how the Plant dynamic model is exported to matlab and co-simulate with the controller designed in chapter 5. Generally the outline of this thesis is as in Fig. 3.2 shown.

Chapter 2

Literature Reviews

2.1 Introduction

In this section, the review of different aspects of the upper limb rehabilitation will be introduced and discussed. Different researchers provide a significant approach to various parts of the human body. However, this thesis will focus on the robots designed for upper limb rehabilitation. For clarity of the review, some aspects such as the type of sensor used, the type of pain for which the robot used and the mechanical structure they designed are discussed in detail. The system of upper-limb rehabilitation robots can be compared with different aspects such as the mechanical properties, capacity of the movement and exercise and the control methods used.

2.2 Rehabilitation Robots for Stroke Patients

Stroke, which is the cause of injuries and diseases for upper and lower limb movements [2]. It is estimated to be the fourth high level cause of reduced disability-adjusted life-years (DALY) by 2030. There are other causes include motor neurons, spinal cord and traumatic brain injuries. Most of the Currently proposed robotic systems for upper limb rehabilitation are typically concerned with stroke patients. Since the mechanism is similar to that of the robotic systems of these post-stroke patients, we have reviewed these systems to enhance our design.

The mechanical design and control of a new 3 degrees of freedom (DOF) exoskeleton robot for shoulder rehabilitation after stroke are presented by Babaiasl et al. [3]. Here, An open circular mechanism has been proposed for the third joint. And also Jacobian matrix, kinematics, dynamics and singular points of the manipulator are presented. They used a sliding mode controller (SMC) to study the ability of the robot to follow and track the optimized (desired) trajectories. It is known that in the rehabilitation robots, the issue is the robot's mechanical design and also they focus on linear controllers for controlling the robot. However, this paper concentrates on the control aspects. Since rehabilitation robots are non-linear in nature due to the patient's hand tremor, the non-linear control system is needed that is why this paper uses SMC. This controller eliminates the uncertainties and is robust for variations of parameters. This paper has a good approach for control as well as mechanical design aspects for the rehabilitation of stroke patients.

Chen et al. [4] presents the rehabilitation robot with its assistive control system. The kinematic structure integrated with sensors i.e force/torque sensors. By integrating the dynamic human model and the toque sensor, the patient interaction is simulated under different mode of rehabilitation: passive, assistive and active modes. This rehabilitation robot gives 7 DOFs motion and practicing the patient to enhance an appropriate mapping between 4 DOFs of the human arm and 7 DOFs of the robot arm. The Stability of the proposed controller design is analyzed by the Lyapunov theory. They are able to utilize patient-cooperative control strategies in passive, active and assistive modes with gravity compensation for robot-aided stroke recovery.

2.2.1 Rehabilitation Robots on Accidental Fracture

Hybrid impedance control of a robot manipulator for wrist and forearm rehabilitation was investigated by Akdogan et al. [5]. This rehabilitation system consists of the robot and controller. It also include HMI to model the exercises for the rehabilitation. These exercises consists of ulnar-extension movements of the wrist and also the pronation-Supination movement of the forearm. The hybrid impedance control is used which includes inverse dynamics and cancellation of some terms for reducing Uncertainties in the system parameters. Finally experiments were carried out with healthy subjects and with patients in a clinical environment. As a result of these experiments, the increase in muscle strength was observed in all the patients. Here the contineous detection and evaluation of the pain level of the patient is not considered.

2.2.2 Electromyography (EMG) Based rehabilitation Robots

Ben et al. [6] designed a biofeedback-based high fidelity smart robot for wrist rehabilitation. This Robot is used for replacing the Human-Human interaction to human-robot interaction and for repetitive exercises without therapist intervention. It uses to perform two sets of wrist movements. These are flexion/extension and radial/ulnar derivation. They uses SEMG signal to understand the pain level of the patients.

Here two feature extractions are used to estimate the pain level. The first one is the Mean Absolute Value (MAV) and the second feature extraction is the simple Square Integral (SSI). To determine the desired angle and velocity of a manipulator, they use the fuzzy control system implemented in Labview-based Human-Machine Interface. Results and parameters of each exercise are recorded and stored for analysis of patient progress.

Shaung Ju [7], address the concept of improving the elbow torque output using assistive torque system for stroke patients. This assistive torque is controlled by EMG signals generated from the biceps and triceps of the patients. The proposed assistive torque algorithm uses the signal differences between the triceps and biceps to calculate the magnitude of the torque that should be applied. The voluntary effort supplied by the patient is proportional to the applied torque. The incorporation of a non-linear damping element is used to enhance the assistive system stability which reduces the co-contraction between the biceps and triceps and the physiological damping of the elbow joint. The experimental results showed that the proposed system is effective in developing a large apparent torque at the elbow joint if system stability is achieved and if the patient is allowed sufficient practice time.

The state of the art of resistant and assistive upper limb exoskeleton robots and their control are thoroughly investigated by Tiboni et al. [8]. They developed 1-DOF elbow-forearm rehabilitation robot for the upper limb movements of physically disabled patients. They concentrate on the control system by using sEMG signal as an input to move and manage robotic arm. Here the correlation between sEMG signal and the force exerted by the subject was studied for validating the stated methodology. Finally, they have developed an innovative surface electromyography force–based active control which adjusts the force exerted by the device during rehabilitation exercise.

In EMG-based control system, the EMG signal will expose to different unwanted signals. For example assuming that the patient's body by nature is vibrating. Then the signal obtained from the EMG sensor will have a noise which will affect the accuracy of the control system. However, in this research, strain gauge-based data acquisition is proposed to measure the pain level of the patient properly.

2.3 Literatures on Physical Model of Elbow Rehabilitation Robot

Different literatures [9], [10], [11], [12], [13], [14] and [15] uses different Physical model for their specific rehabilitation applications. Chen-Hua Yeow et al. [10] provide the design of a Soft Robotic Elbow actuated with elastomeric and fabric-based pneumatics system. In this design, the robotic elbow sleeve will extend through the elbow joint from the biceps of the arm to the forearm. This design consists of two pneumatic actuators to effect the elbow extension and flexion. The flexion actuator is an elastomer constract which is bended based on the input air pressure. To elliminate the issue of non portablity, light weight and soft design is choosen with joints of conventional robotic rehabilitation. However these pneumatic actuators are difficult to control especially in post immoblized rehabilitation which has high pain.

Mahdieh Babaiasl et al. [13] designs the Shoulder Rehabilitation System (SRS) has three DOFs for shoulder flexion/extension, adduction/abduction, and internal/external rotation. In this system, an open circular mechanism was designed and power transmission is achieved by a gear coupled with the shaft of actuator. The proposed mechanism for power transmission from actuator to provide shoulder internal/ external rotation.

Rahmani M, Rahman MH [14] develops the 7-DOF exoskeleton ETS- Motion Assistive Robot for Superior Extremity (ETS- MARSE), which is a redundant robot. The

ETS- MARSE robot was developed for patients whose upper limb was injured, the ETS-MARSE robot was developed in order to in physical therapy and assisted motion. The shoulder part includes three joints; the elbow part comprises one joint, and the wrist part includes three joints. Here the system is quite complex and as the the number od DOF increases, the control complexity will also increase so that the control uncertainity will be high. Especially in fracture patients, the early stage of post immobilization is very sensitive. So the precise control scheme of angular speed and range of motion of the robot link is necessary.
Generally many researches participating on the upper limp rehabilitation robots have their own mechanical designs. However, they have more than two DOF with a complex structure. Since the complexity of the system leads to the uncertainty of the control system [16], design of rehabilitation robots for each joint of the upper limp is preferable.

2.4 Literatures on Data Aquisition in Rehabilitation Application

Jiang et al. [17] developed a polypyrrole-coated electrode enabling sEMG measurement. They compared their measurements with the traditional electrodes Ag/AgCl from the same muscle fibres. This comparison revealed a high correlation, but the electrodes must be reduced in size to be employed.
However, the previous used sensors such as sEMG sensors were not able to detect all small changes in muscle strength. In this context, the strain gauges, known for their accuracy, lightness, and low sampling frequency, are considered a great interest for strain measurements on the human body [18]. Especially, Mori et al. [19] who Properly demonstrated the feasibility of using strain gauge to measure the shape of skin deformation and Muscle Contraction (MC).
Zizoua et al. [20] develops the comparision between strain gauge and sEMG signals. The evaluation is carried out by comparing the strain gauge sensor results with those obtained by sEMG signals. And it can be observed that a high linear correlation (r = 0.89) was observed between the two signals. This indicates that strain gauges are a suitable sensor alternative to detect MCs, which are characterised by their low cost, simplicity and with the advantage of a low sampling frequency compared with sEMG. Consequently, strain gauges have a high potential to replace sEMG to measure the muscle contraction.
Now besed on the these literatures, we are interested on strain gauges to measure the MC. Inturn by combining the patient status(by asking) the pain level of the patient can be estimated so as to control the rehabilitation robot smoothly.

2.5 Summary

In this literature survey, we are concentrating on the type of pain that the patient faced and the type of sensor used to detect the pain condition of the patients. Most researches are dealing with the stroke patients. So, the robotic mechanisms are based on stroke patients. There is a minimum scope of investigations on the rehabilitation of post immobilization of accidental fractures and joint dislocations of upper and lower limp of the human body. On the other hand, most studies have aquire data from patients using Electromyographic sensors which are very expensive. This paper considers these two limitation. We investigated an approach of using Strain gauge sensors to estimate the pain level of patients. We also conduct a survey on the previously developed mechanical designs by taking different approaches such as the number of degree of freedom and the complexity of the structure. We have shown that as the number of degree of freedom increases, complexity of the system also increases, so that the control algorithm will be difficult. By considering this issue, we develop a two degree of freedom elbow-forearm rehablitation robot.

Chapter 3

Mechanical Design of Elbow-Forearm Rehabilitation Robot

3.1 Introduction

Every mechatronic system is the integrated design of a mechanical system and its embedded control system [21]. For those multidisciplinary systems, the mechanical engineer firstly emphasize on the mechanical designs by considering different aspects accordingly. Afterwards, the electrical components are designed by the electrical engineer and also the embedded software is designed and integrated by the control/software staff.
This sequential approach may have a drawback of incompatibility between subsystems which results additional cost and effort to have an optimal integrated system. Another drawback of this approach is that during the design process decisions should have to be made about whether to use a mechatronical or a mechanical solution. Design engineers have to balance mechanical, electrical/electronic and software solutions [22]. So, generally the development of modern mechatronic systems is the synergic integration of mechanical, electrical/electronic, control and software aspects from the very beginning of the earliest design phases, as it can be seen in Fig. 3.1.

Among these design phases, mechanical geometry design come first and during the first phase of mechanical design, the designer should evaluate the concept design including concept generation, selection and scoring. The main goal of this research is addressing the new control concept in rehabilitation robots especially for post immobilization elbow fracture rehabilitations. However there is a need of mechanical robot design to apply the control algorithm. Before going to the control design, the mechanical design and verification is mandatory.
In this research, the mechanical design is selected by providing four conceptual design sketches and by comparing them with different criteria. Then the selected concept design is modeled using solid work 2018 by measuring the average adult upper limp parts. Finally, the Solid Work model is imported to adams and the adams-matlab co-simulation is carried out.

3.2 Concept Generation and Selection

Concept generation and screening is an early as well as key part of any mechatronic researches and projects. The primary aim of concept generation and evaluation is to ensure that the system can perform the desired functions effectively. The concept generation stage will minimize the possibility of misrepresenting a system in need, which may be effective

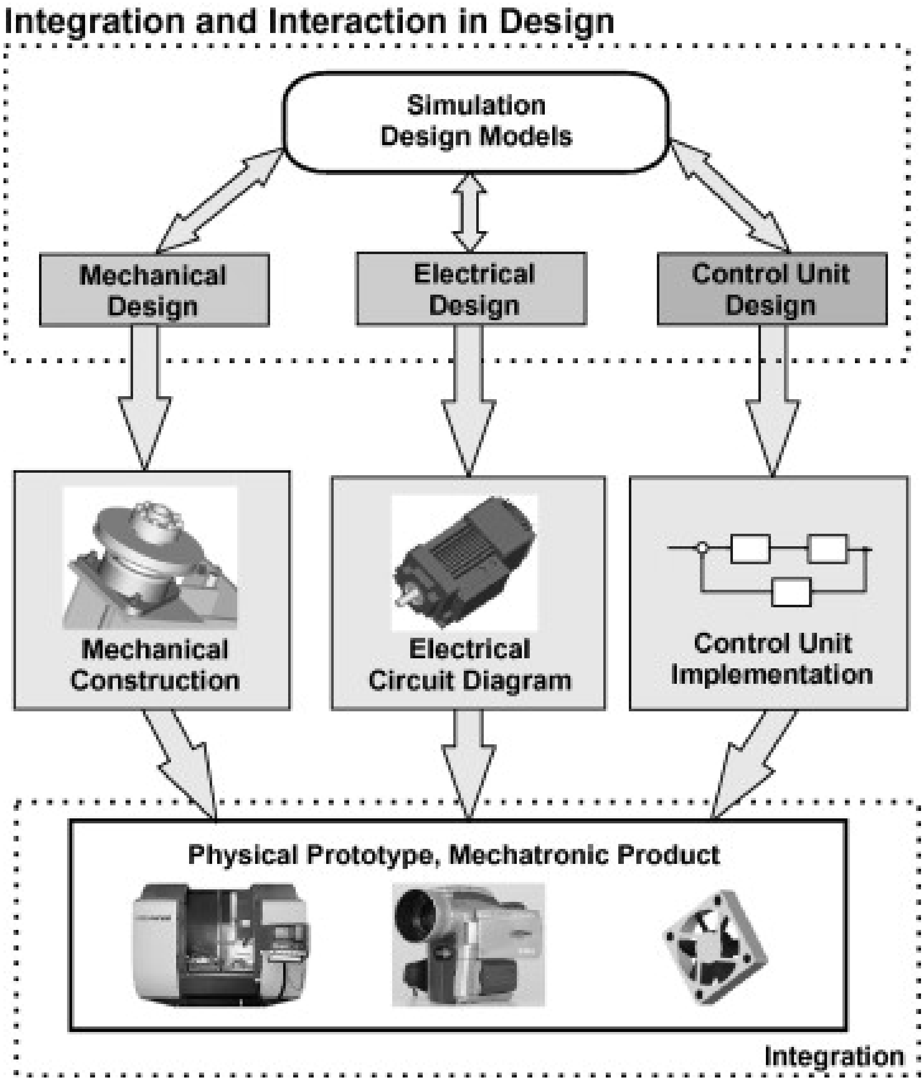


Fig. 3.1: Mechatronic design activities[22]

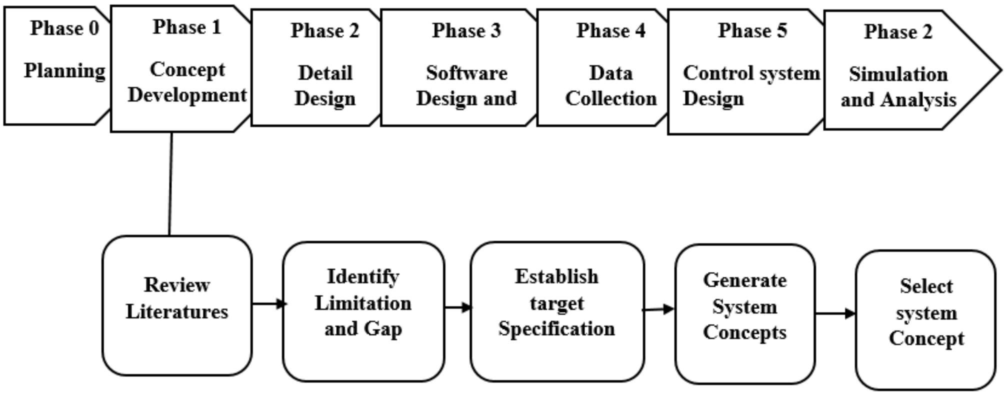


Fig. 3.2: Relation b/n concept generation and concept development activities[23]

by consider different aspects of a final decision.

3.2.1 Concept Generation

To have researching different embedded and control concepts on robotics and mechatronics systems, the accurate mechanical design should be provided to control the system efficiently. To do this, concept generation is the crucial stage in developing the accepted system design. Especially in rehabilitation robots, different aspects of design criteria should be considered to satisfy the need and comfort of patients. First different Literatures should be reviewed and identify the cos and pros for each designs. then the target specification is established and finally the appropriate concept designs are generated and finally the most promising concept is selected and developed. The detailed Design and development process is shown in the Fig. 3.2. Generally, concept generation has the following subsections.

- **Establishing the Target Specification:** A specification is a precise, measurable detail of what the system has to do. It consists of a metric and a value of the metric. Metric is the label for a goal state. When a value is added to the metric will becomes a specification. Establishing target specification will help to this research by providing quality target definitions, a measurable result comparison. Establishing target specification is useful in guiding the subsequent stages of concept generation and selection. A typical system specification of Elbow Rehabilitation Robot includes the following information shown on the Table 3.1.
- **Concept Classification:** To explore various means for selecting a proper design of elbow rehabilitation robot, concept classification trees are used different solutions. The concept classification tree is used to divide the entire space of possible solutions in to several distinct classes which will facilitate comparison and pruning. Concept classification tree for Elbow rehabilitation robot is shown in Fig. 3.3.

Table 3.1: Need for Elbow Rehabilitation Robot and their relative importance

No.	Need	Importance
1	Ergonomic requirements	5
2	Ease to operate (user friendly)	5
3	Smooth Rehabilitation	5
4	Durability	4
5	Reliability	4
6	Automation flexibility	5
7	Ease of fabrication	4
8	Safety requirements	5
9	Impact on its environment	4
10	Less power requirements	4

Table 3.2: List of metrics for Elbow-Forearm Rehabilitation Robot

Metric No.	Need Nos.	Metric	Imp.	Units
1	4,5,9	Robot Performance	5	List
2	7	Time to Assemble and Disassemble	4	Hour
3	2,6	User friendly, Fuzzy based automated system	5	List
4	1,7	Feature and Size of the Robot	4	M3
5	6	Integration or assemble all system	4	List

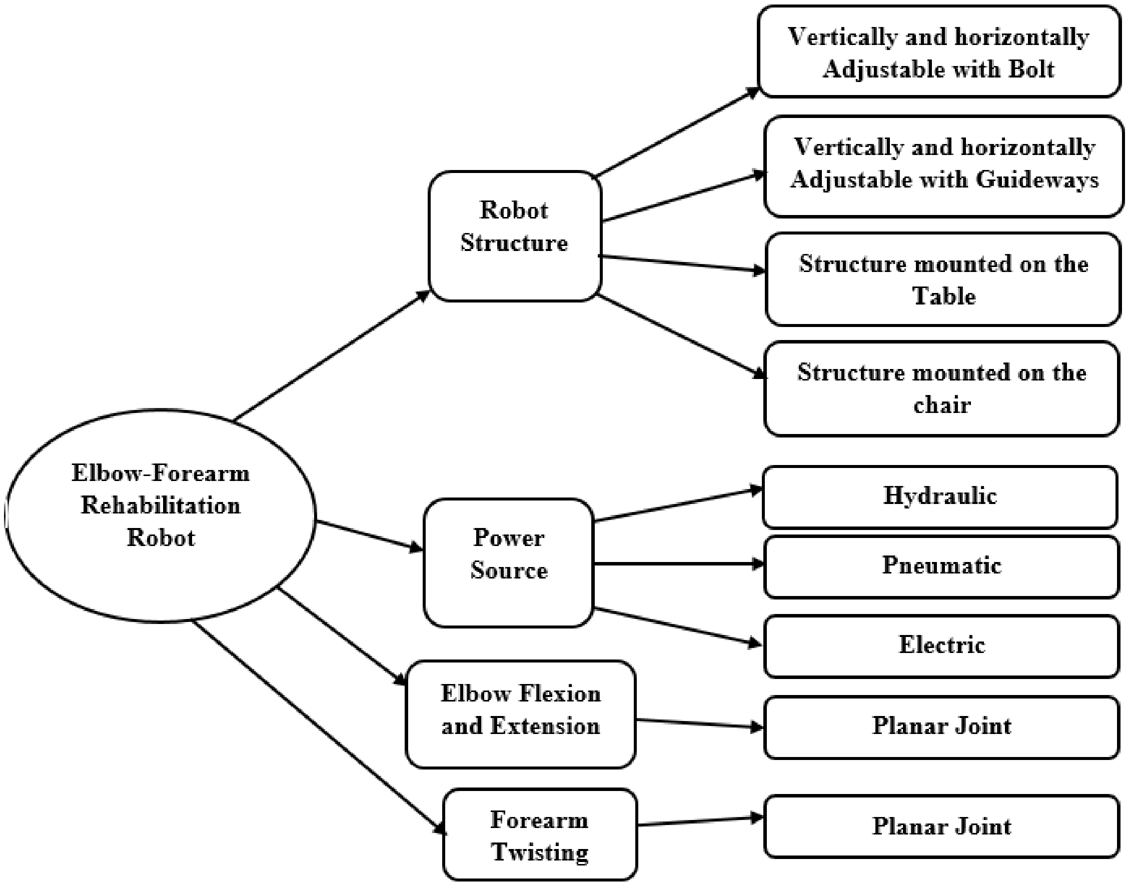


Fig. 3.3: Concept classification tree for Elbow rehabilitation Robot

- **Concept Combination Table:** Here is the concept combination table for Elbow Rehabilitation Robot. It is very similar to the classification tree found above. However, different concepts will come up with a final idea for the Elbow Rehabilitation Robot. This table shows the main focuses for Elbow rehabilitation robot. This included the robot structure, power source, Elbow flexion and extension, and Forearm twisting see Fig. 3.4.
  However, from the given power sources, Electric power sources is selected in the concept design development. Since rehabilitation robot needs precise control of its speed and range of motion, hydraulic and pneumatic systems [24],[25] does not satisfy these requirements. if we consider the range of motion, the elbow joint has a ROM of $140^o - 145^o$ [8] and pneumatic actuators can not achieve this range. so by considering electric actuators and choosing different structure of a robot to have a suitable ergonomic appearance, four concept designs are proposed.
- **Combining Concepts:** This is the step when many fragmented small design concepts are combined to yield a final design concept for Elbow Rehabilitation Robot.

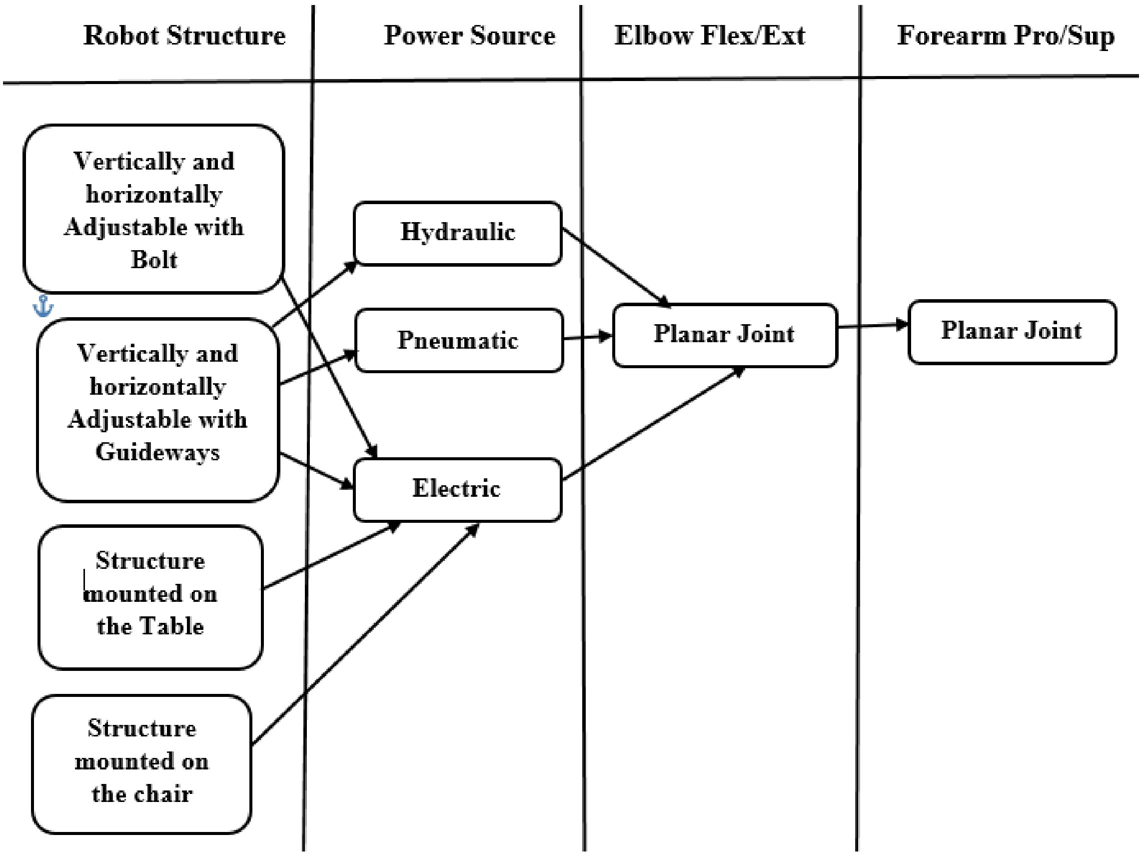


Fig. 3.4: Concept Combination Table

For the above table there will be a lot of possible combinations. All of them should equally be evaluated or checked for viability. But, hydraulic and pneumatic energy sources are not more feasible as compared to electric energy source. Therefore, the next step is to combine more promising critical sub problem concepts to arrive at a set of ultimate design concepts. The following design concepts are selected based on feasibility and these concepts are to be evaluated before the final finished design.

- **Concept Design 1: Vertical Standing robot Adjustable with Bolt**
  This is the first conceptual design which is adjustable both vertically as well as horizontally to provide the required position for the patient. The vertical adjustable base is fixed with the ground. The horizontal adjustable bar is used to make the robot arm in a proper position for different physical appearance of the patient. These parts are fixed with bolt and nut mechanism. The first motor joins the vertical link and the oscillating robot arm which is equivalent to the Elbow of the human arm. This motor is used to rehabilitate the elbow after immobilization. At the end of the arm link, there is a pin which is grasped by fingers. This pin is actuated by the second motor to rehabilitate the hand by twisting in both clockwise and counterclockwise direction. The figure is shown in the Fig. 3.5.

- **Concept Design 2: Vertical Standing robot Adjustable with Guide Ways**

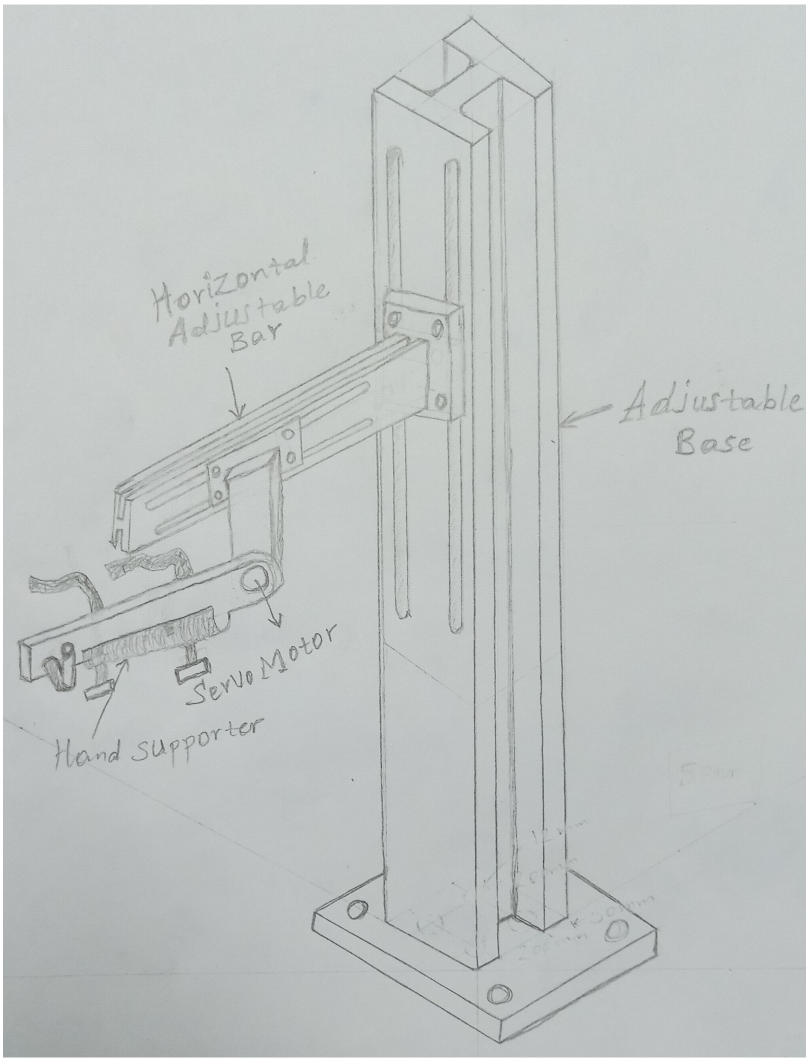


Fig. 3.5: Vertical Standing robot Adjustable with Bolt

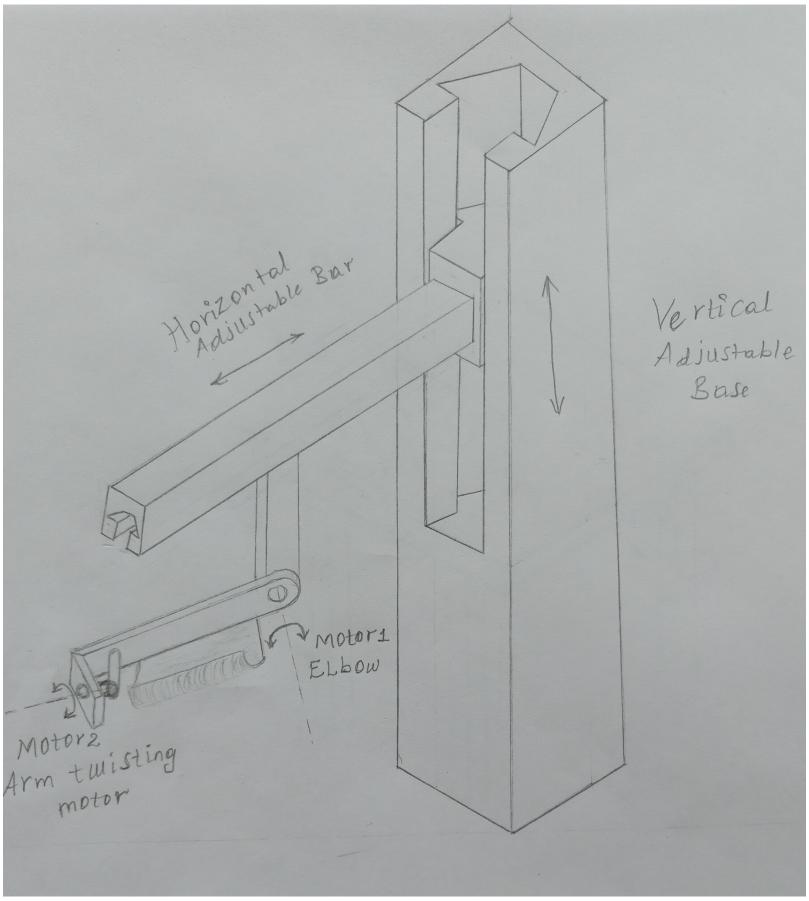


Fig. 3.6: Vertical Standing robot Adjustable with Guide Ways

This conceptual design is the same as the first design but the only difference that both the horizontal and vertical sliding mechanisms are changed to some guidway like structure to avoid load stress on bolts and to increase the surface contact between mates of the sliding parts. The figure is shown in the Fig. 3.6

- **Concept Design 3: Design Mounted on the Table** This is the third conceptual design which is built on the table. The table is made with the average height of the location of the forearm of the seated patient. The structure of the robot arm link is the same as the previous designs. The patient seat on the chair near the table with the adjusted position. The design is shown in the Fig. 3.7.

- **Concept Design 4: Design Mounted beside the chair**
  The fourth design as shown in the Fig.3.8 which is built beside the chair. The mechanism is adjusted upward and downward with some gear mechanism.

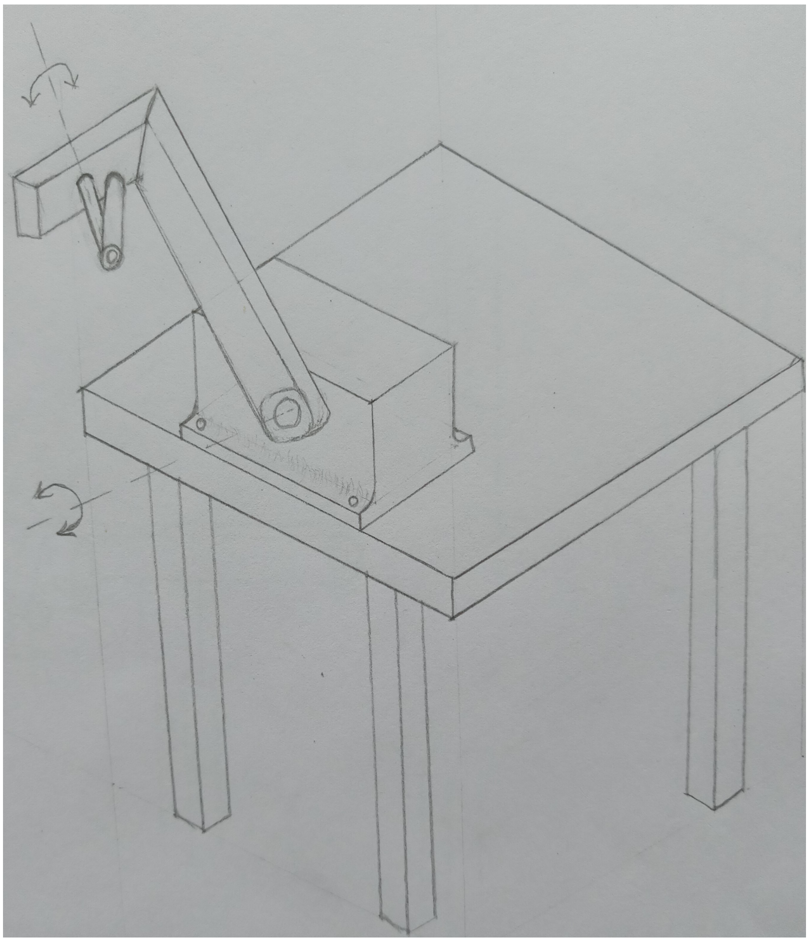


Fig. 3.7: Design Mounted on the Table

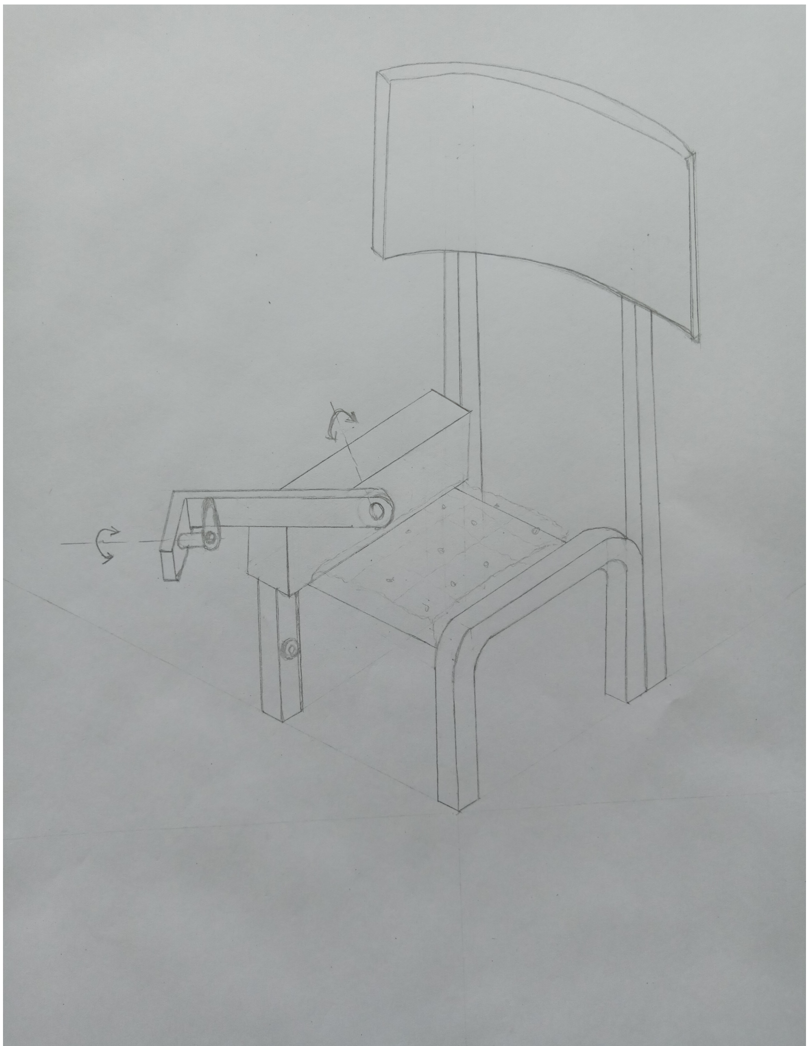


Fig. 3.8: Design Mounted on the chair

3.2.2 Concept Selection and Scoring

Concept selection is the process of evaluating concepts with respect to patient needs in-terms of ergonomics and other criteria. By evaluating the relative strengths and defects of the concepts, one or more concepts will be selected for further investigation. After concepts for the various sub problems were generated, the above four combined Elbow rehabilitation concepts are then compared to each other in order to select the most promising option. A two-stage concept selection methodology is used in this thesis. The first stage is the concept screening and the second one is the concept scoring. Screening is a quick, approximate evaluation and selection of concepts aimed at producing a few refined alternatives. Scoring is a more carefully and precisely analyzing of these relatively few concepts in to choose the single concept which mosty to lead to comfortable robot structure for the patients. Pugh's Concept selection method developed by Stuart Pugh in the1980s is a widely accepted method for comparing and evaluating concepts that are not purely refined for the direct comparison with the rehabilitation requirements [23]. Following are the steps involved in this method. In the comparison of the effectiveness between above four different types of combined concepts that are used in elbow rehabilitation is being done. The concept selection activity for both concept screening and scoring follow the following six-step process [23].

1. Prepare selection matrix
2. Rate the concepts
3. Rank the concepts
4. Combine and improve the concepts
5. Select one or more concepts
6. Reflect on the results and the process

The criteria are identified by examining the Patient requirements and generating a corresponding a set of engineering requirements and targets. The choice of effective concept will conduct based on the following criteria. The developed design criteria are listed below:

1. Comfortability
2. Ergonomics
3. Flexibility
4. Design simplicity

Table 3.3: Evaluation on the basis of Pugh's concept selection method for Elbow rehabilitation Robot

Criteria	**Concept Design 1 (Reference)**	**Concept Design 2**	**Concept Design 3**	**Concept Design 4**
Comfortability	0	0	-	+
Ergonomics	0	0	-	+
Flexibility	0	0	-	0
Design simplicity	0	0	+	+
Reliability	0	+	0	0
Cost	0	0	+	+
Durability	0	+	0	+
Easily Maintainability	0	+	0	+
Sum +'s	0	3	2	6
Sum 0's	8	5	3	2
Sum –'s	0	0	3	0
Net Score	0	3	-1	6
Rank	3	2	4	1
Continue?	YES	YES	NO	YES

5. Reliability
6. Cost
7. Durability
8. Easily maintainable

- **Concept Screening**
  To represent how each concept rates in comparison to the reference concept a relative score of "better than" (+), "same as" (0) or "worse than" (-) is placed in each cell of the matrix relative to the particular criterion.

- **Concept Scoring**
  Because of the need for additional resolution to distinguish among computing concepts, a finer scale is now used. A scale of 1 to 5 is recommended.

Table 3.4: The concept scoring matrix for Elbow Rehabilitation Robot

		Design Concepts					
		Design Concept 1 (Reference)		**Design Concept 2**		**Design Concept 4**	
Criteria	Weight	Rating	weighted score	Rating	weighted score	Rating	Weighted score
Comfortability	25%	3	0.75	3	0.75	4	1
Ergonomics	20%	3	0.6	3	0.6	4	0.8
Flexibility	20%	3	0.6	3	0.6	3	0.6
Design simplicity	10%	3	0.3	3	0.3	4	0.4
Reliability	10%	3	0.3	4	0.4	3	0.3
Cost	5%	3	0.15	3	0.15	4	0.2
Durability	5%	3	0.15	4	0.2	4	0.2
Easily maintainable	5%	3	0.15	4	0.2	4	0.2
	Total Score		3		3.2		3.7
	Rank		3		2		1
	Continue?		NO		NO		DEVELOP

Relative Performance	**Rating**
Much worse than reference	1
Worse than Reference	2
Same as reference	3
Better than Reference	4
Much better than reference	5

Once the ratings of each concepts are entered, then the weighted scores are calculated by multiplying the raw scores by the respective criteria weight. The total score is then evaluated by the sum of the weighted scores. Finally each concept will be ranked with the corresponding total score. So, from the above result of concept scoring matrix for Elbow rehabilitation robot, design mounted with chair mechanisms have been the final selected concept design.

3.3 Dimensioning and development using Solid Work

3.3.1 Design Consideration

The Design of Elbow rehabilitation robot for post immobilization of fractured hand should take safety measures in an important position because of its long-term contact with human body in work process [9]. Thus, design of the rehabilitation robot should satisfy with goals as follows:

1. The length of rehabilitation robot can be adjusted to adapt to different size of patients with rehabilitation training.
2. The rehabilitation robot can realize the movement and activities of daily living function coordinately by elbow.
3. The movement of the robot should be smooth, meanwhile, axes of robot rotation should be the same as human rotation which can protect human from injury.
4. The range of the robot rotation should be as per the pain level of the patient.

3.3.2 Mechanical Structure design of the Robot

The Upper limp rehabilitation robot structures resembles to the human upper limp anatomy. This structure should measure every joint angle of the upper limb precisely. However, it is very crucial to align robot axis and joint axis properly. This is due to the reason that misalignment causes joint injuries in the upper limb of the patient. The structure design of elbow rehabilitation robot is designed using solidwork 2018 as shown in the Fig 3.9.

3.4 Mechanism of the System

The selected concept design of the Elbow Rehabilitation Robot is designed using solid work 2018. The structure has five parts including the chair, Vertically and horizontally adjustable standing the box containing the motor and gearbox assembly, the forearm link(link 1) and link 2.

The chair is designed with the average dimension of human adult. it is connected with the standing by adjustable mechanism. The standing is also adjustable vertically to enhance the ergonomics aspect of the patient. The box containing the motor and gear assembly directly connected witn the arm link and the motor drives the link according to the control

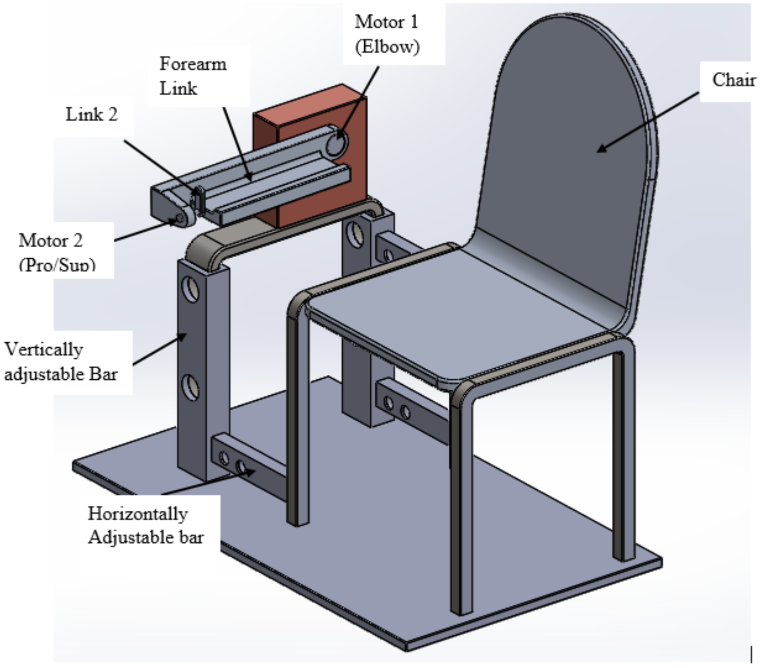


Fig. 3.9: Mechanical Design of Elbow-Forearm Rehabilitation Robot

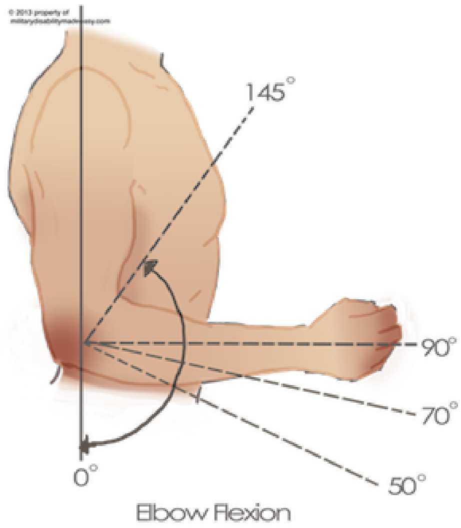
algorithm. The forearm link is designed in such away that to support the enjured hand. This link is used to rehabilitate the elbow according to the pain level of the patient. Then link 2 will perform the Pronation and supination of the forearm.

3.4.1 Flexion and Extension of Elbow

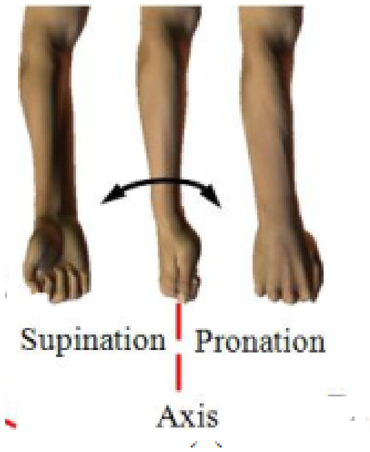
Flexion and Extension of the elbow joint as shown in the Fig.3.10(a) has a maximum range of motion of $140^o - 145^o$ [8]. Depending on the enjuries of the patient, the position of the forearm after immobilization may be at the flexion position. Then the elbow joint of the robot adjusted in similar alignment and the precise oscillatory movement will be carried out based on the pain level of the patient.

3.4.2 Pronation and Supination of Forearm

In addition to the flexion and extension of the elbow, the twisting exercises also necessary. Pronation and supination (see Fig. 3.10(b)) are a pair of unique movements possible only in the forearms and hands, allowing the human body to flip the palm either face up or face down. The muscles,joints and bones of the human forearm are arranged to allow these unique and usefull rotations of the hands. It has a range of motion of $160^o - 180^o$ [8]. Link 2 has the responsiblity of this motion with the pain level of the patient.



(a) Flexion and Extension of Elbow joint



(b) Pronation and Supination of Forearm

Fig. 3.10: Movements of the Joints[9]

Table 3.5: Range of motion for active daily living tasks and rehabilitation robot

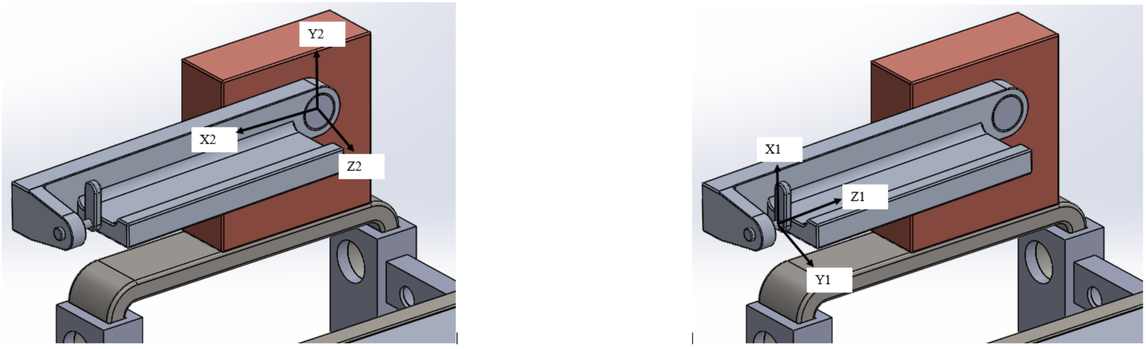
Joint	**ROM of active daily living tasks**	**ROM for rehabilitation robot**
Elbow (Flexion/Extension)	140-145 degree	As per the pain level
Forearm (Pronation/Supination)	160-180 degree	As per the pain level

3.5 Mathematical Modeling

3.5.1 Kinematic Modeling

To develop a rehabilitation robot, many medical aspects should be taken into consideration, such as the segment lengths, range of motion (ROM) and the number of degrees-of-freedom (DOF) of human arms. The human upper limp is kinematically redundant and it has 7 degrees of freedom (DOF) with 3 of them on its shoulder, 1 on elbow, and the remaining 3 on its wrist joints (excluding scapular motion). Here we are concentrating on injuries around elbow so that we are interested on adjustable one degree of freedom elbow rehabilitation robot and other one degree of freedom forearm pronation/supination. The elbow pitch movement has a range of motion of approximately 0 degree of extension and 140-145 degree of flexion [8]. Forearm Pronation/Supination also have a range of motion approximately 0 degreee Pronation and 160-180 degree of Supination.

In order to simplify the control process, kinematics of the elbow rehabilitation and forearm twisting has been calculated alone. First of all, frame attachments have been built



(a) Elbow joint (b) Forearm Twist

Fig. 3.11: Frame Attachments for joints

Table 3.6: Denavit-Hartenberg parameters for rehabilitation robot arm

Joint name	θ	D (mm)	a(mm)	α(deg.)	Range θ(deg.)	Motion
Elbow	θ_e	0	l_2	0	0-140	Rotate the Elbow (Reflex/Exten)
Forearm Twisting	θ_f	0	l_1	0	0-160	Forearm twisting (Pronation/supination)

as shown in Fig.3.11(a) and (b). And then the Denavit-Hartenberg parameters are provided as shown in 3.6, which bases on link frame attachments.

After the DH parameters are formed, the Transformation matrix of each link relative to the reference coordinate can be written according to the information in table 3.6, the transformation matrix of each link of the robot is calculated as shown in Eq. 3.1

The matrix A which represent the four movements of each link is found by postmultiplying the four matrices representing the four movements. Since all transformations are measured and performed relative to the axis of the current frame, all matrices are postmultiplied. The result is as follows.

$$A_{n+1} = Rot(z, \theta_{n+1})xTrans(0,0,d_{n+1})xTrans(a_{n+1},0,0)xRot(x, \alpha_{n+1}) \tag{3.1}$$

$$A_{n+1} = \begin{bmatrix} C\theta_{n+1} & -S\theta_{n+1}C\alpha_{n+1} & S\theta_{n+1}S\alpha_{n+1} & a_{n+1}C\theta_{n+1} \\ S\theta_{n+1} & C\theta_{n+1}C\alpha_{n+1} & -C\theta_{n+1}S\alpha_{n+1} & a_{n+1}S\theta_{n+1} \\ 0 & C\alpha_{n+1} & S\alpha_{n+1} & d_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.2}$$

In this elbow rehabilitation robot, there are two independent motions of one degree of freedom as shown on the DH Table 3.6 and on the Fig. 3.11. The transformation between fixed reference joint and joint 2 will be

$$A_1 = \begin{bmatrix} C\theta_f & -S\theta_f & 0 & l_1 S\theta_f \\ S\theta_f & C\theta_f & 0 & l_1 C\theta_f \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.3}$$

And the transformation between reference frame and joint 1 is

$$A_2 = \begin{bmatrix} C\theta_e & -S\theta_e & 0 & l_2 S\theta_2 \\ S\theta_e & C\theta_e & 0 & l_2 C\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.4}$$

The homogenous transformation matrix defined in eq. 3.3 and 3.4 defines the forward kinematics of the 2-DOF rehabilitation robot arm shown at Fig.3.11 (a) and (b). From this matrix, the position and orientation of end effectors is a non-linear function of joint variables P(x, y) = f (θ_e and θ_f). Having derived the forward kinematics or direct kinematics, it's now possible to obtain the end effector position and orientation from the individual joint angles (θ_e and θ_f). For the forearm twisting using joint 1:

$$
\begin{aligned}
x_f &= l_f cos\theta_f \\
y_f &= l_f sin\theta_f \\
z_f &= 0
\end{aligned} \tag{3.5}
$$

and for elbow joint or joint 2:

$$
\begin{aligned}
x_e &= l_e cos\theta_e \\
y_e &= l_e sin\theta_e \\
z_e &= 0
\end{aligned} \tag{3.6}
$$

By differentiating the above two expressions (3.5 and 3.6)

$$
\begin{aligned}
\dot{x}_f &= -l_1 \dot{\theta}_f sin\theta_f \\
\dot{y}_f &= l_1 \dot{\theta}_f cos\theta_f
\end{aligned} \tag{3.7}
$$

In matrix form:

$$
\begin{aligned}
\begin{bmatrix} x_f \\ \\ y_f \end{bmatrix} &= \begin{bmatrix} -l_1 sin\theta_f \\ \\ l_1 cos\theta_f \end{bmatrix} \begin{bmatrix} \dot{\theta}_f \end{bmatrix}, \\
\dot{X}_f &= \begin{bmatrix} J_f \end{bmatrix} \begin{bmatrix} \dot{\theta}_f \end{bmatrix}
\end{aligned} \tag{3.8}
$$

Similarly for elbow joint

$$
\begin{aligned}
\dot{x}_e &= -l_2 \dot{\theta}_e sin\theta_e \\
\dot{y}_e &= l_2 \dot{\theta}_e cos\theta_e
\end{aligned} \tag{3.9}
$$

In matrix form:

$$\begin{bmatrix} x_e \\ y_e \end{bmatrix} = \begin{bmatrix} -l_2 sin\theta_e \\ l_2 cos\theta_e \end{bmatrix} \begin{bmatrix} \dot{\theta}_e \end{bmatrix} \tag{3.10}$$

$$\dot{X}_e = \begin{bmatrix} J_e \end{bmatrix} \begin{bmatrix} \dot{\theta}_e \end{bmatrix}$$

Where, $\dot{X}_f$ and $\dot{X}_e$ are the velocities of end effector of forearm joint and elbow joint respectively, J_f and J_e are Jacobean matrices and $\dot{\theta}_f$ and $\dot{\theta}_e$ represents joint rates. Jacobean matrices represents the relationship between rates of change of position with respect to joint rates.

3.5.2 Dynamic Modeling

In the previous section we studied the kinematics position and differential motion of robot. Dynamics of robot related to the accelerations, loads, masses and inertia. In order to be able to accelerate a mass have to apply a force on it. Similarly to cause an angular acceleration in a rotation body a torque must be exerted on it. To do this, the robot should have joint motors that can feed enough torques on joints and links of the manipulator. This enables the link to move at a desired velocity and acceleration. Otherwise the links can not be moving as fast as necessary and consequently the robot may not maintain its desired positional accuracy. Here, determining the dynamics of the robot will help to calculate the strength of actuators. These relationships are the force mass acceleration and the torque inertia angular acceleration dynamic equations. Based on this equation and considering the external loads on the robot, the designer can calculate the largest loads to which the actuators may be subjected, thereby designing the actuators to be able to deliver the necessary forces and toques or volts [26]. We can derive the dynamic equation of motion for the two joints of rehabilitation robot arm of the above Fig. 3.11 (a) and (b) using the Euler-Lagrange formulation due to its simple 2 DOF [27]. It is done by considering that the center of mass for each link is at the center of the link and the moments of inertia are I_f and I_e for link 1 and link 2 respectively.

The dynamics of a rehabilitation manipulator is worked out to illustrate the Lagrange-Euler formulation to clarify the problems involved in dynamic modeling. For the manipulator links 1 and 2, joint variables are θ_f and θ_e link lengths are l_f and l_e and mass of links are m_f and m_e and l_{cf} and lce are the distance between the joint and center of mass of the link 1 and 2 respectively.The angular positions and angular velocities are θ_f, θ_e, $\dot{\theta}_f$, and $\dot{\theta}_e$ respectively. In this case, the datum (zero potential energy) is chosen at the axis of rotation "O".

Kinetic and Potential Energy

To drive the dynamics using lagrangian, first the kinetic and potential energies should be formulated. For link 1 the kinetic and potential energies are:

Lagrangian Equation

$$L = K – P \tag{3.11}$$

First, the kinetic energy of link one is calculated as:

$$K_f = 1/2 m_f V_f^2 + 1/2 I_f \theta_f^2 \tag{3.12}$$

where, The tangential velocity squared term is calculated as:

$$V_f^2 = \dot{x}_f^2 + \dot{y}_f^2 \tag{3.13}$$

By substituting $\dot{x}_f$ and $\dot{y}_f$ from eq. 3.5, we will have

$$K_f = 1/2 m_f l_{cf}^2 \dot{\theta}_f^2 + 1/2 I_f \theta_f^2 \tag{3.14}$$

and the potential energy can be calculated as

$$P_f = 1/2 m_f g l_{cf} sin(\theta_f) \tag{3.15}$$

Then the Lagrangian will be

$$\begin{aligned} L_f &= K_f – P_f \\ &= 1/2 m_f l_{cf}^2 \dot{\theta}_f^2 + 1/2 I_f \theta_f^2 - 1/2 m_f g l_{cf} sin(\theta_f) \end{aligned} \tag{3.16}$$

Then, the kinetic energy of link two is calculated similarly as:

$$K_e = 1/2 m_e V_e^2 + 1/2 I_e \theta_e^2 \tag{3.17}$$

where, The tangential velocity squared term is calculated as:

$$V_e^2 = \dot{x}_e^2 + \dot{y}_e^2 \tag{3.18}$$

By substituting $\dot{x}_e$ and $\dot{y}_e$ from eq. 3.5, we will have

$$K_e = 1/2 m_e l_{ce}^2 \dot{\theta}_e^2 + 1/2 I_e \theta_e^2 \tag{3.19}$$

and the potential energy can be calculated as

$$P_e = 1/2m_e g l_{ce} sin(\theta_e) \tag{3.20}$$

Then the Lagrangian will be

$$\begin{aligned} L_e &= K_e – P_e \\ &= 1/2m_e l_{ce}^2 \dot{\theta}_e^2 + 1/2I_e \theta_e^2 - 1/2m_e g l_{ce} sin(\theta_e) \end{aligned} \tag{3.21}$$

The derivatives of the lagrangian from the above equation are

$$\begin{aligned} \frac{\partial L_f}{\partial \dot{\theta}_f} &= m_f l_{cf}^2 \dot{\theta}_f + I_f \dot{\theta}_f \\ \frac{\partial}{\partial t}(\frac{\partial L_f}{\partial \dot{\theta}_f}) &= m_f l_{cf}^2 \ddot{\theta}_f + I_f \ddot{\theta}_f \\ \frac{\partial L_f}{\partial \theta_f} &= -1/2m_f g l_{cf} cos(\theta_f) \end{aligned} \tag{3.22}$$

and similarly for link 2

$$\begin{aligned} \frac{\partial L_e}{\partial \dot{\theta}_e} &= m_e l_{ce}^2 \dot{\theta}_e + I_e \dot{\theta}_e \\ \frac{\partial}{\partial t}(\frac{\partial L_e}{\partial \dot{\theta}_e}) &= m_e l_{ce}^2 \ddot{\theta}_e + I_f \ddot{\theta}_e \\ \frac{\partial L_e}{\partial \theta_e} &= -1/2m_e g l_{ce} cos(\theta_e) \end{aligned} \tag{3.23}$$

From above derivation, the equation of motion for the two joints is given as follows:

$$\begin{aligned} \tau_f &= \frac{\partial}{\partial t}(\frac{\partial L_f}{\partial \dot{\theta}_f}) - \frac{\partial L_f}{\partial \theta_e} \\ &= m_f l_{cf}^2 \ddot{\theta}_f + I_f \ddot{\theta}_f + 1/2m_f g l_{cf} cos(\theta_f) \end{aligned} \tag{3.24}$$

and

$$\begin{aligned} \tau_e &= \frac{\partial}{\partial t}(\frac{\partial L_e}{\partial \dot{\theta}_e}) - \frac{\partial L_e}{\partial \theta_e} \\ &= m_f l_{ce}^2 \ddot{\theta}_e + I_e \ddot{\theta}_e + 1/2m_e g l_{ce} cos(\theta_e) \end{aligned} \tag{3.25}$$

Manipulator Dynamics

Rewriting the above robot arm dynamics in vector form yields:

$$M(\theta)\begin{bmatrix}\ddot{\theta}_f\\ \\ \ddot{\theta}_e\end{bmatrix}+\begin{bmatrix}1/2m_f g l_{cf} cos(\theta_f)\\ \\ 1/2m_e g l_{ce} cos(\theta_e)\end{bmatrix}=\begin{bmatrix}\tau_f\\ \\ \tau_e\end{bmatrix} \tag{3.26}$$

The dynamic equation for the nonlinear model of n-DOF robotic manipulator with a set of n generalized coordinates θ^T = [θ_1,θ_2... θ_n] is given as [3].

$$M(\theta)\ddot{\theta}+V(\theta,\dot{\theta})+G(\theta)=\tau \tag{3.27}$$

where

$$M(\theta)=\begin{bmatrix}m_f l_{cf}^2+I_f\\ \\ m_e l_{ce}^2+I_e\end{bmatrix} \tag{3.28}$$

3.6 Dynamic Model of Elbow-Forearm Rehabilitation Robot using ADAMS

The physical model of the elbow-forearm rehabilitation robot is designed with solidwork 2018. The mathematical model both kinematic and dynamic model is computed analytically. Then, the other models such as parametric models and Multi body models which are developed with Adam's software [28]. The parametric model of the elbow rehabilitation manipulator was imported in ADAMS View from solidwork 2018 and it is shown in Fig. 3.12. The model contains bodies, gear boxes, Servo motors, joints, gears, gravity, applied torques and forces, damping forces and friction in joints.

The length of the arm link is considered as a design variable and its dimension could be adjusted as desired. The system parameters including material, inertia moment and mass could be optimized using the results of co-simulation afterwards [28]. Additionally, The multi-body model (MTB) of the system could be achieved using a joint motion. In this motion, the kinematic analysis would have been studied. On the other hand, the applied torque drives the body and the dynamic property will have been analyzed. Here are some of the procedures to have the dynamic model of the system. First, the solid work model file is saved in parasolid file format or in ".x_t" file extension which is suited in ADAMS. then after opening the ADAMS file option, go to the import option and use the directory we have saved to open the model as shown in Fig.3.12.

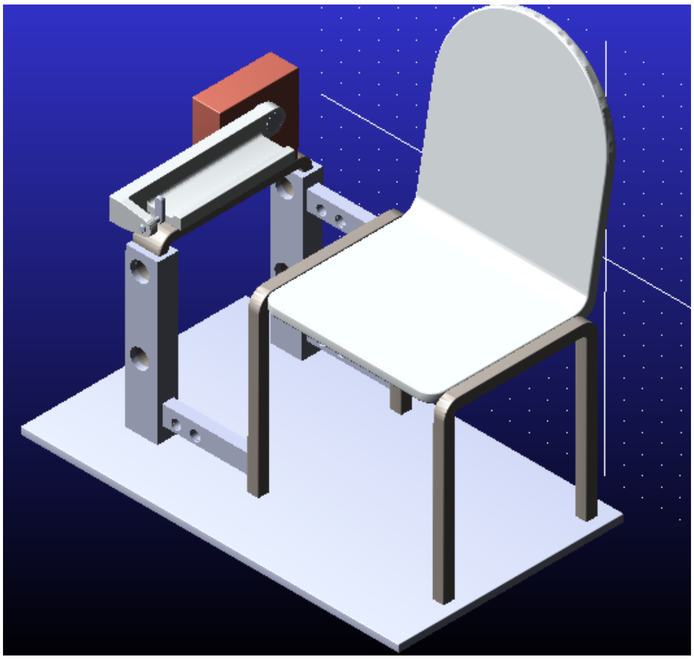


Fig. 3.12: Imported Mechanical Model in Adams

3.6.1 Importing Mechanical Model from Solid work

The Mechanical model developed in solidwork see Fig.3.9 is imported into ADAMS in order to perform the cosimulation. First the SOLID WORKS assembly document that has hidden or suppressed components are exported using parasolid option in the form of Parasolid text or binary file, as $(*.x_t, *x_b)$ file extension will be saved to a specific folder or directory. Then by opening the MSC-ADAMS and selecting the 'select' file radio button, we select the file type that we have exported before and open it.

3.6.2 Creating Joints and Motions

The first task after opening the imported model is to merge fixed parts together. Then the whole assembly is fixed with ground by fixed joint. Since we have two joints i.e the elbow joint and the forearm twisting joint, these joints are created by revolute joint. With the respective revolute joints, motions are created as shown in Fig.3.13. The input of this motion will be the variable torque. So, in this model, there are three joints and two motions to perform both the elbow Flexion-Extension and the forearm pronation-Supination exercises.

3.6.3 Determining Input and Output Variables

The input and output data from ADAMS is the communication interface with the MATLAB control system. The output variable in ADAMS is the input variables into the control system where as the output variable of the control system is the input variables of ADAMS,

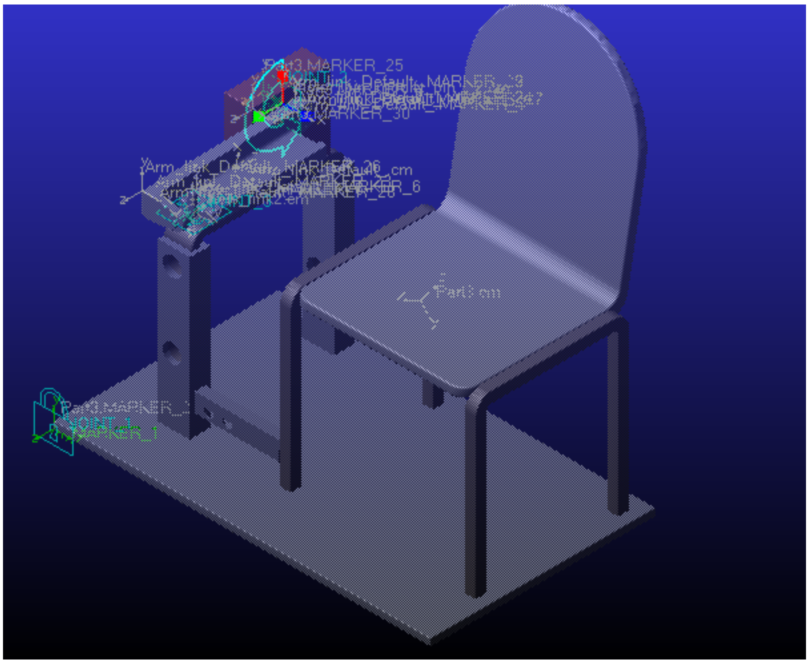


Fig. 3.13: Joints and Motions of the Manipulator Mechanism

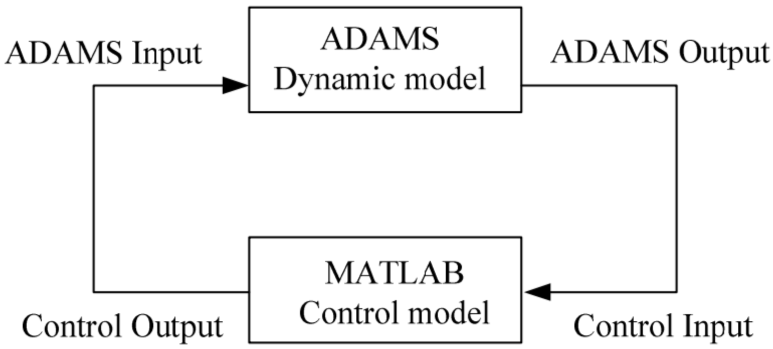


Fig. 3.14: The input/output process between ADAMS and MATLAB [29]

and it completes a closed-loop control from ADAMS to MATLAB [29]. The input/output process is shown in Fig. 3.14. Here in our system, Control Torque is created as an input variable whereas Range of Motion and angular speed are created as an output variables in ADAMS perspective.

3.6.4 Exporting ADAMS Plant to Matlab/Simulink

In ADAMS 2018, there is Menu bar called Plugins, Go through 'Controls' and 'Plant Export' then 'Adama Control Plant Export' will appear as shown in Fig.3.15. Here the Plant name, the input and output signals are defined. Finally by selecting the target software in our case MATLAB, the Adams Plant will be exported.

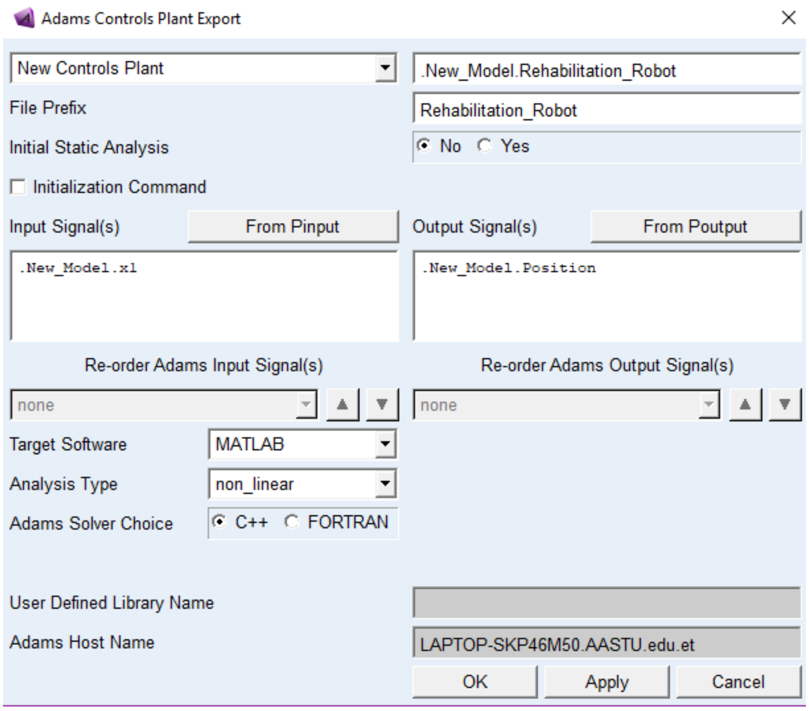
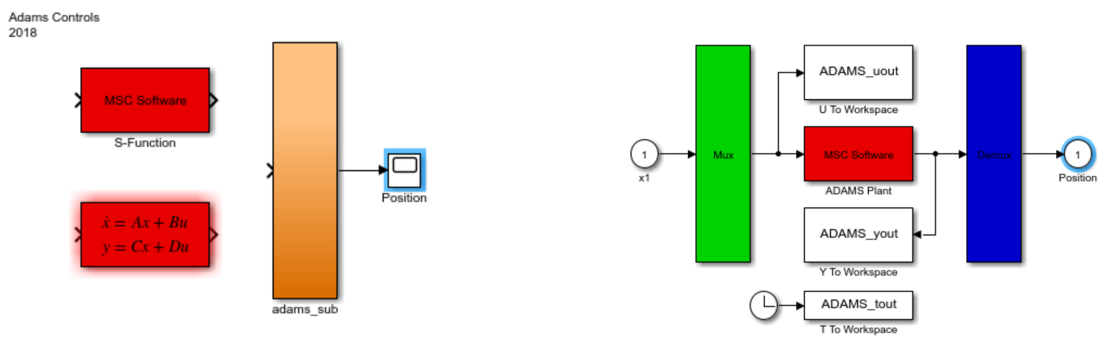


Fig. 3.15: Exporting Adams Plant

3.6.5 Importing the Dynamic model to Matlab

To import the Adams Model in matlab, first the Matlab should be opened and the working directory of the matlab should be changed to the one in which the exported Adams file(Rehabilitation Plant.m) resides. Now by writing the 'Rehabilitation Plant' on the command prompt the input and output state variables will be displayed. the by typing $<< adams - sys$, the dynamic Plant model will appear in simulink as shown in Fig.3.16

In MATLAB, we will run the m-file which is generated during the plant export. It defines the variables with all the relevant information. Then we enter adams-sys to the MATLAB prompt. This will builds a new model in Simulink named adams-sys.mdl. Meaning



(a) The whole block (b) Adams Sub-block

Fig. 3.16: Adams Dynamic Model

of individual blocks is based on [30]:

- The S-function block representing the mechanical system
- The Adams-sub containing the S-Function (or the state-space block, if the model is linear), but also creates several useful variables (input, output variables)
- The State-Space block representing linearized Adams model

3.7 Summary

Here we summarize that the mechanical model of the proposed Elbow-Forearm rehabilitation robot has been selected and developed successfully. This two degree of freedom manipulator has rugged and Adjustable structure which is developed by considering the ergonomic conditions of the patients. The concept generation and selection plays a great role in selecting the proposed concept designs. Finally the design is developed using Solid work 2018 and then imported to ADAMS to generate and analyzes the Dynamic model of the system. And it is ready to further investigation on the system.

Chapter 4

Data Aquisition System

4.1 Introduction

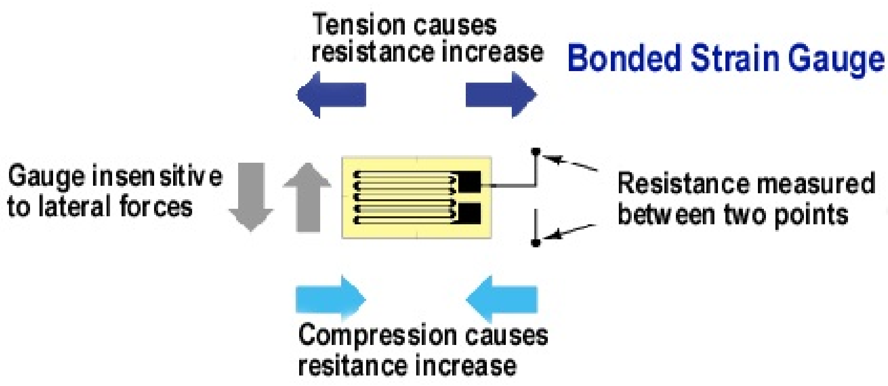
Data acquisition (DAQ) is the measure of physical or an electrical quantities such as voltage, temperature, current, pressure, or sound with a computer. It consists of sensors, DAQ measurement hardware and a computer with programmable software to measure the quantity. PC-based DAQ systems provides the productivity, the processing power, display and connectivity of industry-standard computers providing a more flexible, powerful and cost-effective measurement solution as Compared to traditional measurement systems.

In this research, pain level of the patients for Fractured hand especially around elbow will be detected using strain gauge sensors. Most Rehabilitation robot developments [6] uses surface electromyography (sEMG) electrodes. The number of sensors required increases with the increase of the number of degrees of freedom in the recent Upper limp rehabilitation robots, i.e. dozens of sensors today. However, sEMG sensor requires a high sampling frequency of about 1000 Hz, which limits the number of sensors that the processors can manage [20]. The objective is to develop a device which enable us to measure muscle strain/ muscle contractions (MCs) with a sampling frequency compared with the movement frequencies. Strain gauges are known in their accuracy. So, the use of these sensors to detect MCs could help to predict the pain level by measuring the muscle contraction and by asking patients with different injury level. The designed device includes the integration of four strain gauges that are attached to human skin. The advantage of a low sampling frequency compared with sEMG is the potential development of matrices with many strain gauges [20].

4.2 Theoretical Background of Strain gauge Measurement

This section presents the measurement of muscle contraction using strain-gauges, where the data acquired using an Arduino Uno board. We choose arduino due to its low-cost and easy manipulation [31]. A Wheatstone Bridge, the instrumentation amplifier and Analog-Digital Converter (ADC) of the Arduino are used for signal conditioning. This proposed measurement system is applied on patients of fractured hand especially around elbow and forearm.

There are different experimental procedures for measuring mechanical strain using electrical strain gauges, that can be based on resistive [32], inductive [33], capacitive [34] and photoelectric [35]. Among these, the most common applied method is based on the use of resistive-based strain-gauges. These devices directly used to measure the strain by measur-



(a) Strain Gauge inner working principle

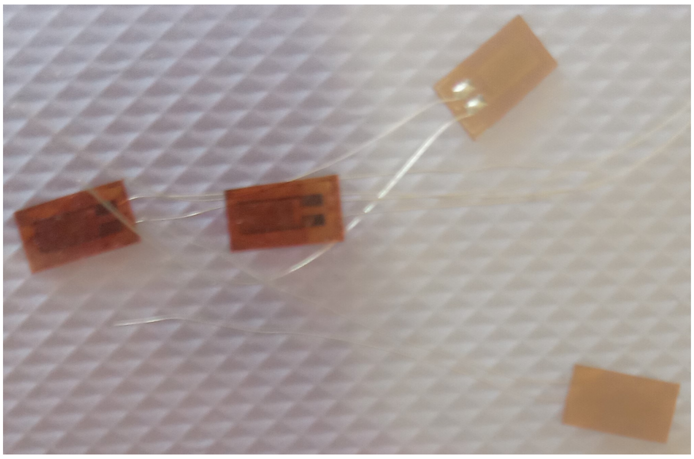

(b) Strain gauge Sensor

Fig. 4.1: Strain Gauge and its inner working principle [36]

ing the change in the electrical resistance as they are subjected to physical deformations, which is commonly done by using a Wheatstone bridge.

4.2.1 Strain Gauge

A strain gauge is used to measure the strain that occurs in an object. It is used in many electronic circuits as the principle sensing element for sensors like load cells, torque sensors, pressure sensors and so on. It's electrical resistance varies in a proportional manner to the amount of strain in the device to be studied. The commonly used strain gauge sensor is the bonded-metallic strain gauge. It consists of a very fine wire or, metallic foil arranged in a grid like pattern.

Sensitivity to strain is fundamental parameter of the strain gauge which is expressed quantitatively as the gauge factor (GF). Gage Factor is the ratio of the fractional change in electrical resistance to the fractional change in length, or strain:

$$GF = \frac{\delta R/R}{\delta L/L} = \frac{\delta R/R}{\varepsilon} \tag{4.1}$$

where ε is the strain The force exerted to elongate or shorten the strip can be determined with the help of the obtained output resistance. The resistance of an ideal strain gauge varies from a few 3 ohms to 3 kilo ohms when it is unstressed condition. Then this value will change by a small fraction for the full force range of the strain gauge. If a strip of conductive metal is stretched see Fig.4.1, it will become skinnier and longer, which will result an increasing electrical resistance. On the other hand, when we compress the strain gauge, it will broaden and shorten, hence the electrical resistance will decrease as well. If these stretches don't exceed strain gauge's elasticity, the strip can be used for measuring weight.

4.2.2 Wheatstone Bridge

Since the change of resistance in strain gauge measurement is very small, it is difficult to measure the resistance between two points. The change could be in micro-ohms. The usual way to measure such small changes is to use a wheatstone bridge see Fig. 4.2. The Wheatstone bridge consists of four resistors connected in a square arms. It works in a way that when the bridge is balanced, then the output voltage will be zero. But when the resistance of one of the bridge arm changes, the bridge will produce an output voltage. This circuit is used for converting the micro-strains into micro-voltage changes. These micro-voltages are amplified with an instrumentation amplifier. Then it will fed into ADC pin in arduino micro-controller.

4.3 Experimental Setup For Data Collection

To detect and measure the deformations of the strain gauge in turn, the muscle contraction , a simple electronic circuitry is used which consists two main circuits. i.e the Wheatstone bridge circuit and the Amplifier Circuit.

4.3.1 Practical wheatstone Bridge Circuit

The matreial used for setting up the wheatstaone bridge circuit includes:

- Strain Gauge(BF120-6AA model)
- Arduino Uno Board
- Computer(Laptop)
- Connecting wires for Circuitry

The Wheatstone bridge shown in the Fig. 4.4 is demonstrated to show how the bridge is connected and to show that it is working well. Generally, the two opposite arm of the

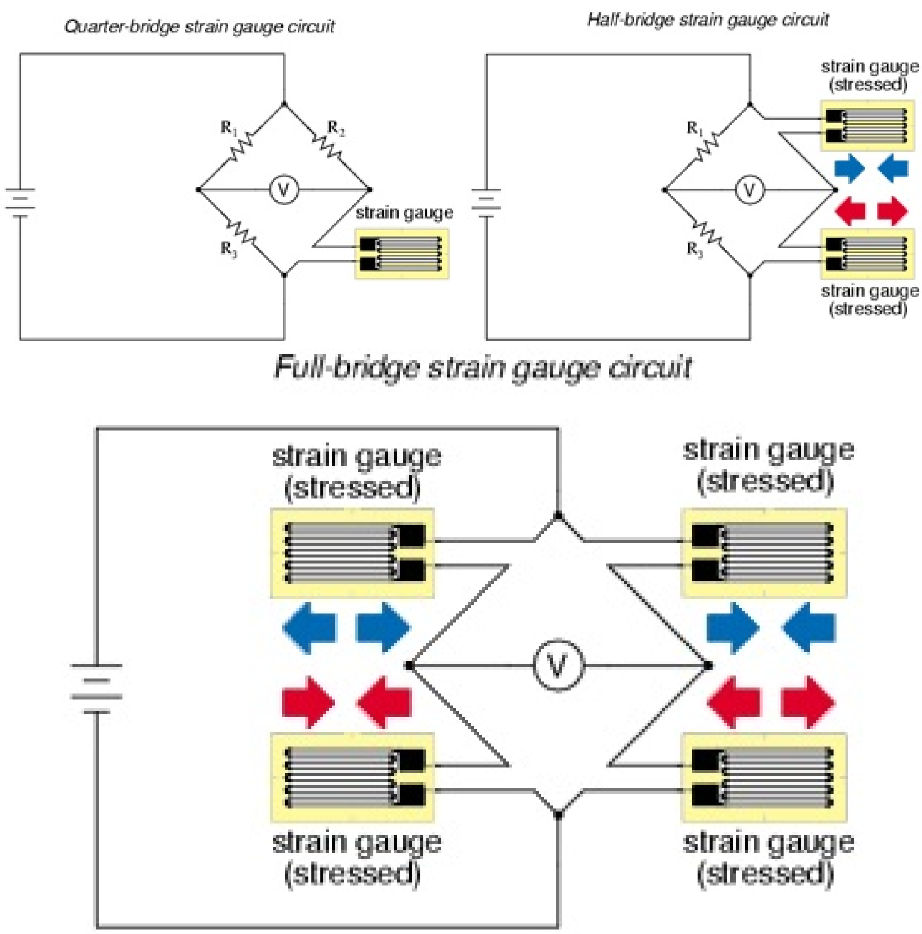
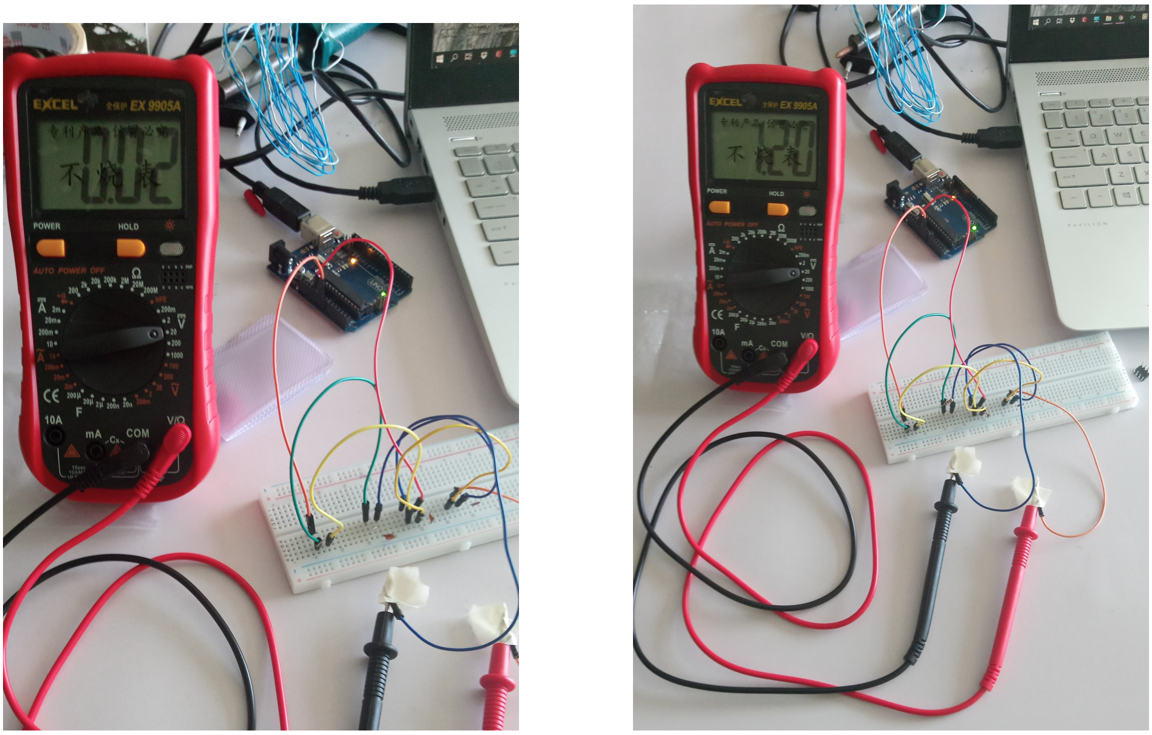


Fig. 4.2: Types of Wheat stone Bridge [36]

Fig. 4.3: Signal Transformation



(a) One arm resistor Strain gauge circuit (b) Full-Bridge Strain gauge Circuit

Fig. 4.4: Practical Wheatstone Bridge Circuits

Bridge is powered from Arduino 5V port which is connected to the PC using USB. The other two opposite arms are connected to the Multimeter to read the output Voltage. Fig. 4.4 (a) is the full bridge strain gauge circuit which consists of four strain gauge. Since it is balanced, the output should indicate a zero Voltage. However it indicates 0.02V. This is because the strain gauges are deflected/bended in some extent so that there will be some change in resistance inturn in output voltage. In the Fig. 4.4 (b), one arm of the bridge is replaced with resistor of 950 ohms. Here the bridge is unbalanced and there is a visible output voltage of 1.2V. So, we can generalize that the circuit works properly for further investigation.

4.3.2 The Combined Circuit with Amplifier circuit

The bridge circuit converts the change in resistance into a voltage that can be measured. Then after, an instrumentation amplifier amplifies the small amplitude of the signal.
First, full circuit design is designed in Proteus as shown in Fig. 4.5

The AD623/INA125 can be used with an amplifier gain of 450 and an offset of 1.3 V. However, we develop an amplifier circuit with a gain of 16 and of an offset voltage of $\pm 30mV$. Here the strain gauge sensors are extended through thin flexieble wire to make it suitable for the patients and the bridge circuit is well suited. The remaining is the amplifier circuit which is composed of two LM358 model op-amps and different resistors as shown

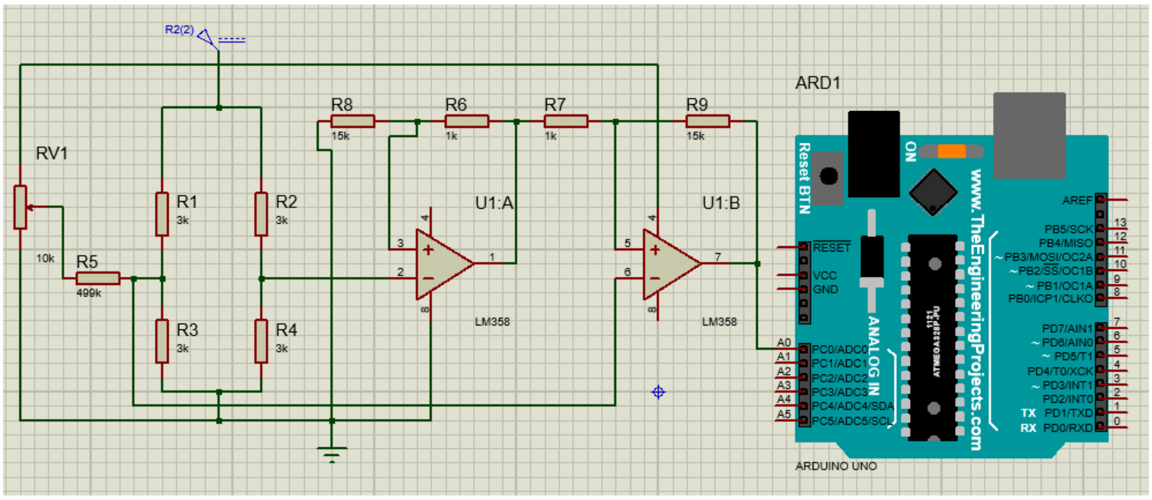


Fig. 4.5: Proteus Circuit Design

in the Fig.4.6.

4.4 Integration of the Circuit with Arduino

The developed instrumentation circuit is successfully integrated with Arduino. First the output of the Wheatstone bridge is feed to the instrumentation Amplifier. Then the output voltage of the amplifier is directly connected to the Analog input of the Arduino board $A0$. The arduino has a ten bit ADC which converts the analog input to the digital output. We use a 5V reference Voltage from the Arduino so that each output voltage of the strain gauge will be converted to the corresponding ten bit digital value. It has a resolution of 0.005V which is calculated as follows

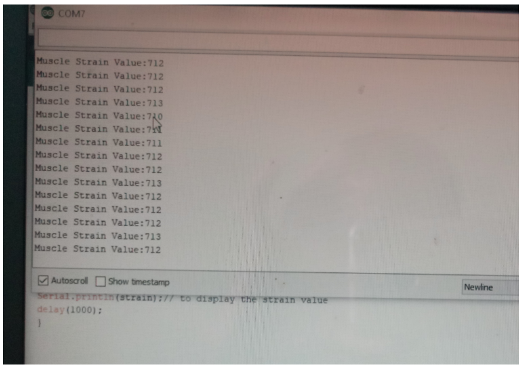
$$Resolution = \frac{ReferenceVoltage}{2^n} \tag{4.2}$$

Where n is the number of bit of the ADC. Since we are using a ten bit ADC, $2^{10} = 1024$ range of digital value will be there. Now substituting 5V to a reference voltage will give the resolution.

$$\begin{aligned} Resolution &= \frac{5V}{2^{10}} \\ &\approx 0.005V \end{aligned} \tag{4.3}$$

Therefore, 0-5V of the strain gauge output will be converted to the corresponding 0-1023 digital value with a resolution of 0.005V and displayed on the Arduino monitor.
The Arduino Program to do this task is as shown in the Appendix A.

(a) Attaching the strain gauge sensor



(b) Display data on Arduino monitor

Fig. 4.6: Data Aquisition from Patients

4.5 Adjustment of patients for Data Aquisition

The data is aquired from patients in "TIRUNESH BEJING GENERAL HOSPITAL AND ABET GENERAL HOSPITAL" found in Addis ababa. First, we have faced a problem in buying a strain gauge and instrumentation amplifier. After finishing the setup of the circuitry, we went to Tirunesh Bejing Hospital. Here also things are not as simple forward as thinking. Most patients are not willing to permit the data acquisition. We are considering adults as a subjects of the experiment. The three general conditions of the patient are considered during the data aquisition by classifying them into Flaccid, Intermediate and Spastic patient conditions. Since the spastic type of patients have stiff pain, their data is estimated by the therapists with their past experience.

4.6 Data Aquisition

The data obtained from the data acquisition which indicates the muscle contraction are acquired by arduino using strain gauge. The pain level correspondingly asked from the patient and recorded manually and tabularize on the Appendix B.1 - B.3

But, to collect the accurately estimated data, the expert therapists consider the general condition of the patients. These are Flaccid, Intermediate and Spastic conditions[37]. Based on these Conditions,the expert physical therapist classify the strain measurements and the corresponding pain level using his past experience and by asking the patients.

Even though the theoretical range of muscle strain is 0-1023 ADC value, the practical

obtained range is 0-750 ADC value. This is due to the reason either on the error of the amplification circuit or on the adjustment of strain gauge sensor on the human body. There are acceptable measurement results which is tabulated on the Appendix B.1 - B.3
As shown on the table, the muscle strain values for for the three conditions of the patient are different. For the Flaccid type of patient, The first range 0-170 ADC value has not significance on the pain level of the patient. So the exercise starts from strain value of 170 and above. Since the state of enjury of this type of patient is relatively small, the duration of rehabilitation takes around 3 weeks. The intermediate type of patient also has the exercise duration of almost 4 weeks according to the expert's.

4.7 Summary

Generally from this data aquisition system, acceptable muscle strain is obtained and recorded. This mechanical strain of the muscle contraction is mapped to the pain level by considering different aspects such as the patient's general condition and the duration of the patient at which he/she starts the exercise.
All the data are recorded and evaluated by past experience of the expert therapist and by interacting with the patients. Even though some uncertainities are there in the instrumentation system, it is elliminated by taking the range and also by using fuzzy control algorithm.

Chapter 5

Control System Design

5.1 Introduction

Control system design in practice requires cyclic effort of iterating between modeling, design, simulation, testing, and implementation. Control system design also takes several different forms and each requires a slightly different approach [38]. In Rehabilitation Robotic Systems,various researchers uses different control approaches as stated in Literatures.

However, this research paper proposes an approach of generating input(reference) signal which is the determination of a desired range of motion of a manipulator. And also since the model is developed in ADAMS, the behavior of this ADAMS dynamic model is analyzed by using PID control approach. The whole control system has two sections. The First section deals with generating actual input signal (Reference signal) of Position of a manipulator developed with a fuzzy logic System. The second control system is the main controller which is PID control design as shown in the Fig.5.1 The value of the output signal of the first fuzzy system becomes the input as reference value of motor's position. Fuzzy Logic controls are smart system controls which have the ability to solve problems on complex systems that are not owned by conventional controllers[39]. We can control position for fixed speed or speed for a fixed position since both are directly related. So, in this work, we prefer position control for desired speed, which means our fuzzy controls the position of the actuator at a certain speed.

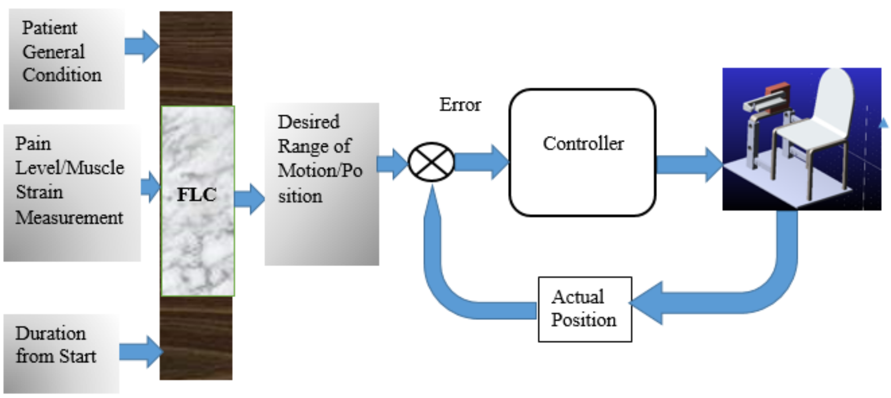


Fig. 5.1: Proposed Control System

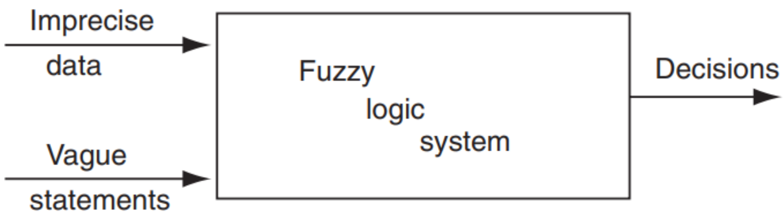


Fig. 5.2: A fuzzy logic system [41]

5.2 Fuzzy Logic Controller for Determination of desired Range of Motion

The emergence of fuzzy logic and its applications has dramatically changed the face of robotic and industrial control engineering [40]. The Fuzzy Logic tool was first introduced in 1965 by Lotfi Zadeh, and is a mathematical tool for dealing with uncertainty [41]. It provides a way of representing linguistic constructs such as " few ", " medium ", " many ". The reasoning capablities of human is enabled by inference structure of fuzzy logic. However, the ordinary binary set describe the crisp events that either on or off; true or false; do or do not occur. It is all about measuring the chance that the given event will or will not occur. The notion of fuzzy logic system is the relative membership grade and it is a function of cognitive process [41].
Real world problems are complex which involves the degree of uncertainty. So, appropriate assumptions and simplifications should be introduced to have acceptable compromise between the information we have and the level of uncertainty that we accept. The theory of fuzzy system like other engineering theories represents the real world in approximation. So, fuzzy set enables us to model the uncertainty with regard to the impression, vagueness of the problem.

In our case, the fuzzy system is used for developing the actual input signal of position of a link during the rehabilitation exercise.

5.3 Description and Analysis of Fuzzy Logic Systems

In the conventional physical therapy of the hand of the post stroke patients, the therapist determines the optimal exercise speed based on three parameters: (1) the elbow angle (2) the corresponding resistive torque, and (3) the patient's general condition [37].However, we are considering the rehabilitation of the fractured/ broken hand after immobilization. Here we are proposed a mechanism to estimate the excercise speed and the angle/range of motion based on three parameters. These are the (1) the Patient's general condition. (2) The pain level of the the patient correlated from the strain gauge measurement, and (3) Duration of exercise from starting day.

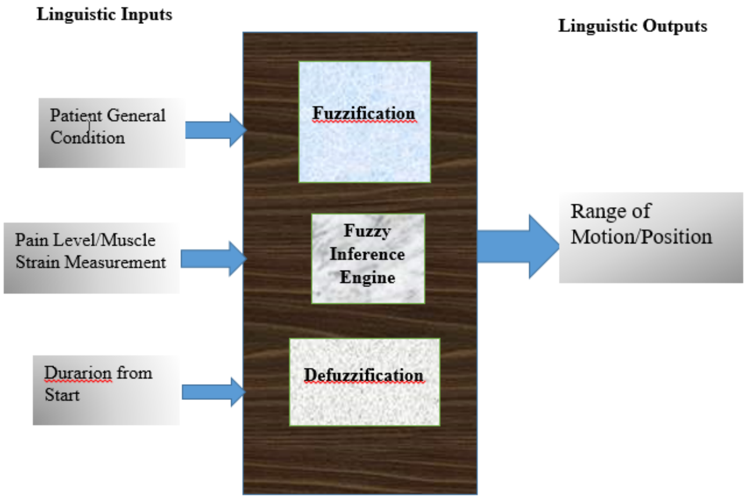


Fig. 5.3: FLC of Elbow Forearm Rehabilitation Robot

The Patient's general condition is decided by the expert therapist.Therapists have a great experience in classifying patients as Flaccid, Intermediate and Spastic [37]. Even though it is a simple task, they try to classify by trying to rehabilitate for the first time and try to see the feedback of the patient.

The second one is the pain level estimation from strain gauge which give the inteligence for the robot. After classifying the patients status, the strain gauge assembly will attached to the responsive muscle of the patient on the Forearm. Then the Muscle strain and the corresponding pain level will be Recorded in all conditions of the patient status.

The third case that should be considered is the duration of exercise from the start of the rehabilitation. it has a great effect on the range of motion of the manipulator. By combining these three determining characteristics with Fuzzy Logic, we can achieve a smooth rehabilitation exercises by providing the accurate input(reference)signal.

We assumed these parameters as the Linguistic inputs (LI) of the fuzzy controller see Fig. 5.3 and defined their membership functions considering their importance, evaluated through a critical consultation with an expert physical therapist.

5.3.1 Designing the Fuzzy Logic Using Matlab

The designed fuzzy logic has three inputs and one output as shown in the Appendix C.1 The Fuzzy Inference System (FIS) is used for determining the range of motion of the manipulator. In this design Menbership Function (MF) used for both input and output variables was triangular.

The General Condition of the patient is the first input variable of FIS. It has range of 1-10 and three membership Function i.e Flaccid, Intermediate and Spastic. as shown in Appendix C.2 (a). The membership plots are automatically generated by the fuzzy logic

toolbox. we only need to provide the range and the number of membership functions.
The pain level is directly mapped from the Muscle strain. Since the Arduino has 10 bit ADC, then the range of Muscle strain ranges from 0-1023 and it has Five membership function starts from very low to Very High see Appendix C.2 (b). Here due to some measurement errors and sensor mispositioning, the muscle strain ranges from 0-750 only.
The third Input variable is the time elapse from the first day of rehabilitation. As the expert therapist, the average duration of rehabilitation is 6-8 weeks. So in this research, 6 weeks are taken into consideration i.e 6 membership functions see Appendix C.2 (c). The range of the membership function is taken from 0-1.
To deal with fuzzy logic controller, the values for the input and output variables are determined in advanced. There is membership function (MF) which is used to map the crisp input values to the fuzzy values and suitable operation is applied on them. This process is known as fuzzification and fuzzifier is used for performing the fuzzification. Then the output of the FIS system is the desired range of motion or desired position of the manipulator during rehabilitation exercise. The range of motion of the human elbow is about 140-145 degrees [8], however we are considering 110 degree for practical aspect. So, the range of the first output is taken 0-110.

5.3.2 Fuzzy Inference Rules

The proposed Fuzzy Logic Controller inference engine is designed using 63 rules. This is because there are conditions which are not exists in practice as decided by the expert physiotherapist. The rules formed in this research are derived from the interaction with patients and based on experience of the physical therapist. The decisions made by the Fuzzy Logic Controller (FLC) are derived from these rules.
The 63 rules are formed using LIs for the respective LOs discussed in terms of IF and THEN statements below:
Rule 1: IF (The PGC is Flaccid) and (The Muscle Strain/Pain level is Very Low) and (If it is at 1st week from start) THEN (The range of motion is Medium)
Rule 2:IF (The PGC is Flassid) and (Pain Level is Low) and (Duration is 2nd Week) THEN (Range of Motion is Medium) ....
....
Rule 63: IF (The PGC is Spastic) and (Pain Level is Medium) and (Duration is 3rd Week) then (Range of Motion is Low)

All the above discussed rules combined together using MIN-MAX fuzzy inference technique. These rules are generated and edited on Matlab/Simulink/Fizzy Logic Tool Box as shown in the Appendix C.3

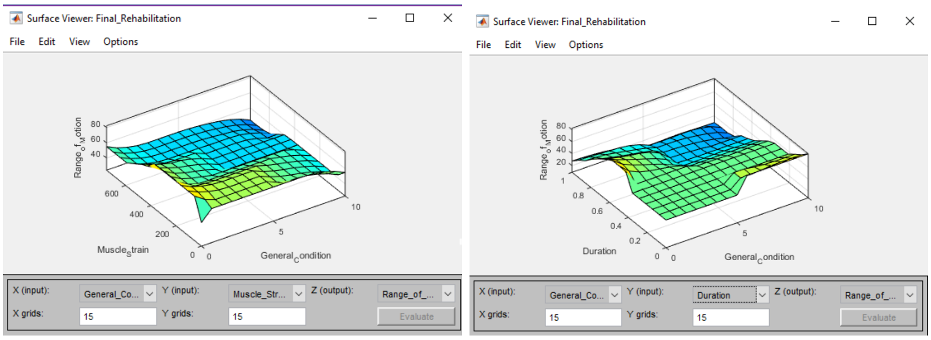


Fig. 5.4: Output Surfaces of different combinations of LIs and IOs

Defuzzification: The result obtained from fuzzy inference rule is then processed to produce a quantifiable result i.e. the range of motion and the angular speed. Defuzzification process is used to interpret the membership degrees of the fuzzy sets in some specific real value (i.e. in crisp value opposite to that Fuzzification do). Centroid method is used for defuzzification Operation.

5.3.3 Output Surface of FIS

Using fuzzy logic tool box, we can examine the output surface of the FIS for any one or two inputs. However we have three inputs and two outputs which cannot be correlated simultaneously in viewing output surface. So, here we can examine different combination of LIs and LOs separately. However, to evaluate the output, we use the combined effect of the three inputs. As shown on the Fig. 5.4, the surfaces are seems to be smooth which indicates that the output position reference varies smoothly with respect to time.

5.3.4 Correlation of Output Signal of the FIS and Rule Viewer

The output signal of the fuzzy control system which is the desired signal (reference signal) of the main control system is examined in simulink. By giving sinusoidal signal, we can see the output response of FIS. This is because the output signal of this fuzzy control system is the reference signal for the main control system and so that the ADAMS-MATLAB co-simulation will yields the rotational motion which is the desired signal.
The simulink Block as shown in the Fig. 5.5 is used to observe the resulting signal of the FIS and the respective output waveform are depicted in the Fig. 5.6.

The signal shown in the Fig. 5.6 indicates the desired signal of position for the main control system. The fuzzy Inference system computes the mean value of the output and takes as an oscillating line for the sinusoidal input. For our case the range of motion is 0-110 degree so that it takes 55 degree as a mean value and oscillates about this point as shown in Fig. 5.6 (a). This mean value corresponds to idle condition of the inference rule as shown in Fig. 5.6 (b).This indicates that in this FIS system, the mean value, in this case

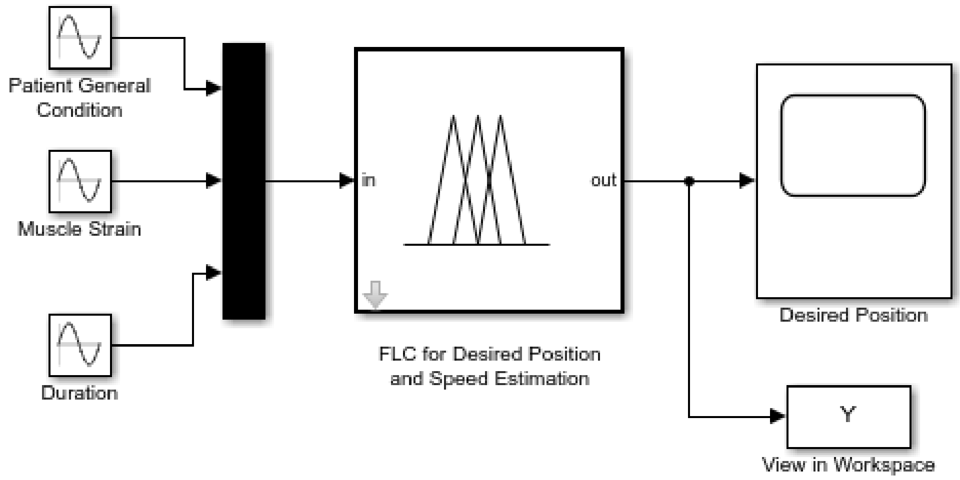


Fig. 5.5: Simulink Block Diagram for FIS

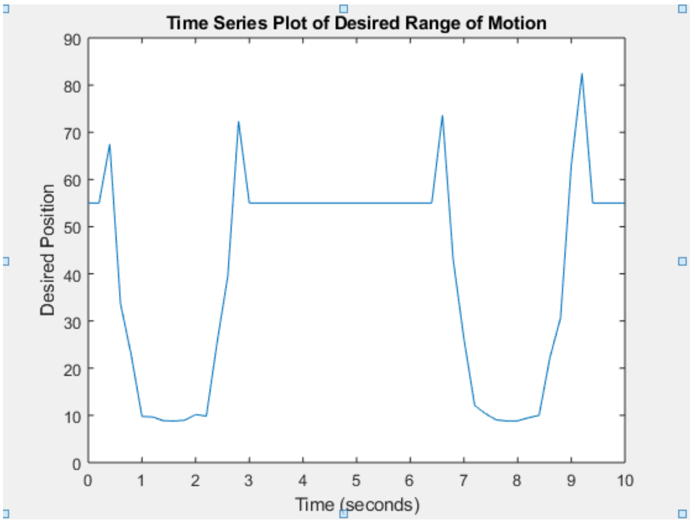
55 deg. is used as a reference so that other conditions are treated based on this value. When we see the worest case, the minimum range of motion is observed in both output waveform and rule viewer see Fig. 5.6 (a) and (c). So we can say that both the output of FIS system for a given sinusoidal input and the rules are correctly correlated.

5.4 PID Control System for Controlling the Range of Motion

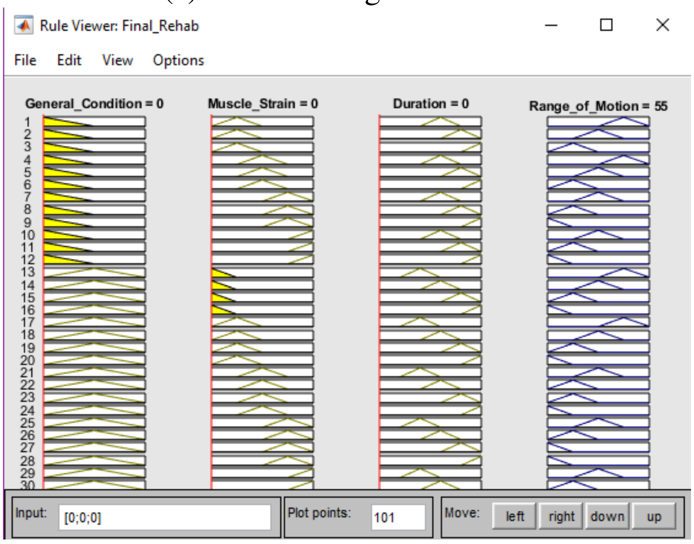
The development of PID control theories has already started in early sixty Centuries [42]. Nowadays, PID control has been one of the control system design methods. This controller is mainly used to set an appropriate control gains K_p, K_i and K_d to achieve the optimal control performance of the system [42], [43]. The relationship between the input e(t) and output u(t) can be formulated in the following:

$$U(t) = K_p e(t) + K_i \int_0^t e(t) + K_d \frac{d}{dt} e(t) \tag{5.1}$$

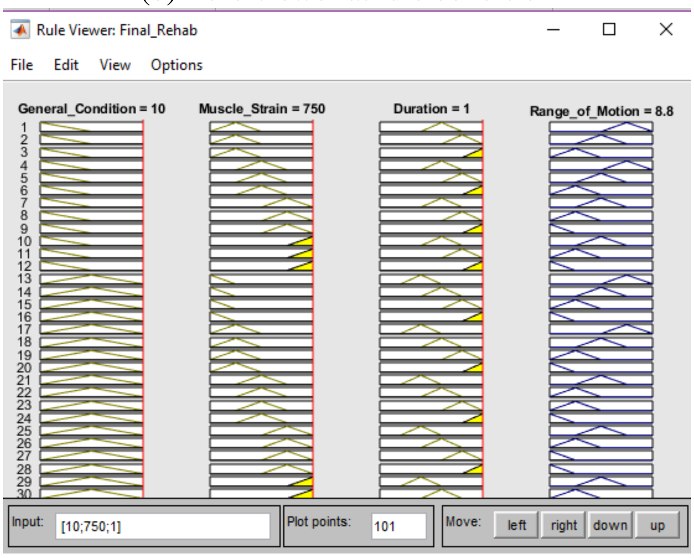
There are different methods to tune the PID controller. However, tuning manually or calculating are the two commonly used methods. Since we have a complete control of how to tune PID, we have decided for manual tuning. By adjusting the PID gains Kp, Ki and Kd appropriately, we can satisfy the desired characteristics of the system. This Controller is cascaded for Position control of the the system. By integrating this with Fuzzy control of



(a) Desired Range of Motion



(b) Rule viewer at idle condition



(c) Rule Viewer for worst case

Fig. 5.6: The Output Waveforms and the rule viewer of the FIS

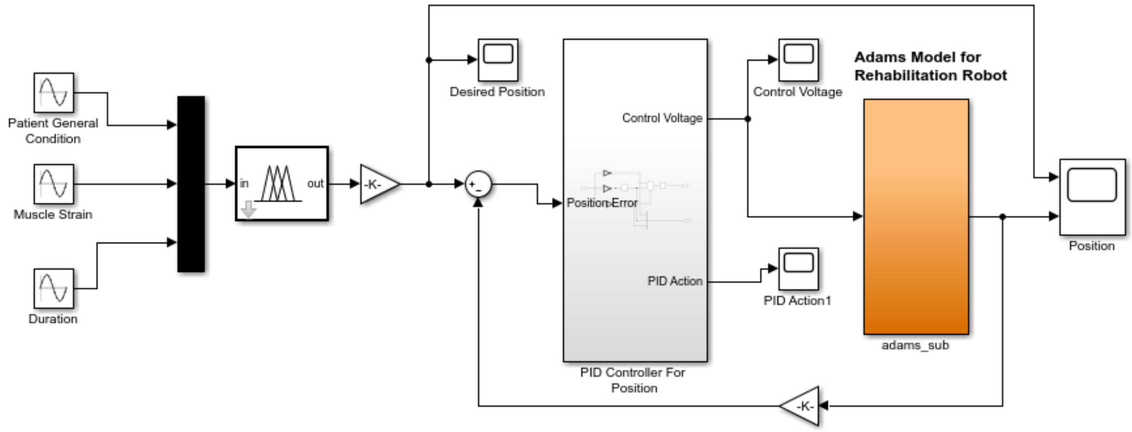


Fig. 5.7: Full Designed Control System Using PID Controller

the desired position and velocity of the system, we will develop the whole control system as shown in the Fig. 5.7

5.5 Summary

Here we can summarized that in this system we have designed two control parts. the first one is the fuzzy logic system for determination of the desired range of motion based on the three inputs of the patient status. The second one is the main controller of the system which is PID controller and we have designed the control Simulink block for this control schemes. So, this section make the control system ready for simulation analysis of the next section.

Chapter 6

Simulation Results and Discussions

6.1 Introduction

Robotics and other Mechatronic systems these days rely heavily on computer simulation to study the general trends of the mechanism before investing on actual experimental testing. Testing typically requires multiple hardware parts of manipulator which are very expensive [44]. To obtain an indicative data on all the relevant parameters, and to acquire the desired results on the whole experiment without waste of resources, a model is first created and simulations are run on it, to make sure that the trend shows improvement and that one may certainly go ahead and invest in the experimentation.

Simulation is the key stage in prototype design by providing a significant reduction in costs and effective manufacture time management, raising the productivity level. As a methodology tool, simulation provides a wide view of a system behavior, enabling error detection, parameters optimization or analysis for testing results [45]. To do this, the use of different software tools and combine them together is recommended. This work also shows this option by integrating ADAMS and MATLAB/SIMULINK as a co-simulation tools.

6.2 ADAMS-MATLAB Integration

This work deals with the co-simulation of Elbow-Forearm Post immobilization rehabilitation robot using ADAMS software and the Matlab/Simulink toolbox. Co-simulation is the integration of informatics applications in respect to withstand shortcomings from one of those applications in a specific circumstance. Here ADAMS allows to import mechanical systems model, to modify systems parameters. Once the simulation model of the system is built, various control strategies can be implemented by using MATLAB [45].

The ADAMS platform is a simulation software of mechanical systems for testing virtual prototypes, where the designers can improve the performance, security and comfort of the projects and researches without building them. It also allows the user to perform control objectives through the usual PID controllers. However, to implement more sophisticated controllers, alternative procedures must be taking into account. The toolbox Simulink of MATLAB is a powerful tool widely used to develop the control system solutions. The proposed co-simulation joins the qualities of the softwares, the modeling and simulation features of the ADAMS with the computational facilities of the Matlab environment [44].

Here, we are going to Perform the simulation in two ways:

- Simulation on ADAMS/Post Processor
- Adams-Matlab Co-simulation

6.3 Simulation on ADAMS/Postprocessor

In ADAMS Post-processor, the simulation is done by providing Motion function for all joints. Here no control signals are provided to the simulation unless the control design is imported. The other option for controlling the adams Plant is by exporting the plant to other target software such as MATLAB and Easy 5. ADAMS/PostProcessor has two modes, depending on the active view port:

- Animation
- Plotting

The tools in the Main toolbar change when we load an animation or a plot into the view port as shown in the Fig. 6.1

To verify correctness and effectiveness of the system, here we exerts sine moment function at elbow joint:

$$Motion1 = 30d * sin(0.1 * time) \tag{6.1}$$

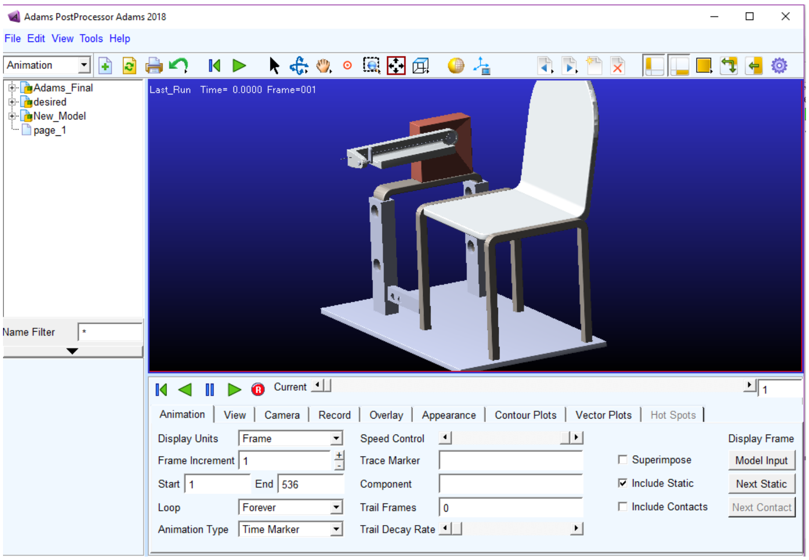
With this function driving, we set simulation time as 100 s and simulation step as 0.1 and then centre of mass of robot arm in postprocessor in ADAMS see Fig. 6.2.

From the position curve of the simulation in Fig. 6.2, we can see that the motion achieves the desired angle of 30 degree with an error of ± 1.23 degrees. This value indicates an accuracy of 94.9% with out introducing any controller. The animation of the system is also successfully done with the help of animation window as shown in Fig. 6.1 (a). Even though this simulation has no control input for the system, the behavior and motion accuracy has been proven successfully. In the next section, by designing the control block on the target software, in our case MATLAB/simulink, we can control the system as desired.

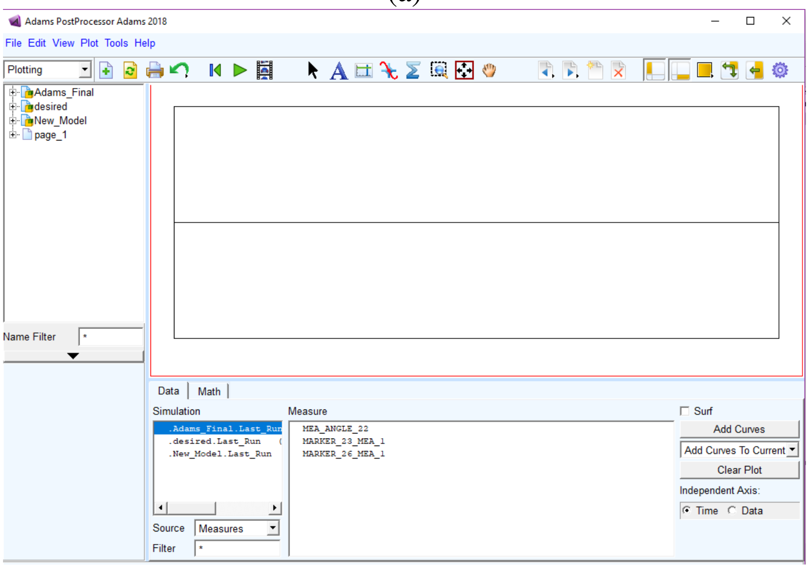
6.4 Adams-Matlab Co-Simulation and Discussion

Now, the ADAMS-MATLAB co-simulation will be carried out to investigate the desired Range of motion of the Manipulator by controlling with the developed control block in chapter 5. Here, we are going to the simulation and discussion part. In this section, we have observed the behaviour of the system using Three reference signal. These are

- Step Input



(a)



(b)

Fig. 6.1: Modes of Post Processing in ADAMS (a) Animation (b) Plotting

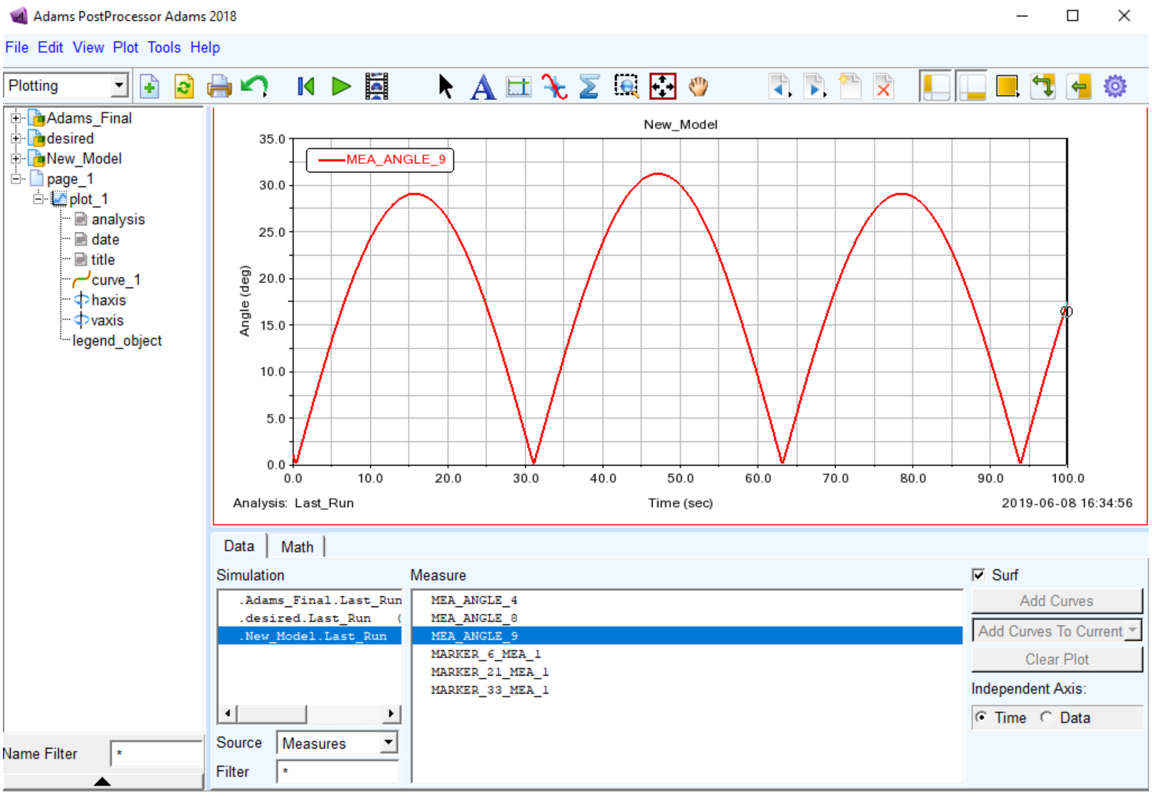


Fig. 6.2: Position Curve of ADAMS PostProcessing

- Sinusoidal input
- Fuzzy Input Signal

6.4.1 Step Response of the System in Co-Simulation

Here we are dealing the step response of the system by giving the step of 1sec and final value of 30 deg. When we give the step input to the Adams plant, no oscillating motion is experienced in ADAMS-MATLAB Co-simulation rather it just go to 30 degree and remains at this 30 degree. This is due to the reason that the desired oscillatory motion is obtained when we give a sinusoidal input. This is simply to justify the steady and transient characteristics of the system and to know how much the desired position of the manipulator is achieved with controller. The block diagram is build with PID controller as shown in Fig. 6.5. We choose this controller due to the reason that since we are applying an approach of using fuzzy system for reference signal of the control system. Using fuzzy as a reference input is difficult with advanced control algorithms. So we start from the conventional PID controller. The behaviour of the system is critically examined and discussed.
The step response of the system is observed with different gain combination of the PID controller and the corresponding indication of the result is examined. And the appropriate combination of the PID controller that provide the desired characteristics is selected. First we start by increasing the proportional gain of the PID controller. The simulation is done

Table 6.1: The effect of Kp on the Position Response

The effect of Proportional Gain				
Kp	Ki	Rise Time(ms)	Overshoot/Undershoot	Settling Time(ms)
0.002	0.05	809.817	0.505/1.974	-
0.005	0.05	872.068	0.505/1.979	-
0.008	0.05	923.485	0.505/1.98	-
0.01	0.05	953.538	0.505/1.998	-

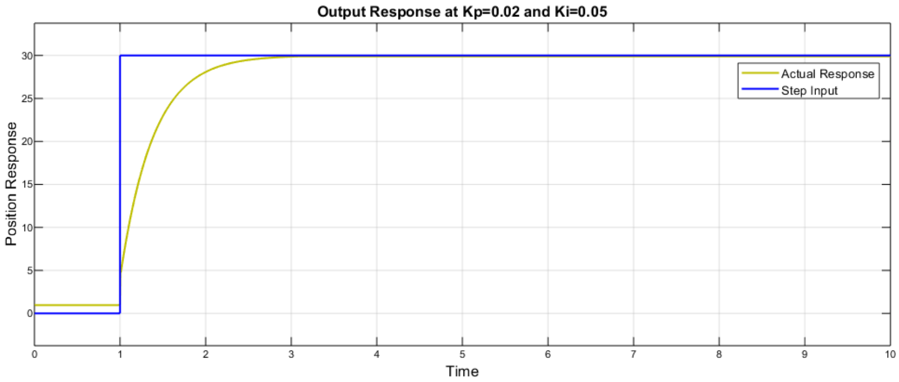
with four different Kp values and the corresponding parameters are recorded on the Table 6.1.

Fig.6.3 also shows the effect of the proportional gain parameter on a step input. The response of the parameter is modeled using SIMULINK. We have shown that the error signal and the control signal have direct relationship with a proportional gain Kp. If the error is large, a large input signal is used and vice versa.

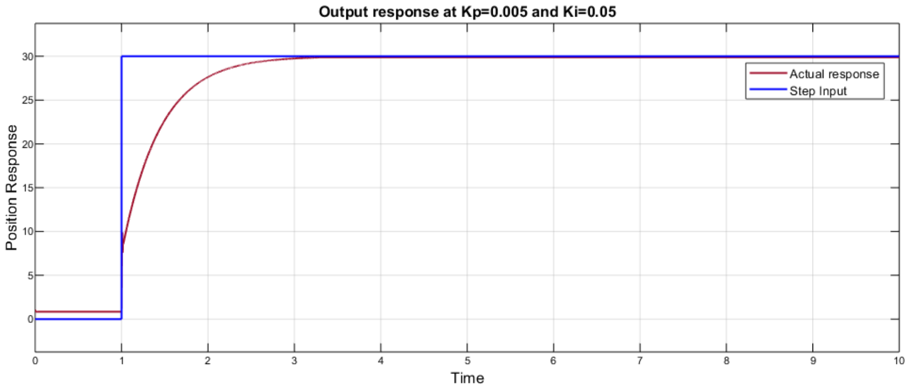
From the simulation results shown in the Fig. 6.3 and the corresponding characterstics parameters shown in the Table 6.1, the rise time increases from 809.817 to 953.538 ms with small change as the proportional gain Kp increases. As we increase the proportional gain more and more, the oscilating characterstics of the system will also increases as clearly shown in the Fig. 6.3 (c) and (d). As seen from the graph, at Kp=0.008, the system starts to oscillates and at Kp=0.01. This disturbance increases. So we can see that as Proportional action Kp improves the system rising time, and reduces the steady state error. This means the larger proportional gain, the larger control signal needs to correct the error. However, the higher value of Kp produces an oscillating as shown in the Fig. 6.3 (c) and (d); Since this system is critically damped type, so that settling time and the overshoot will not characterize the system as shown in the Table 6.1. Therefore, integral action Ki is used to eliminate the steady state error, reduce the Rise time and eliminate the oscillating effect. This is illustrated in the Fig. 6.4.

Fig. 6.4 and Table 6.2 shows the effect of the Integral gain parameter on a step input. As the Integral gain increases, the rise time decreases drastically from 809.963ms to 1.55 ms which indicates that the higher integral gain, the fast response of the system. As shown in the Fig. 6.4 (a) to (d), the response of the system to attain the desired position is progressively become faster. At the Ki=5, the system perfectly attain 30 degree with time of 1.55ms.

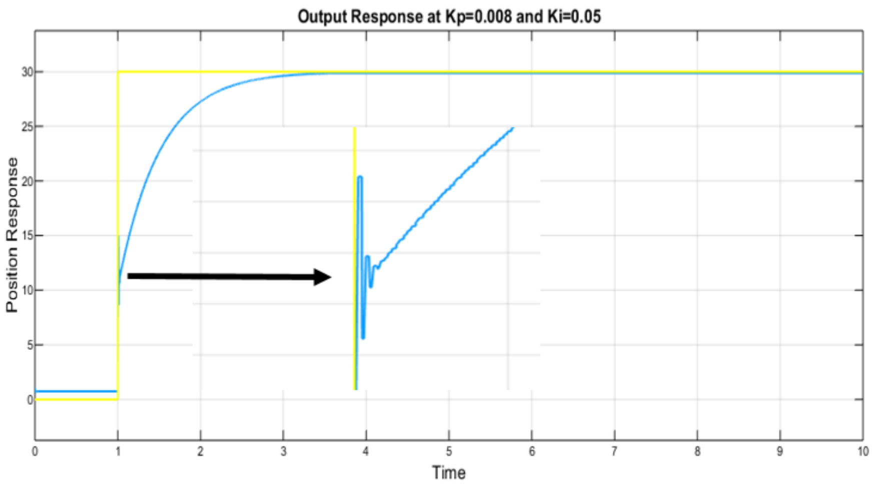
However, the real application of this system needs a slow motion to attain the de-



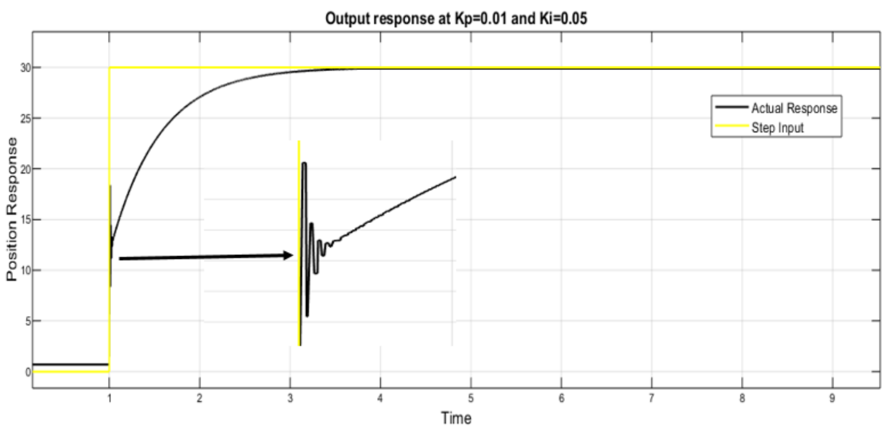
(a)



(b)

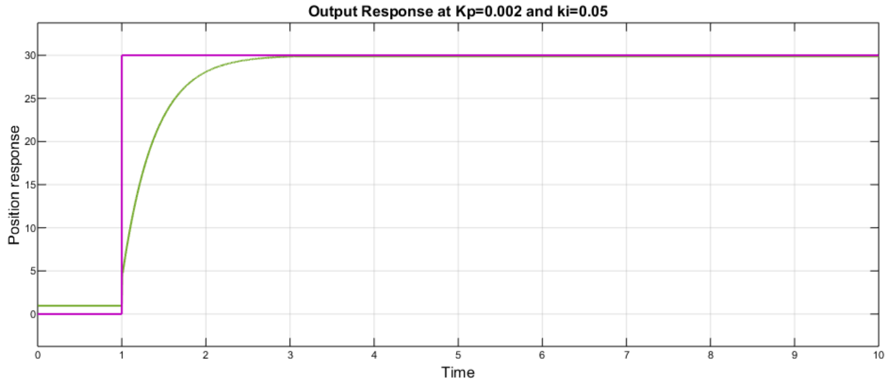


(c)

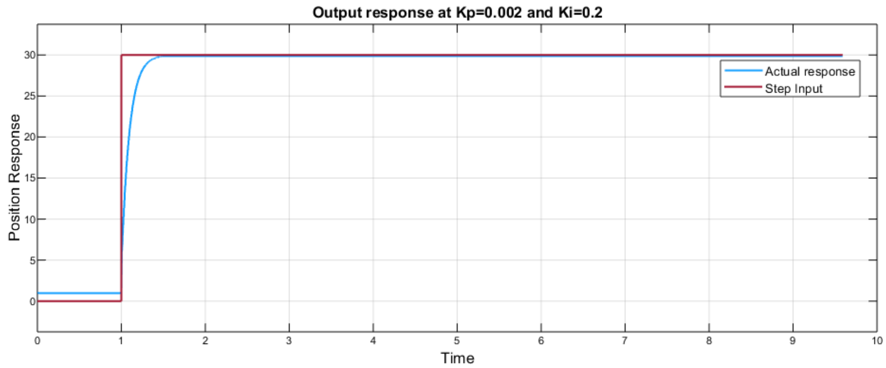


(d)

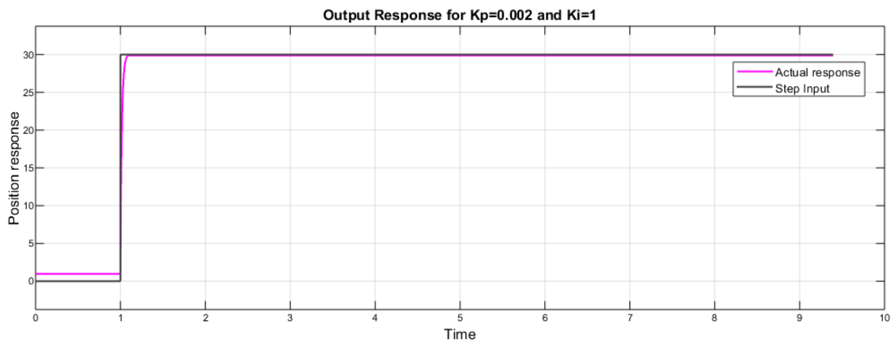
Fig. 6.3: The effect of Proportional gain (Kp)



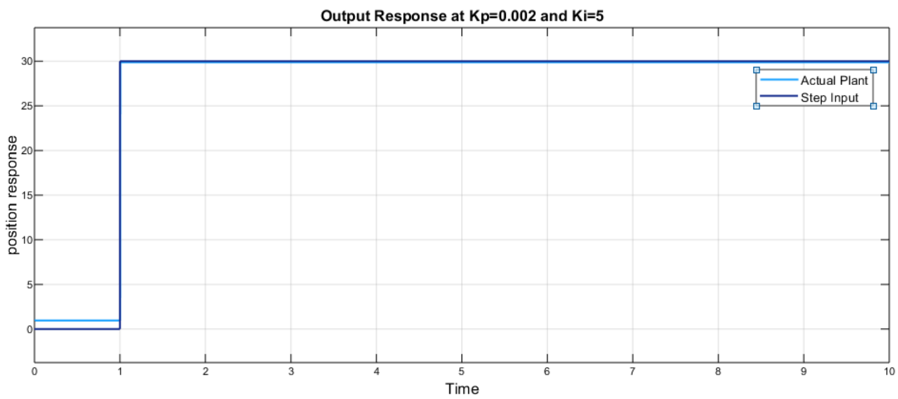
(a)



(b)



(c)



(d)

Fig. 6.4: The effect of Integral gain (Ki)

Table 6.2: The effect of Ki on the Position Response

The effect of Integral Gain				
Kp	Ki	Rise Time(ms)	Overshoot/Undershoot	Settling Time(ms)
0.002	0.05	809.963	0.505/1.974	-
0.002	0.2	196.478	0.505/1.979	-
0.002	1	36.390	0.505/1.98	-
0.002	5	1.550	0.505/1.998	-

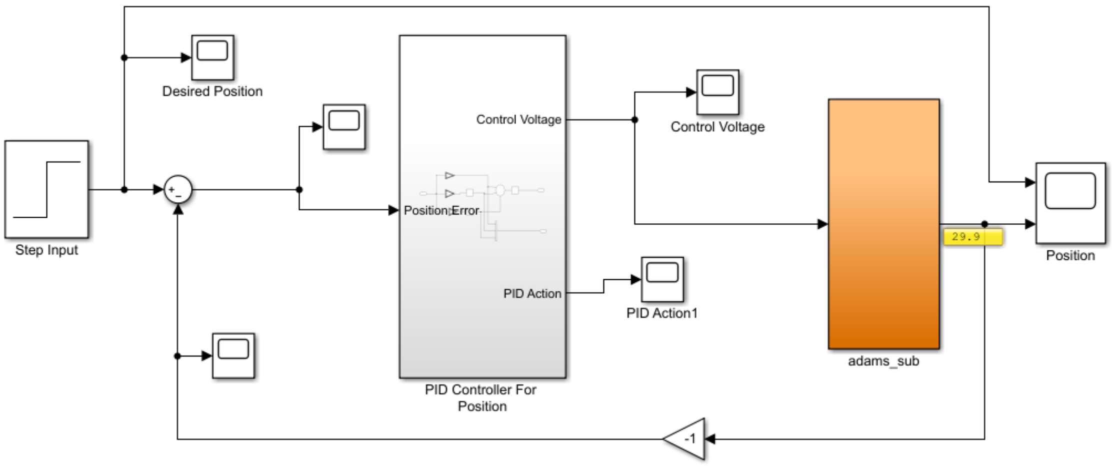


Fig. 6.5: Block diagram of step reference with PID Controller

sired position. Since we are dealing with elbow-forearm fractures patients, their pain level should be considered critically. Here, the step response indicates how the manipulator takes the immobilized forearm to the desired range of motion. To do this, slow enough motion is required not to create extra pain to the patient. Now, by combining both proportional and integral gains. we have develop the PID controller with Kp=0.001 and Ki=0.01 that yields the desired response of the system as shown in Fig. 6.6. With these gain combination, slow enough motion is obtained with the rise time of 3.885 seconds.

6.4.2 Co-Simulation Based on Sinusoidal reference Input

The proposed Rehabilitation robot has an oscillating type of motion at elbow and forearm twist joints. To achieve this motion and to proceed the adams-matlab co-simulation, we have to use sinusoidal input signal which can form oscillating motion. The control block is designed on simulink using conventional PID controller as shown in Fig. 6.7 for observing the behavior of the system. The virtual ADAMS-MATLAB Co-simulation as shown in

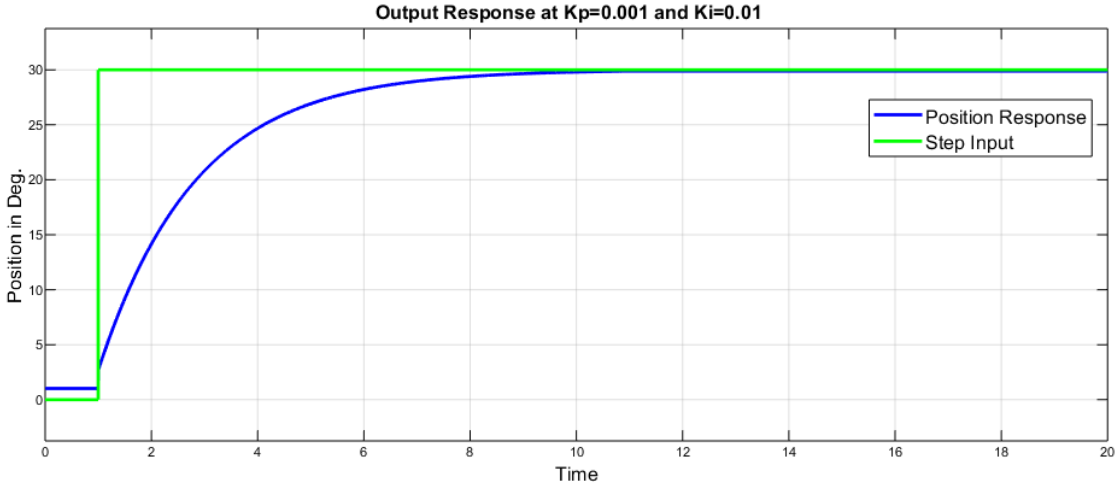


Fig. 6.6: Step response of the system with PID controller

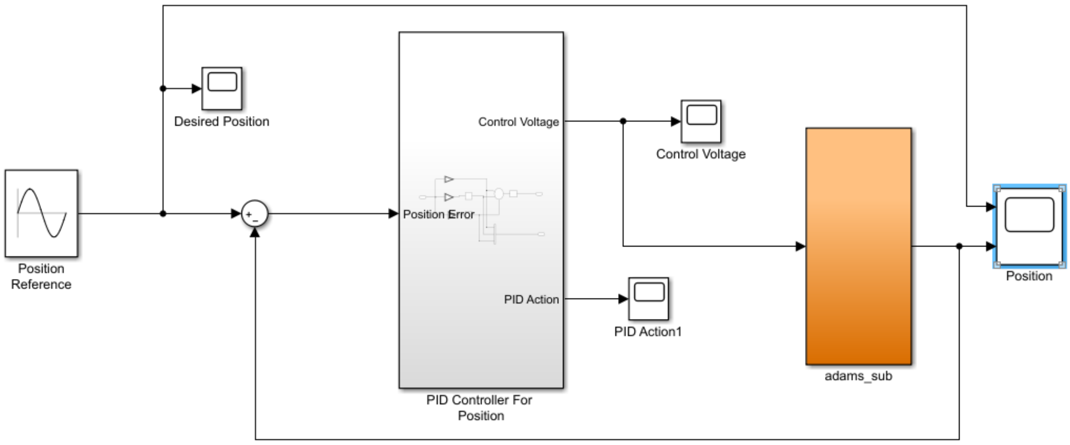


Fig. 6.7: PID control block diagram for Sinusoidal Input

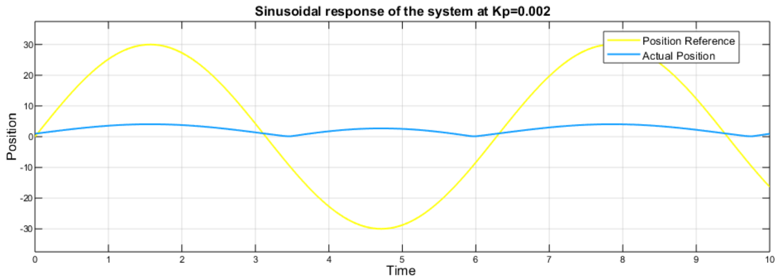
Fig. 6.10 is used to show the motion of the manipulator on ADAMS software.

Now, the action of the PID controller will be discussed in detail. To observe the behavior of the system for sinusoidal input, we exerts sine input function as follows.

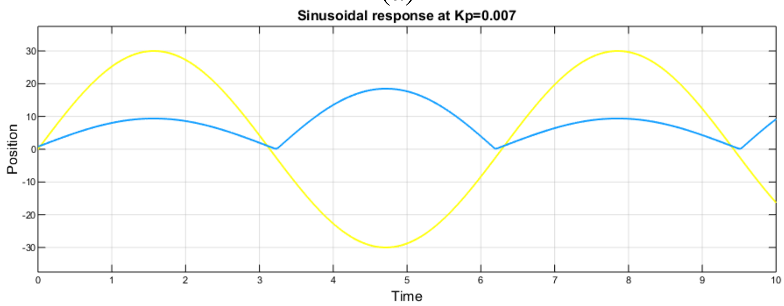
$$Motion = 30 * sin(time) \tag{6.2}$$

Now we are going to see the effect of the proportional gain, Kp on the system. By setting Ki and Kd to zero and increasing Kp. we observe the effects.

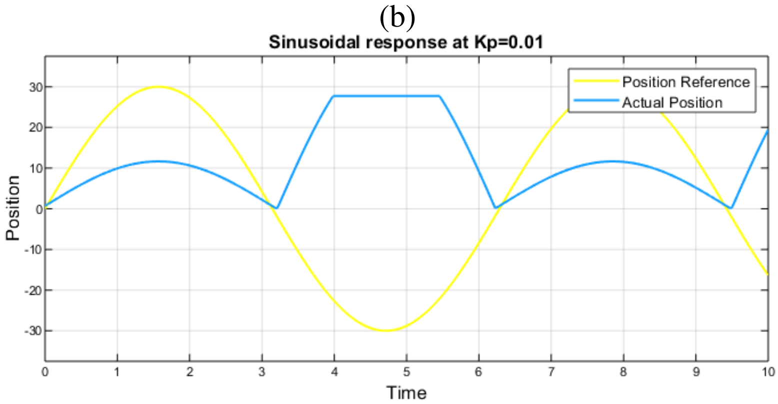
Here we can see that, the response of the actuator at the positive and negative part of the sinusoidal input is different. And also the gains of the PID controller have respective effects on these parts. From the results, we have seen that the proportional gain is responsible to the negative part of the sinusoidal input. As the Proportional gain increases, the amplitude (range of motion) also increases as shown in Fig.6.8 and on the Table 6.3. From the table we have seen that the rate of change of position in the negative sinusoidal input is more



(a)



(b)



(c)

Fig. 6.8: The effect of Kp on sinusoidal response

Table 6.3: Effect of Proportional gain on the sinusoidal response

Gains		Amplitude (Range of Motion) in deg.	
Kp	Ki	Sin(+ve)	Sin(-ve)
0.002	0	4.061	2.702
0.007	0	18.49	9.387
0.01	0	27.74	12.9

Table 6.4: Effect of Integral gain on the sinusoidal response

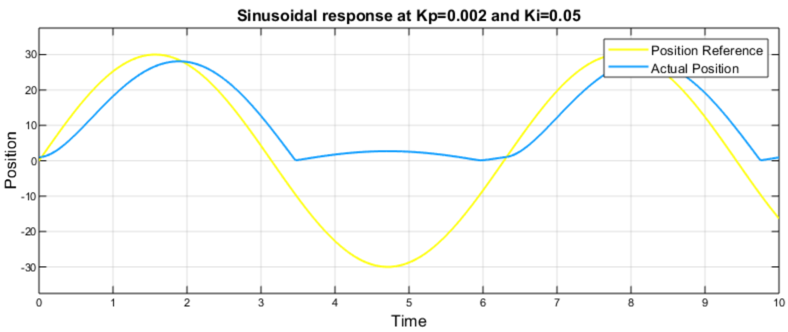
Gains		Amplitude (Range of Motion) in deg.	
Kp	Ki	Sin(+ve)	Sin(-ve)
0.002	0.05	28.08	2.702
0.002	0.15	29.57	2.702
0.002	1	29.88	2.702

than that of the positive input. This implies that the ROM of the manipulator in the negative sinusoidal input is controlled controlled by the proportional gain. We also observed that as the increases of integral gain, there will be a chopping of the highest amplitude of the output responses at which the link will be idle.

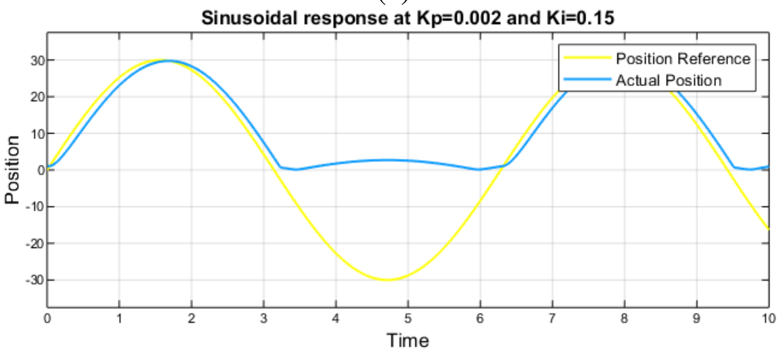
When we come to the integral gain, it will have an effect on the positive sinusoidal input. As seen from the Table 6.4 and Fig. 6.9, small increase in the integral gain will results the rapid rising of the plant output to track the reference signal. However, there is some error in degree which is eliminated by increasing the integral gain. This change is clearly observed in the Fig.6.9.

Now, by combining the two gains at the optimum gain values, we can achieve the desired characteristics of the system. To do this, we have used Kp=0.01 and Ki=1 and we can achieve 29.88 degree in the positive sinusoidal input and 27.74 degree in the negative side of the reference input as shown in the Fig. 6.11. The Co-simulation is also shown in the Fig. 6.10. This simulation results shows an accuracy of 99.6% with that of the reference input.

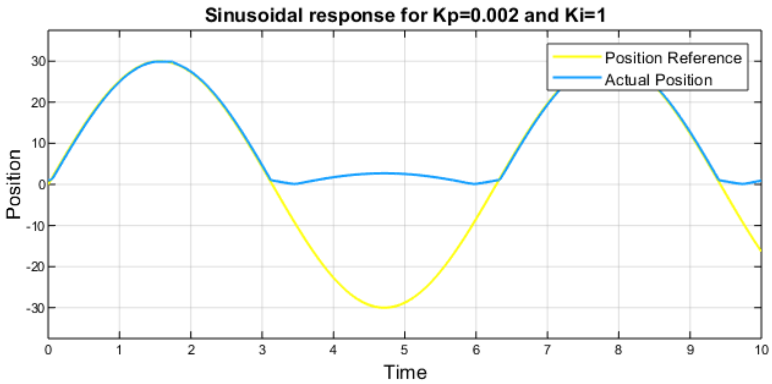
From this Simulation, we have seen that the resulting output position curve for both adams PostProcessing plots and PID control of a sinusoidal input simulation have almost the same feature as shown in Fig. 6.2 and 6.11 respectively. However, the overall simula-



(a)



(b)



(c)

Fig. 6.9: The effect of Integral Gain

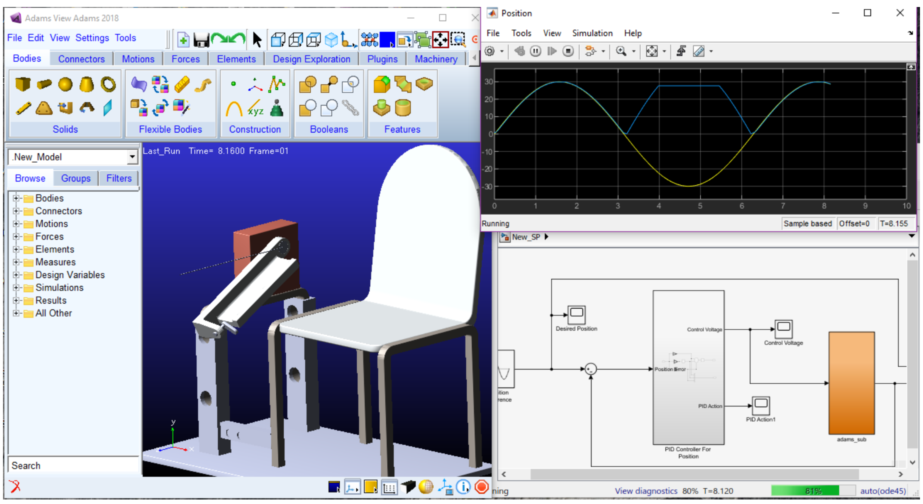


Fig. 6.10: The ADAMS-MATLAB Co-simulation

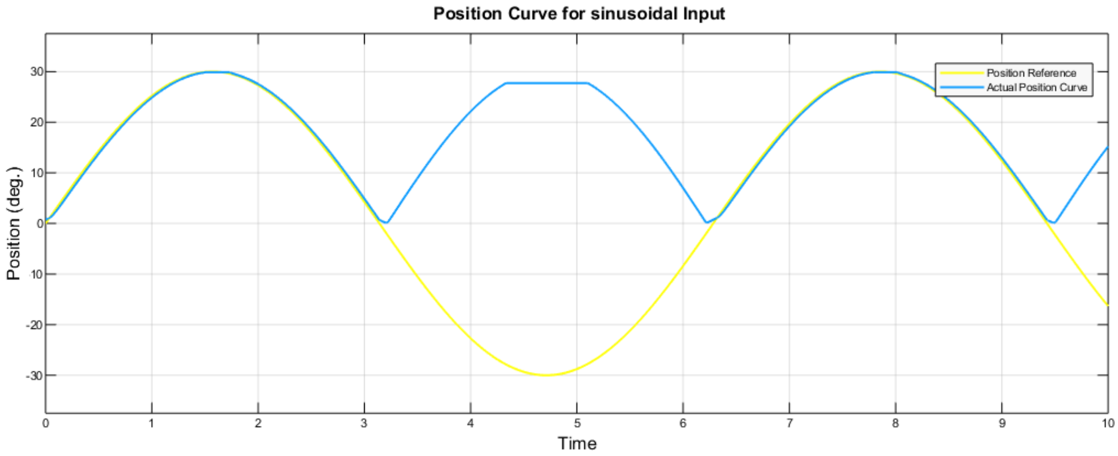


Fig. 6.11: The Output Position curve for Sinusoidal Input

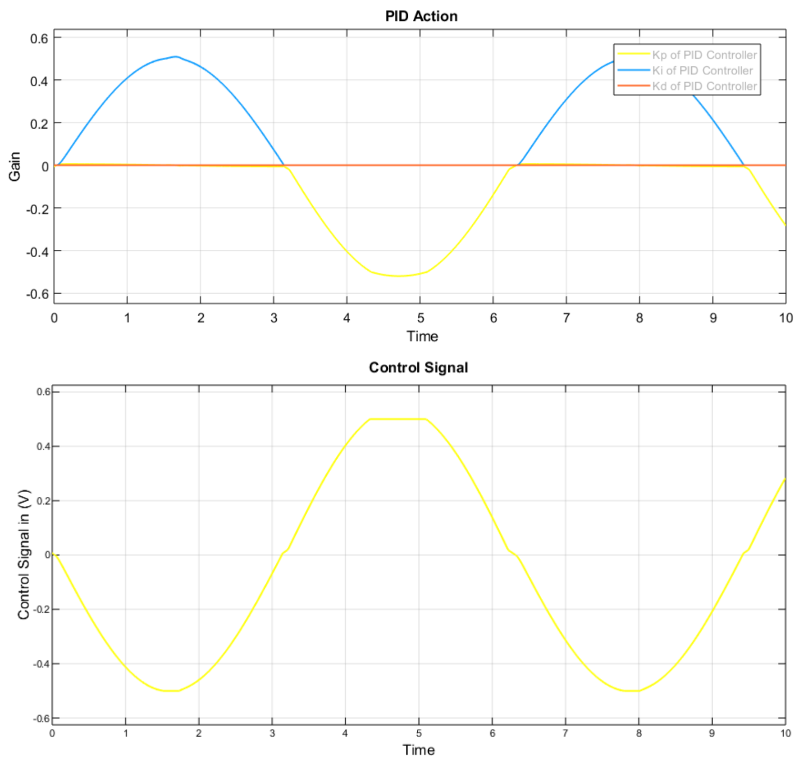


Fig. 6.12: PID Action and the corresponding control signal

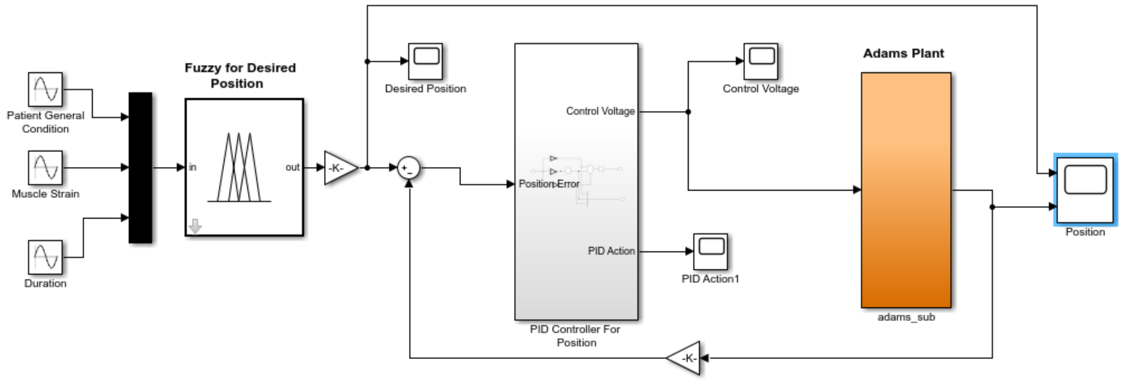


Fig. 6.13: Block diagram for PID control of Fuzzy Reference Input

tion result shows that more accuracy is achieved by introducing a controller to the system. This shows that the PID controller is successfully applied on the Adams plant with the same sinusoidal input and it has improved the efficiency of the system.

6.4.3 Co-Simulation Based on Desired output of FIS

In Chapter 5, we have designed FIS for determining the desired range of motion of the manipulator by considering three parameters which are mentioned in Chapter 4. This desired output is used here as reference input to the control system. The main contribution of this paper is actuating the robot joints based on the pain level of the patients. To do this, fuzzy logic controller takes the role for determination of the desired range of motion of the elbow as well as forearm twist.

We have seen in the previous chapter that the output of the FIS for Position takes the mean of the given range (0-110 deg) that is 55 degree and oscillates with this mean value. In this case, we have scaled down with a gain of 0.0741 and results a new mean value of 4.075 to make the control signal Suitable for the control action. Here also we are going to investigate the action of PID gains on this system with fuzzy reference input. In this case the simulation is done only for observing the behavior of the system and to know how much the system tracks the reference fuzzy input. The dynamic motion of the adams model doesn't represent the real movement of the system. It is just for the simulation purpose only. Since the fuzzy logic system oscillates about its mean value, the tracking accuracy is evaluated by this mean value of the actual and reference signals. Here, the proportional gain only controls the system. The integral gain will lead to the oscillation of the system. Now we are considering the proportional gain and increasing the value, we can see the behavior to determine how much it tracks the reference signal. As shown in the Fig.6.14, when Kp increase from 0.005 to 0.015, the error decreases but at Kp=0.02, the error become negative i.e the the output increases beyond the reference. By manually tuning the gain, finally the exact tracking of the output to that of the reference signal at

Table 6.5: The Response of the actual with different Kp value

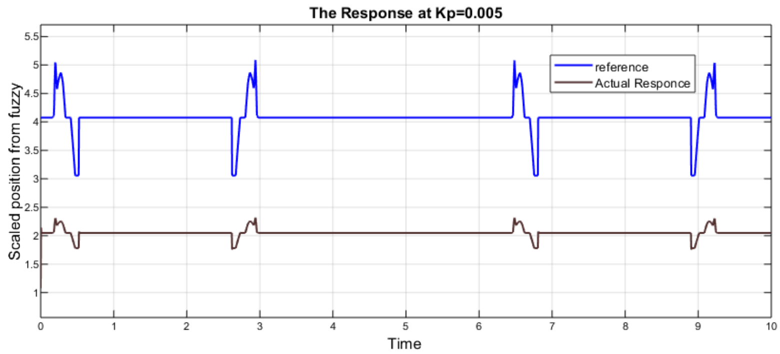
Kp	Reference	Actual	Error
0.005	4.075	2.05	2.025
0.01	4.075	2.866	1.209
0.015	4.075	3.561	0.514
0.02	4.075	4.159	-0.084

which the error will be zero as shown in Fig.6.15.

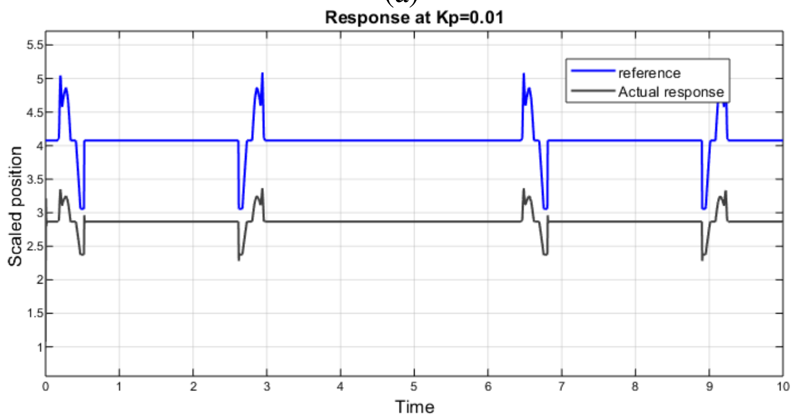
Finally after some iterating, we have get the gain at which the actual response exactly tracks the reference signal with zero error as shown in the Fig. 6.15. From the simulation, we have seen that the output Position curve tracks the the reference determined by the fuzzy Inference system. Using Fuzzy system for reference is difficult for simulation. However it is advantageous and have realistic concepts in real application. This simulation is used simply to show how the system behaves according to the given reference input.
When we come to the PID controller, Here also we start by manual tunning of the proportional gain and we get satisfactory result at Kp=0.01925 as shown in Fig. 6.15.
Here we want to notice that unlike other systems modeled mathematically with transfer function, it is difficult to characterize such ADAMS dynamic model of the plant with transient or steady state characteristics. Additionally, the use of fuzzy inference system as an input makes it more complicate for simulation. However, it is more persuasive in practical application especially in rehabilitation system at which the pain level of the patient is purely fuzzy in nature.

6.5 Summary

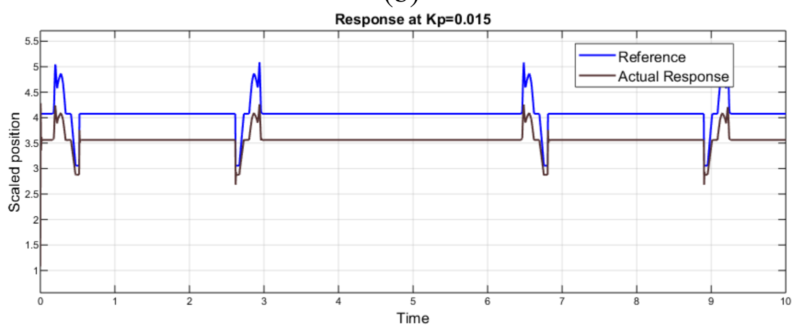
In this simulation and result section, we have integrated the two softwares(ADAMS and MATLAB) to perform the co-simulation in order to realize the vertual prototype of the elbow-forearm rehabilitation robot. This co-simulation has been done successfully with step, sinusoidal and fuzzy inputs and satisfactory results has been obtained. Firstly, the PID controller is evaluated with step response and we have decided that PID controller gives the desired tracking of the system with the pain level of the patient.
Secondly, the system is evaluated with the sinusoidal input at which the both the dynamic simulation of ADAMS model and the resulting waveform is observed. Here the positive and negative part of the sinusoidal input have different effects on the output of the system and also these two phases controlled by Ki and Kp gains respectively. Finally, the system



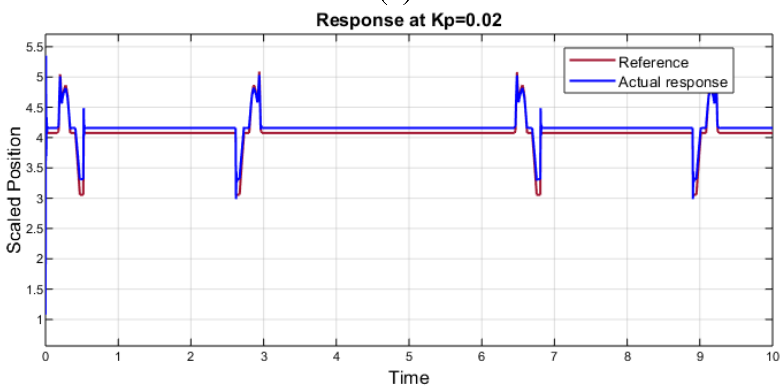
(a)



(b)



(c)



(d)

Fig. 6.14: The response with the proportional gain

Fig. 6.15: Simulation Result of Position Curve

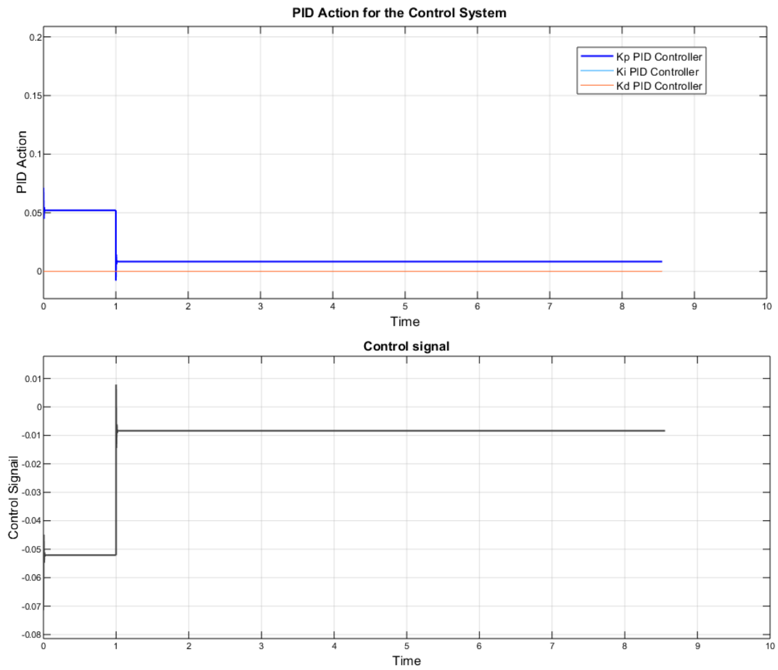


Fig. 6.16: The Action of Gains of PID and the corresponding control signal

is evaluated by providing the fuzzy input. Here the proportional gain has a great effect on the system performance and the accurate tracking of the actual plant with that of the reference input signal.

Chapter 7

Conclusion and Future Works

7.1 Conclusion

Researchers were not focus on the use of Rehabilitation robot for patients of accidental fracture after immobilization. However this thesis has developed the elbow-forearm rehabilitation robot and control the range of motion and speed of the manipulator by considering the pain level of the patient. Since we can control the position at fixed speed or the speed at fixed position, we preferred the position control at fixed speed. First, adjustable and rugged mechanical design is designed by considering ergonomics of the patient. Then by collecting the relevant data from patients, we develop the fuzzy control system to determine the desired range of motion of the elbow. Finally we develop PID control system to achieve this desired range of motion. The Adams-Matlab co-simulation gives us the expected motion with the given 30 degree range of motion. And then by applying the fuzzy output of the reference position, we can see good tracking simulation results. Here the simulation results shows that the accuracy of the system is enhanced by introducing the PID controller. To summarize, This thesis contributes relevant approach on the development of Upper limp rehabilitation robot by giving a great attention on the pain level of the patients.

7.2 Future Work

This thesis concentrates on the mechanical design, acquisition of relevant data from patients and manipulate this data with fuzzy logic to determine the desired range of motion of the manipulator and Co-simulating this mechanism with a Conventional PID controller. So, we recommend to investigate other advanced controllers to enhance the control system. In the future, we are intended to include the model of motors of the joints. And also it is recommended to consider external disturbances such as the weight of the hand tremor. Finally, as future work, we recommend to control the real system of the rehabilitation robot in order to confront the responses obtained by this Co-simulation.

Bibliography

[1] O. Lambercy, R. Ranzani, and R. Gassert, "Robot-assisted rehabilitation of hand function," in *Rehabilitation Robotics*. Elsevier, 2018, pp. 205–225.

[2] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation," *Journal of neuroengineering and rehabilitation*, vol. 11, no. 1, p. 3, 2014.

[3] M. Babaiasl, S. N. Goldar, M. H. Barhaghtalab, and V. Meigoli, "Sliding mode control of an exoskeleton robot for use in upper-limb rehabilitation," in *2015 3rd RSI International Conference on Robotics and Mechatronics (ICROM)*. IEEE, 2015, pp. 694–701.

[4] S.-H. Chen, W.-M. Lien, W.-W. Wang, G.-D. Lee, L.-C. Hsu, K.-W. Lee, S.-Y. Lin, C.-H. Lin, L.-C. Fu, J.-S. Lai *et al.*, "Assistive control system for upper limb rehabilitation robot," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 24, no. 11, pp. 1199–1209, 2016.

[5] E. Akdoğan, M. E. Aktan, A. T. Koru, M. S. Arslan, M. Atlıhan, and B. Kuran, "Hybrid impedance control of a robot manipulator for wrist and forearm rehabilitation: Performance analysis and clinical results," *Mechatronics*, vol. 49, pp. 77–91, 2018.

[6] I. Ben Aabdallah, Y. Bouteraa, and C. Rekik, "Design of smart robot for wrist rehabilitation." *International Journal on Smart Sensing & Intelligent Systems*, vol. 9, no. 2, 2016.

[7] H.-S. Cheng, M.-S. Ju, and C.-C. K. Lin, "Improving elbow torque output of stroke patients with assistive torque controlled by emg signals," *Journal of biomechanical engineering*, vol. 125, no. 6, pp. 881–886, 2003.

[8] M. Tiboni, A. Borboni, R. Faglia, and N. Pellegrini, "Robotics rehabilitation of the elbow based on surface electromyography signals," *Advances in Mechanical Engineering*, vol. 10, no. 2, p. 1687814018754590, 2018.

[9] R. Gopura and K. Kiguchi, "Mechanical designs of active upper-limb exoskeleton robots: State-of-the-art and design difficulties," in *2009 IEEE International Conference on Rehabilitation Robotics*. IEEE, 2009, pp. 178–187.

[10] T. H. Koh, N. Cheng, H. K. Yap, and C.-H. Yeow, "Design of a soft robotic elbow sleeve with passive and intent-controlled actuation," *Frontiers in neuroscience*, vol. 11, p. 597, 2017.

[11] G. Ma, M. Lin, and Q. Wang, "Mechanical design of a whole-arm exoskeleton rehabilitation robot based on pnf," in *2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*. IEEE, 2016, pp. 777–780.

[12] S. Cai, G. Huang, L. Huang, and L. Xie, "Kinematics analysis, design, and simulation of a dual-arm robot for upper limb physiotherapy," in *IOP Conference Series: Materials Science and Engineering*, vol. 397, no. 1. IOP Publishing, 2018, p. 012049.

[13] M. Babaiasl, A. Ghanbari, and S. M. R. Noorani, “Mechanical design, simulation and nonlinear control of a new exoskeleton robot for use in upper-limb rehabilitation after stroke,” in *2013 20th Iranian Conference on Biomedical Engineering (ICBME)*. IEEE, 2013, pp. 5–10.

[14] M. Rahmani and M. H. Rahman, “Novel robust control of a 7-dof exoskeleton robot,” *PloS one*, vol. 13, no. 9, p. e0203440, 2018.

[15] H. Bian, Z. Chen, H. Wang, and T. Zhao, “Mechanical design of efw exo ii: a hybrid exoskeleton for elbow-forearm-wrist rehabilitation,” in *2017 International Conference on Rehabilitation Robotics (ICORR)*. IEEE, 2017, pp. 689–694.

[16] R. Salloum, M. R. Arvan, and B. Moaveni, “Identification, uncertainty modeling and robust controller design for an electromechanical actuator,” *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 230, no. 20, pp. 3631–3641, 2016.

[17] Y. Jiang, S. Sakoda, M. Togane, S. Morishita, B. Lu, and H. Yokoi, “A highly usable and customizable semg sensor for prosthetic limb control using polypyrrole-coated nonwoven fabric sheet,” in *2015 IEEE SENSORS*. IEEE, 2015, pp. 1–4.

[18] M. Zens, J. Ruhhammer, F. Goldschmidtboeing, M. Feucht, A. Bernstein, P. Niemeyer, H. Mayr, and P. Woias, “Polydimethylsiloxane strain gauges for biomedical applications,” in *2015 Transducers-2015 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)*. IEEE, 2015, pp. 1763–1766.

[19] T. Mori, Y. Tanaka, K. Yoshikawa, D. Katane, H. Torishima, Y. Shimizu, and Y. Hara, “Proposal of bioinstrumentation using shape deformation of amputated upper limb,” in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2013, pp. 882–885.

[20] C. Zizoua, M. Raison, S. Boukhenous, M. Attari, and S. Achiche, “Detecting muscle contractions using strain gauges,” *Electronics Letters*, vol. 52, no. 22, pp. 1836–1838, 2016.

[21] J. van Amerongen, “Mechatronic design,” *Mechatronics*, vol. 13, no. 10, pp. 1045–1066, 2003.

[22] P. Hehenberger, F. Poltschak, K. Zeman, and W. Amrhein, “Hierarchical design models in the mechatronic product development process of synchronous machines,” *Mechatronics*, vol. 20, no. 8, pp. 864–875, 2010.

[23] K. T. Ulrich, “Product design and development.”

[24] R. Morales, F. J. Badesa, N. García-Aracil, J. M. Sabater, and C. Pérez-Vidal, “Pneumatic robotic systems for upper limb rehabilitation,” *Medical & biological engineering & computing*, vol. 49, no. 10, p. 1145, 2011.

[25] R. Natividad and C.-H. Yeow, “Development of a soft robotic shoulder assistive device for shoulder abduction,” in *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. IEEE, 2016, pp. 989–993.

[26] S. B. Niku, *Introduction to Robotics*. Prentice Hall Professional Technical Reference, 2001.

[27] H. Høifødt, "Dynamic modeling and simulation of robot manipulators: The newton-euler formulation," Master's thesis, Institutt for teknisk kybernetikk, 2011.

[28] T. Brezina, Z. Hadas, and J. Vetiska, "Using of co-simulation adams-simulink for development of mechatronic systems," in *14th International Conference Mechatronika*. IEEE, 2011, pp. 59–64.

[29] Z. Hu, D. Xu, G. Liu, and C. Jia, "Study on co-simulation technology based on adams and matlab," in *2015 International Symposium on Material, Energy and Environment Engineering*. Atlantis Press, 2015.

[30] L. PŘÍLESKÝ and I. Z. HADAŠ, "Robot virtual prototype in adams," 2012.

[31] A. L. Silva, M. Varanis, A. G. Mereles, C. Oliveira, and J. M. Balthazar, "A study of strain and deformation measurement using the arduino microcontroller and strain gauges devices," *Revista Brasileira de Ensino de Física*, vol. 41, no. 3, 2019.

[32] S. Wen and D. Chung, "Carbon fiber-reinforced cement as a strain-sensing coating," *Cement and Concrete Research*, vol. 31, no. 4, pp. 665–667, 2001.

[33] J. C. Butler, A. J. Vigliotti, F. W. Verdi, and S. M. Walsh, "Wireless, passive, resonant-circuit, inductively coupled, inductive strain sensor," *Sensors and Actuators A: Physical*, vol. 102, no. 1-2, pp. 61–66, 2002.

[34] D. J. Cohen, D. Mitra, K. Peterson, and M. M. Maharbiz, "A highly elastic, capacitive strain gauge based on percolating nanotube networks," *Nano letters*, vol. 12, no. 4, pp. 1821–1825, 2012.

[35] A. Lonsdale, "Dynamic rotary torque measurement using surface acoustic waves," *Sensors-the Journal of Applied Sensing Technology*, vol. 18, no. 10, pp. 51–55, 2001.

[36] R. Strogonovs. (2013) Strain gauge based weight sensor (load cell).

[37] M. A. Baniasad, M. Akbar, A. Alasty, and F. Farahmand, "Fuzzy control of a hand rehabilitation robot to optimize the exercise speed in passive working mode." in *MMVR*, 2011, pp. 39–43.

[38] G. C. Goodwin, S. F. Graebe, M. E. Salgado *et al.*, *Control system design*. Prentice Hall New Jersey, 2001, vol. 240.

[39] N. Wulandari and A. Abdullah, "Design and simulation of washing machine using fuzzy logic controller (flc)," in *IOP Conference Series: Materials Science and Engineering*, vol. 384, no. 1. IOP Publishing, 2018, p. 012044.

[40] C. W. De Silva, *Intelligent control: fuzzy logic applications*. CRC press, 2018.

[41] S. Sivanandam, S. Sumathi, S. Deepa *et al.*, *Introduction to fuzzy logic using MATLAB*. Springer, 2007, vol. 1.

[42] J. O. Salim, "Fuzzy based pid controller for speed control of dc motor using labview," *WSEAS transactions on systems and control*, 2015.

[43] B. R. Copeland, "Using the labview pid control toolkit with the labview control design and simulation module," *Report*, 2009.

[44] D. Santos and A. A. Siqueira, "Adams/matlab co-simulation of an exoskeleton for lower limbs," in *International Congress of Mechanical Engineering (COBEM 2009), Gramado, RS*, 2009.

[45] L. Angel, M. Pérez, C. Díaz-Quintero, and C. Mendoza, "Adams/matlab co-simulation: Dynamic systems analysis and control tool," in *Applied Mechanics and Materials*, vol. 232. Trans Tech Publ, 2012, pp. 527–531.

Appendix A

Arduino Code for Strain Gauge Measurement

This is a simple Arduino Program for Human Muscle Strain Measurement.The Arduino Accepts the Analog 0-5V of the Strain gauge value through its Analog input Port A0 and Displays the corresponding 0-1023 digital Value.

int strain=0;//Assigning the variable'Strain'
void setup()
pinMode(A0, INPUT);//Configering the the analog pin A0 as an input port.
Serial.begin(9600);

void loop()
strain=analogRead(A0);//Directing the Analog value read from A0 to the variable 'Strain'
Serial.print("Muscle Strain Value:");// to display 'Muscle Strain Value' on the monitor
Serial.println(strain);// to display the strain value
delay(1000);

Appendix B

Collected data from patients

The muscle strain or muscle contraction is measured using the strain guage to estimate the pain level of the patients.

Table B.1: Collected data from Flaccid patient's condition

Duration	Musle Strain(10 bit ADC)	Pain level
First week	170-315	Low
	315-460	Medium
	460-605	High
	605-750	Very High
Second week	315-460	Low
	460-605	Medium
	605-750	High

Table B.2: Collected data from Intermidiate pacient's condition on the Experiment

Duration	Musle Strain(10 bit ADC)	Pain level
First week	25-170	Very Low
	170-315	Low
	315-460	Medium
	460-605	high
	605-750	Very High
Second week	315-460	Very Low
	460-605	Low
	605-750	High

Table B.3: Collected data from Spastic pacient's condition on the Experiment

Duration	Musle Strain(10 bit ADC)	Pain level
First week	25-170	Medium
	170-315	Medium
	315-460	High
	460-605	Very High
	605-750	Very High
Second Week	25-170	Very Low
	170-315	Low
	315-460	Medium
	460-605	high
	605-750	Very High

Appendix C

Fuzzy Logic System

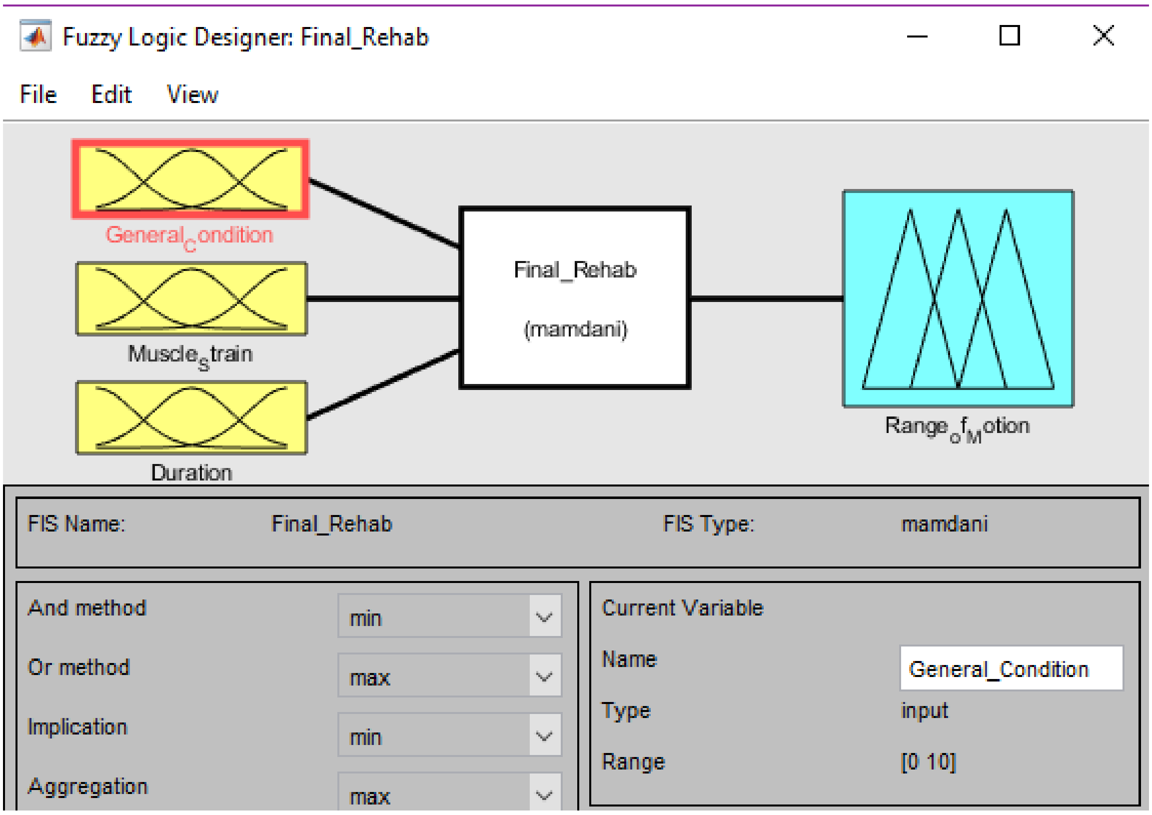
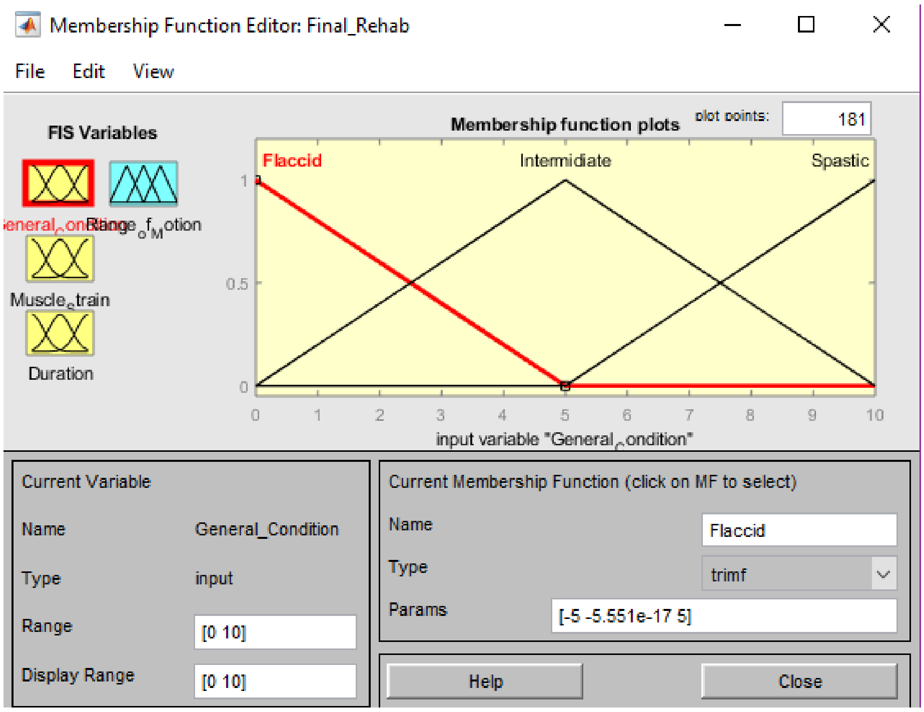
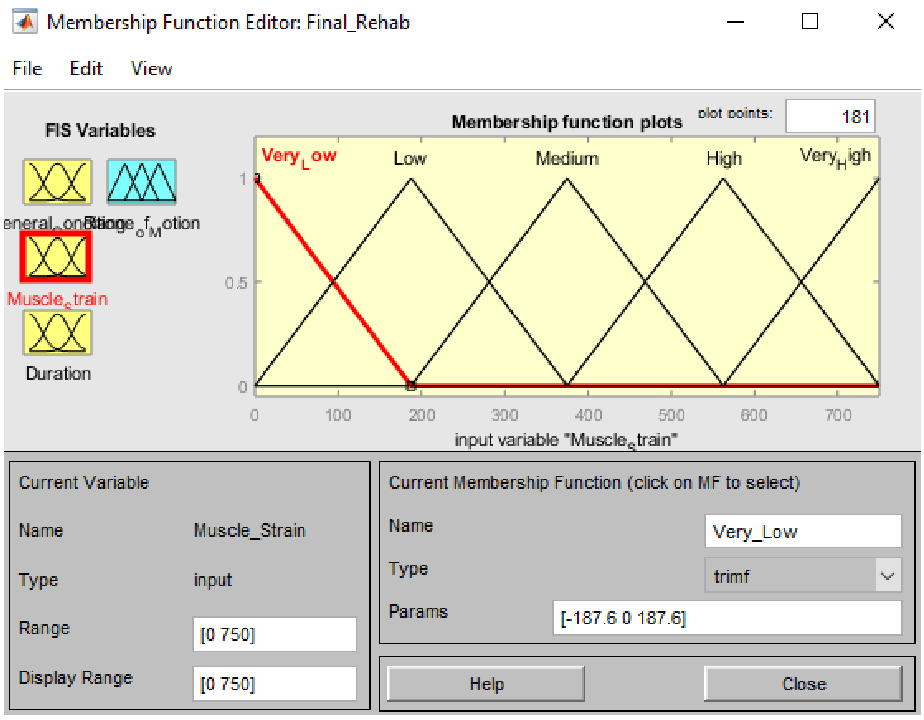


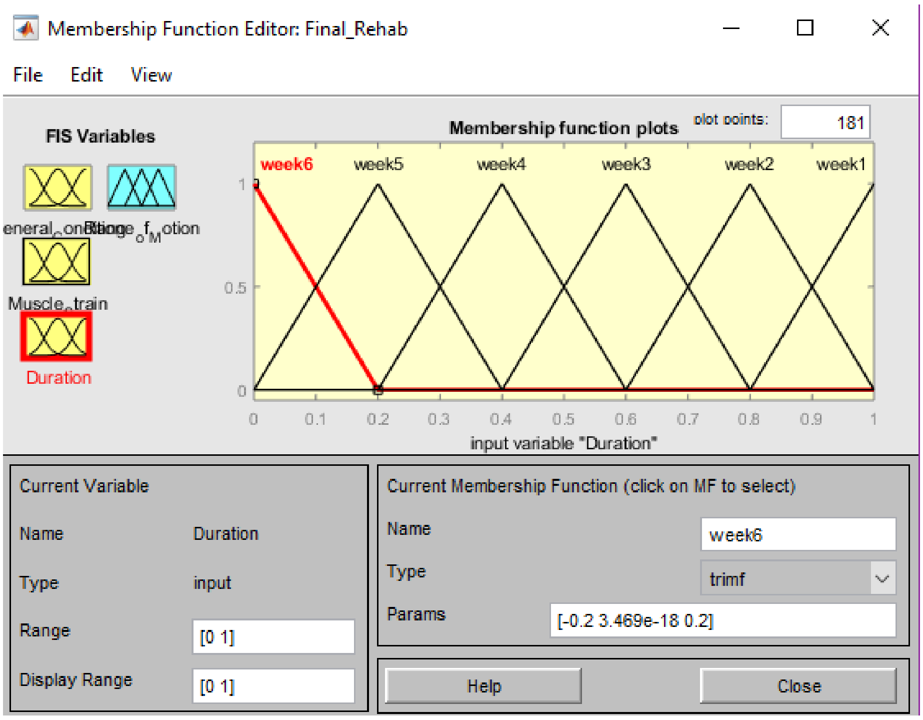
Fig. C.1: Fuzzy Logic Design


Membership Function Editor: Final_Rehab
File
Edit
View
FIS Variables
Membership function plots
plot points:
181
Flaccid
Intermidiate
Spastic
Muscle_strain
Duration
input variable "General_condition"
Current Variable
Name
General_Condition
Type
input
Range
[0 10]
Display Range
[0 10]
Current Membership Function (click on MF to select)
Name
Flaccid
Type
trimf
Params
[-5 -5.551e-17 5]
Help
Close

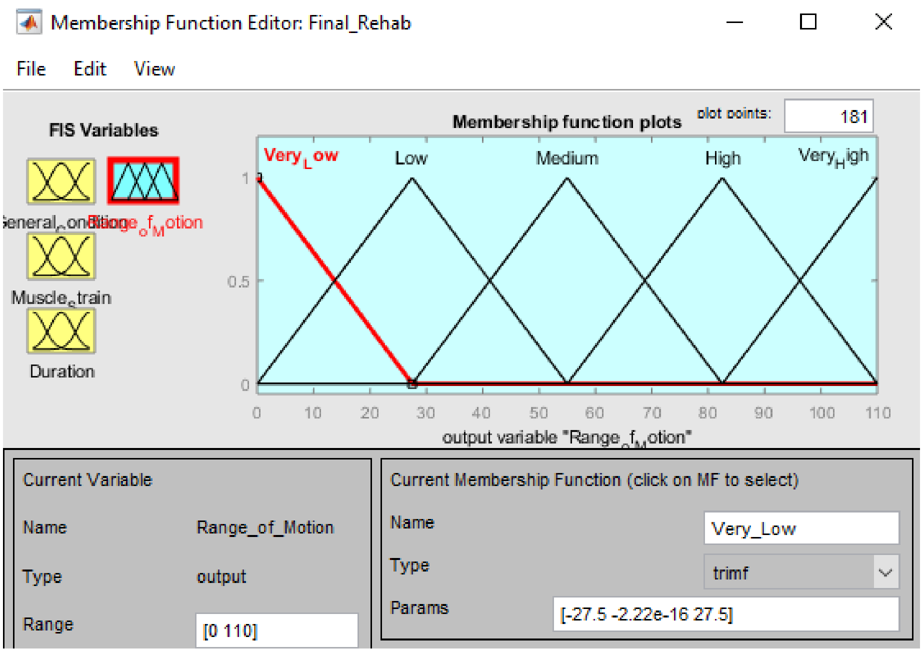
(a)


Membership Function Editor: Final_Rehab
File
Edit
View
FIS Variables
Membership function plots
plot points:
181
Very_Low
Low
Medium
High
Very_High
Muscle_strain
Duration
input variable "Muscle_strain"
Current Variable
Name
Muscle_Strain
Type
input
Range
[0 750]
Display Range
[0 750]
Current Membership Function (click on MF to select)
Name
Very_Low
Type
trimf
Params
[-187.6 0 187.6]
Help
Close

(b)



(c)



(d)

Fig. C.2: Membership Function of Input Variables

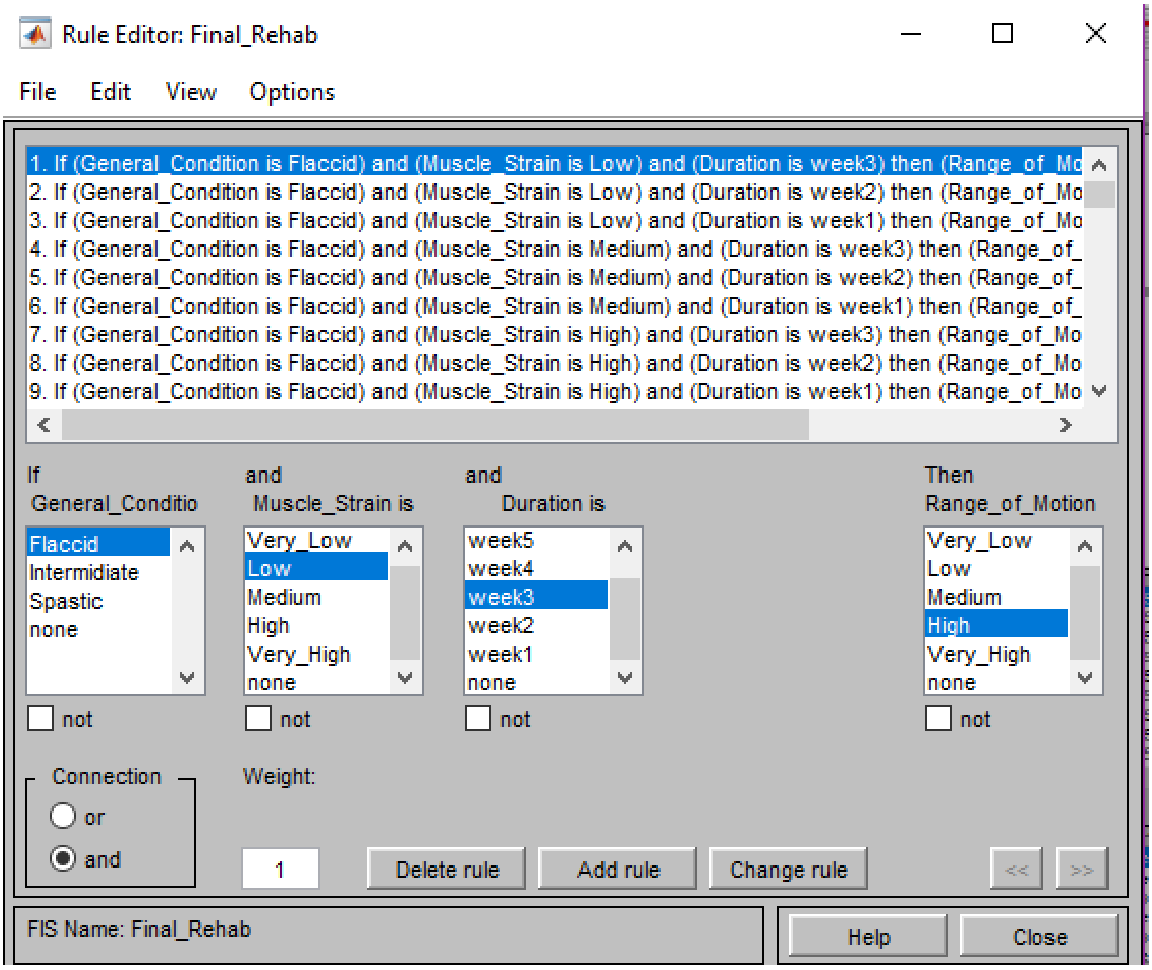


Fig. C.3: Fuzzy Inference Rule

Fuzzy Inference Rule in MATLAB

>> fis = readfis("Final-Rehabilitation")
fis = mamfis with properties:
Name: "Final-Rehabilitation"
AndMethod: "min"
OrMethod: "max"
ImplicationMethod: "min"
AggregationMethod: "max"
DefuzzificationMethod: "centroid"
Inputs: [1*3 fisvar]
Outputs: [1*2 fisvar]
Rules: [1*63 fisrule]
DisableStructuralChecks: 0

>> fis.rule
ans = 1*63 fisrule array with properties:
Details: Description

---

1 "General-Condition==Flaccid and Muscle-Strain==Low and Duration==week3 => Range-of-Motion=High (1)"
2 "General-Condition==Flaccid and Muscle-Strain==Low and Duration==week2 => Range-of-Motion=Medium (1)"
3 "General-Condition==Flaccid and Muscle-Strain==Low and Duration==week1 => Range-of-Motion=Low (1)"
4 "General-Condition==Flaccid and Muscle-Strain==Medium and Duration==week3 => Range-of-Motion=High (1)"

5 ”General-Condition==Flaccid and Muscle-Strain==Medium and Duration==week2 => Range-of-Motion=Medium (1)”
6 ”General-Condition==Flaccid and Muscle-Strain==Medium and Duration==week1 => Range-of-Motion=Low (1)”
7 ”General-Condition==Flaccid and Muscle-Strain==High and Duration==week3 => Range-of-Motion=Medium (1)”
8 ”General-Condition==Flaccid and Muscle-Strain==High and Duration==week2 => Range-of-Motion=Low (1)”
9 ”General-Condition==Flaccid and Muscle-Strain==High and Duration==week1 => Range-of-Motion=Very-Low (1)”
10 ”General-Condition==Flaccid and Muscle-Strain==Very-High and Duration==week3 => Range-of-Motion=Medium (1)”
11 ”General-Condition==Flaccid and Muscle-Strain==Very-High and Duration==week2 => Range-of-Motion=Low (1)”
12 ”General-Condition==Flaccid and Muscle-Strain==Very-High and Duration==week1 => Range-of-Motion=Very-Low (1)”
13 ”General-Condition==Intermidiate and Muscle-Strain==Very-Low and Duration==week4 => Range-of-Motion=High (1)”
14 ”General-Condition==Intermidiate and Muscle-Strain==Very-Low and Duration==week3 => Range-of-Motion=Medium (1)”
15 ”General-Condition==Intermidiate and Muscle-Strain==Very-Low and Duration==week2 => Range-of-Motion=Low (1)”
16 ”General-Condition==Intermidiate and Muscle-Strain==Very-Low and Duration==week1 => Range-of-Motion=Very-Low (1)”
17 ”General-Condition==Intermidiate and Muscle-Strain==Low and Duration==week4 => Range-of-Motion=High (1)”
18 ”General-Condition==Intermidiate and Muscle-Strain==Low and Duration==week3 => Range-of-Motion=Medium (1)”
19 ”General-Condition==Intermidiate and Muscle-Strain==Low and Duration==week2 => Range-of-Motion=Low (1)”
20 ”General-Condition==Intermidiate and Muscle-Strain==Low and Duration==week1 => Range-of-Motion=Very-Low (1)”
21 ”General-Condition==Intermidiate and Muscle-Strain==Medium and Duration==week4 => Range-of-Motion=Medium (1)”
22 ”General-Condition==Intermidiate and Muscle-Strain==Medium and Duration==week3 => Range-of-Motion=Low (1)”
23 ”General-Condition==Intermidiate and Muscle-Strain==Medium and Duration==week2 => Range-of-Motion=Low (1)”
24 ”General-Condition==Intermidiate and Muscle-Strain==Medium and Duration==week1 => Range-of-Motion=Very-Low (1)”
25 ”General-Condition==Intermidiate and Muscle-Strain==High and Duration==week4 => Range-of-Motion=Medium (1)”
26 ”General-Condition==Intermidiate and Muscle-Strain==High and Duration==week3 => Range-of-Motion=Low (1)”
27 ”General-Condition==Intermidiate and Muscle-Strain==High and Duration==week2 => Range-of-Motion=Very-Low (1)”
28 ”General-Condition==Intermidiate and Muscle-Strain==High and Duration==week1 => Range-of-Motion=Very-Low (1)”
29 ”General-Condition==Intermidiate and Muscle-Strain==Very-High and Duration==week4 => Range-of-Motion=Medium (1)”
30 ”General-Condition==Intermidiate and Muscle-Strain==Very-High and Duration==week3 => Range-of-Motion=Low (1)”
31 ”General-Condition==Intermidiate and Muscle-Strain==Very-High and Duration==week2 => Range-of-Motion=Very-Low (1)”
32 ”General-Condition==Intermidiate and Muscle-Strain==Very-High and Duration==week1 => Range-of-Motion=Very-Low (1)”
33 ”General-Condition==Spastic and Muscle-Strain==Very-Low and Duration==week6 => Range-of-Motion=Very-Low (1)”
34 ”General-Condition==Spastic and Muscle-Strain==Very-Low and Duration==week6 => Range-of-Motion=Very-High (1)”
35 ”General-Condition==Spastic and Muscle-Strain==Very-Low and Duration==week5 => Range-of-Motion=High (1)”
36 ”General-Condition==Spastic and Muscle-Strain==Very-Low and Duration==week4 => Range-of-Motion=Medium (1)”
37 ”General-Condition==Spastic and Muscle-Strain==Very-Low and Duration==week3 => Range-of-Motion=Medium (1)”
38 ”General-Condition==Spastic and Muscle-Strain==Very-Low and Duration==week2 => Range-of-Motion=Low (1)”
39 ”General-Condition==Spastic and Muscle-Strain==Very-Low and Duration==week1 => Range-of-Motion=Very-Low (1)”
40 ”General-Condition==Spastic and Muscle-Strain==Low and Duration==week6 => Range-of-Motion=High (1)”
41 ”General-Condition==Spastic and Muscle-Strain==Low and Duration==week5 => Range-of-Motion=Medium (1)”
42 ”General-Condition==Spastic and Muscle-Strain==Low and Duration==week4 => Range-of-Motion=Medium (1)”
43 ”General-Condition==Spastic and Muscle-Strain==Low and Duration==week3 => Range-of-Motion=Low (1)”
44 ”General-Condition==Spastic and Muscle-Strain==Low and Duration==week2 => Range-of-Motion=Low (1)”
45 ”General-Condition==Spastic and Muscle-Strain==Low and Duration==week1 => Range-of-Motion=Very-Low (1)”
46 ”General-Condition==Spastic and Muscle-Strain==Medium and Duration==week6 => Range-of-Motion=High (1)”
47 ”General-Condition==Spastic and Muscle-Strain==Medium and Duration==week5 => Range-of-Motion=Medium (1)”
48 ”General-Condition==Spastic and Muscle-Strain==Medium and Duration==week4 => Range-of-Motion=Medium (1)”
49 ”General-Condition==Spastic and Muscle-Strain==Medium and Duration==week3 => Range-of-Motion=Low (1)”
50 ”General-Condition==Spastic and Muscle-Strain==Medium and Duration==week2 => Range-of-Motion=Very-Low (1)”
51 ”General-Condition==Spastic and Muscle-Strain==Medium and Duration==week1 => Range-of-Motion=Very-Low (1)”
52 ”General-Condition==Spastic and Muscle-Strain==High and Duration==week6 => Range-of-Motion=Medium (1)”
53 ”General-Condition==Spastic and Muscle-Strain==High and Duration==week5 => Range-of-Motion=Medium (1)”
54 ”General-Condition==Spastic and Muscle-Strain==High and Duration==week4 => Range-of-Motion=Low (1)”
55 ”General-Condition==Spastic and Muscle-Strain==High and Duration==week3 => Range-of-Motion=Low (1)”
56 ”General-Condition==Spastic and Muscle-Strain==High and Duration==week2 => Range-of-Motion=Very-Low (1)”
57 ”General-Condition==Spastic and Muscle-Strain==High and Duration==week1 => Range-of-Motion=Very-Low (1)”
58 ”General-Condition==Spastic and Muscle-Strain==Very-High and Duration==week6 => Range-of-Motion=Low (1)”
59 ”General-Condition==Spastic and Muscle-Strain==Very-High and Duration==week5 => Range-of-Motion=Low (1)”
60 ”General-Condition==Spastic and Muscle-Strain==Very-High and Duration==week4 => Range-of-Motion=Low (1)”
61 ”General-Condition==Spastic and Muscle-Strain==Very-High and Duration==week3 => Range-of-Motion=Very-Low (1)”
62 ”General-Condition==Spastic and Muscle-Strain==Very-High and Duration==week2 => Range-of-Motion=Very-Low (1)”
63 ”General-Condition==Spastic and Muscle-Strain==Very-High and Duration==week1 => Range-of-Motion=Very-Low (1)”