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Design and Analysis of Fuzzy Based Proportional-Integral-Derivative Controller for Elbow-Forearm Rehabilitation Robot

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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 an accidental physical fracture. Since the pain condition of such accidents needs a critical treatment, precise control of such robotic manipulators is mandatory. This paper presents the design and control of the Elbow-Forearm Rehabilitation Robot by considering the pain level of the patient. This design consists of the mechatronic design processes including mechanical design, controller design, and Virtual prototyping using ADAMS-MATLAB Co-simulation. 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. Based on these three input parameters, the manipulator's desired range of motion has been determined using the Fuzzy Logic System. The output of this fuzzy logic system would be an input to the main control system. ADAMS-MATLAB Co-simulation is carried out based on 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. From the above three simulation schemes, we can conclude that the Elbow-Forearm rehabilitation robot could be controlled as per the desired signal. Since this desired signal is developed from the pain level of the patient, we can say that the system is controlled as per the pain level of the patient.

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

1. Introduction

The upper limb is a complex neuro-mechanical system that occupies an essential role in our day to day activities including interacting and communicating with our environment, manipulating objects and other activities [1]. This upper limp may be exposed to two major problems. The first one is that it may have a neurological injury such as stroke. Secondly, it might be exposed to 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 hand to be restored to its normal function with physiotherapists.

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 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 fracture of upper limp or joint dislocations which have highly sensitive pain. Here, precisely controlled i.e with pain level, rehabilitation robot is needed. Consequently, fuzzy based PID controlled rehabilitation robot is proposed to eliminate the stated problems.

2. Literature Review

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. Different researchers provide a significant approach to the upper limb parts of the human body. Besides, most developed rehabilitation manipulator systems [2-4] are concerned about injuries caused by stroke which is mostly long term injury. However, Hybrid impedance control of a robot manipulator for wrist and forearm rehabilitation was investigated by Akdogan et al. [5]. This article include HMI (Human Machine Interface) to model the exercises for the rehabilitation but, continuous detection and evaluation of the pain level of the patient is not considered.

Since the robotic designs consists of full mechatronic design, various design aspects are considered. The first aspect is the mechanical structure (number of degree of freedom) at which different structures [6-10] can be used for various parts of upper limb rehabilitation robot. 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 [11], design of rehabilitation robots for each joint of the upper limp is preferable.

The second aspect is the type of sensor used for detecting the pain condition of the patients. Here, most of the robotic systems [12-14] uses the surface electromyography sensors (sEMG) to acquire data from the muscle. 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 [15]. Especially, Mori et al. [16] properly demonstrated the feasibility of using strain gauge to measure the shape of skin deformation and Muscle Contraction (MC). To summarize, there were a minimum scope of investigations on the rehabilitation of post immobilization of accidental fractures and joint dislocations. In addition, most studies have acquired data from patients using Electromyography sensors which are very expensive and unsuitable. By considering these limitations, we use Strain gauge sensors to acquire data and develop a controller for the Elbow-Forearm Rehabilitation Robot. We also survey the previously developed mechanical designs by taking different approaches such as the number of DOFs and the complexity of the structure. We have shown that as the number of DOFs increases, the 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 rehabilitation robot.

3. Mechanical Design

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 limb parts as shown in Fig. 1. 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 the human body in the work process [17]. Thus, the design of the rehabilitation robot has been satisfying with goals as follows:

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

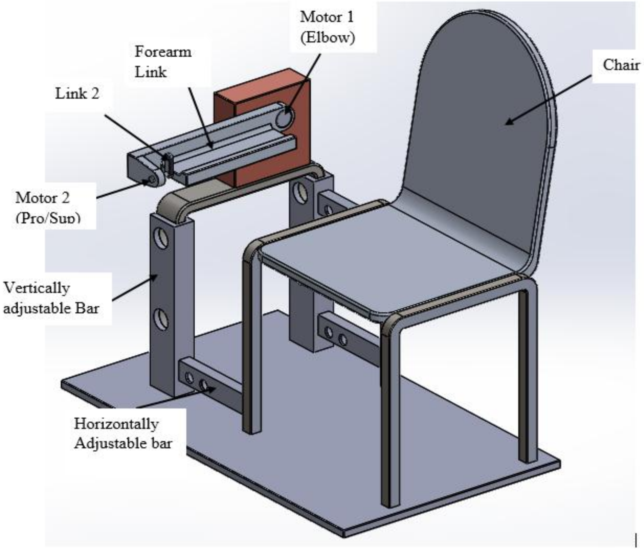

Fig. 1. Mechanical Design of Elbow-Forearm Rehabilitation Robot.

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 the human adult. It is connected with the standing by horizontally adjustable bolt-fastening mechanism. The standing is also adjustable vertically to enhance the ergonomics aspect of the patient. The box containing the motor 1 and the gear assembly directly connected with the arm link. This motor drives the link according to the control algorithm stated in the control system. The forearm link is designed in such a way to support the injured hand. This link is used to rehabilitate the elbow in flexion and extension motions according to the pain level of the patient. Then with some time interval, link 2 (using motor 2) will perform the pronation and supination of the forearm. The two rehabilitation operations of the manipulator are discussed in detail as follows:

A. Flexion and Extension of Elbow

Flexion and Extension of the human elbow joint as shown in Fig. 2 has a maximum range of motion of 140^0 to 145^0 [13]. This human elbow joint is directly aligned to the elbow joint of the robot shown in the Fig. 1. Depending on the injuries of the patient, the position of the forearm after immobilization may be at the flexion or extension position. Then the elbow joint of the robot adjusted in similar alignment and the precisely controlled oscillatory movement/rehabilitation will be carried out based on the pain level of the patient.

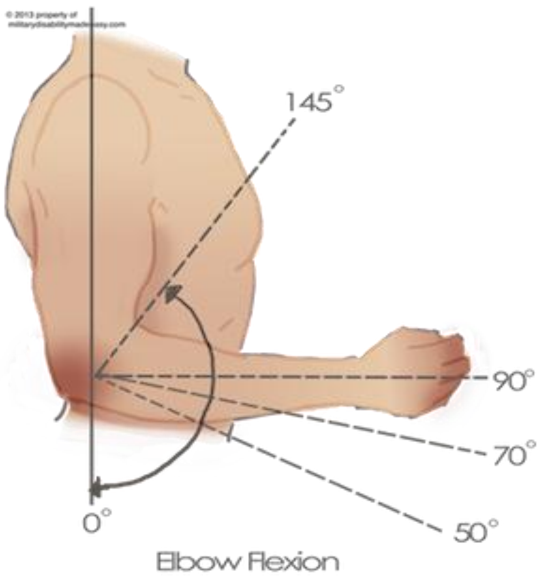

Fig. 2. Flexion and Extension of Elbow [9] joint.

B. Pronation and Supination of Forearm

In addition to the extension and flexion of the elbow, the twisting exercises on the forearm is also necessary. This exercise is done by the Supination and Pronation of hands and forearms as shown in the Fig. 3. This helps the body to twist the palm either face down or face up. Further, the bones, muscles and joints of the forearm are arranged to facilitate these movements. It has a range of motion of 160^0 to 180^0 [13]. Link 2 in Fig. 1 has the responsibility of this motion with the pain level of the patient. The patient will grasp link 2 with the palm. As the motor 2 rotates in an oscillatory motion, all muscles of the forearm will rehabilitate efficiently.

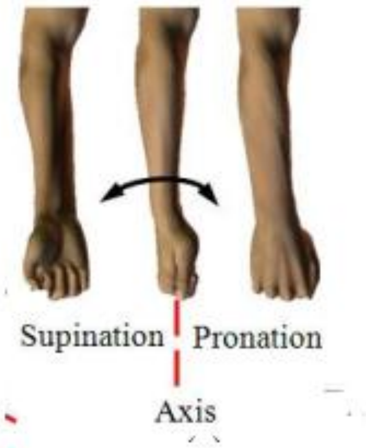

Fig. 3. Pronation and Supination of Forearm [9]

4. Modeling

A. 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 seven 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-forearm so that we are interested on adjustable one DOF elbow rehabilitation robot and the other one DOF forearm pronation/supination. The elbow pitch Flexion/extension movements has a ROM of approximately 140-145 degree [13]. Forearm Pronation/Supination also have a ROM approximately 160-180 degrees. In order to simplify the control process, kinematics of the elbow rehabilitation and forearm twisting has been calculated alone. This is because the patient perform those exercises individually with different time. Consequently, the two motors are controlled separately. The final kinematic model of the two joints will be as shown in Eq. 2 and Eq. 4.

$$\begin{bmatrix} X_f \\ Y_f \end{bmatrix} = \begin{bmatrix} -l_1 \sin \theta_f \\ l_1 \cos \theta_f \end{bmatrix} \dot{\theta}_f \tag{1}$$

$$\dot{X}_f = [J_f]\dot{\theta}_f \tag{2}$$

Similarly for elbow joint

$$\begin{bmatrix} X_e \\ Y_e \end{bmatrix} = \begin{bmatrix} -l_2 \sin \theta_e \\ l_2 \cos \theta_e \end{bmatrix} \dot{\theta}_e \tag{3}$$

$$\dot{X}_e = [J_e]\dot{\theta}_e \tag{4}$$

Where, X_f and X_e are the positions of end effector of forearm joint and elbow joint respectively; $\dot{X}_f$ and $\dot{X}_e$ are the velocities; J_f and J_e are Jacobean matrices; θ_f and θ_e represents the angular positions; $\dot{\theta}_f$ and $\dot{\theta}_e$ represents joint rates.

B. Dynamic Modeling

We can derive the dynamic equation of motion for the two joints of rehabilitation robot arm using the Euler-Lagrange formulation due to its simple 2 DOF. It is done by considering that the center of masses m_f and m_e for each link lengths l_{cf} and l_{ce} 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. Then, the final equation of motion for the two joints with torques τ_f and τ_e is given as shown in Eq. 5:

$$M(\theta)\begin{bmatrix}\ddot{\theta}_f\\ \ddot{\theta}_e\end{bmatrix}+\begin{bmatrix}0.5m_f g l_{cf}\cos(\theta_f)\\ 0.5m_f g l_{ce}\cos(\theta_e)\end{bmatrix}\dot{\theta}_f=\begin{bmatrix}\tau_f\\ \tau_e\end{bmatrix} \tag{5}$$

$$M(\theta)=\begin{bmatrix}m_f g l_{cf}^{2}+I_f\\ m_f g l_{ce}^{2}+I_e\end{bmatrix} \tag{6}$$

C. 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 [18]. The inertia moment, mass, material and cross section geometry represent parameters of this system and they can be optimized on the base of co-simulation results. Additionally, ADAMS View environment is able to provide the multi-body model (MTB) for static, kinematic and dynamic analysis. First the SOLIDWORKS assembly is exported to ADAMS environment. Then, the joints and motions of the manipulator are created on the elbow and forearm twisting joints. Revolute joint type and the oscillatory motion type are selected due to the reason that the nature of the rehabilitation of elbow and forearm is oscillatory. The simulation is tested on ADAMS post processor by providing 30 degree oscillatory motion and it is successfully simulated without applying any controller.

However, the aim of the research is to control the system with the proposed fuzzy based PID controller. To do this, it is required to develop the dynamic model by determining the input and output variables. The input variable is the torque X1 and the output variable is the angular position as shown in the Fig. 4. After specifying these variables, the dynamic model (plant) will be exported to the targeted software i.e

MATLAM/SIMULINK or EASY 5 to design the control system.

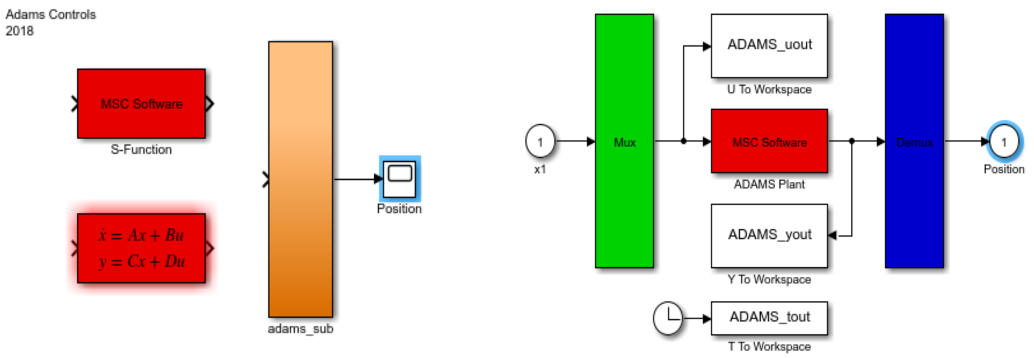

Fig. 4. Adams Dynamic Model

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 of individual blocks is based on [19]:

- 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

5. Data Acquisition

In this research, pain level of the patients with fractured hand especially around elbow will be detected using strain gauge sensors. Most Rehabilitation robot developments [12-14] uses surface electromyography (sEMG) electrodes. The number of sensors required increases with the increase in the number of DOF in the recent Upper limp rehabilitation robots. However, sEMG sensor needs a higher sampling frequency. This will limits the number of sensors that the processors can manage [20]. The objective of this paper 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 helps to predict the pain level by measuring the muscle contraction and by asking patients with different injury level see in Fig. 5. The advantage of a low sampling frequency compared with sEMG is the potential development of the usage of strain gauges [20].

The data acquisition is done by using an Arduino Uno board due to its low-cost and easy manipulation. A Wheatstone bridge is used for signal conditioning and then the signal is processed by an Analog-Digital Converter (ADC) of the Arduino.

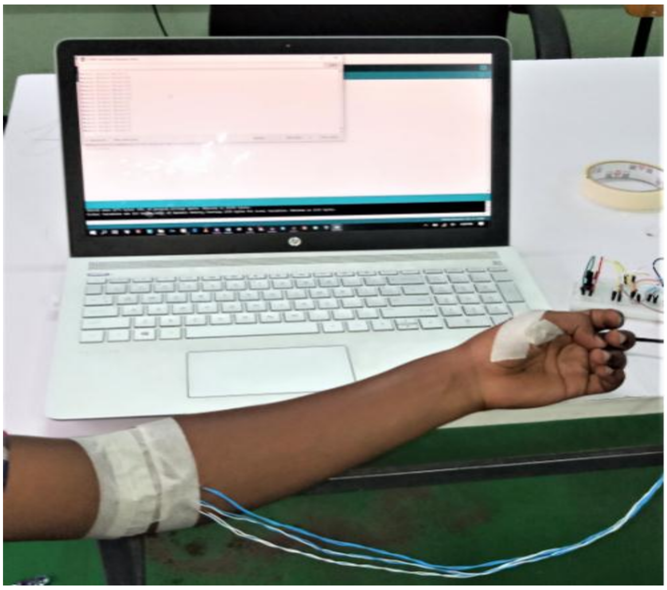

Fig. 5. Data Acquisition from Patients

This proposed measurement system is applied on patients of fractured hand especially around elbow. To detect and measure the deformations of the strain gauge, a simple electronic circuitry is used which consists two main circuits i.e the Wheatstone bridge circuit and the Amplifier Circuit. Here the strain gauge sensors are extended through thin flexible 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. The data is collected from patients in "TIRUNESH BEJING GENERAL HOSPITAL AND ABET GENERAL HOSPITAL" found in Addis Ababa. To collect the accurately estimated data, the expert therapists consider the general condition of the patients. These are Flaccid, Intermediate and Spastic conditions [20]. 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. Here we are considering adults as a subjects of the experiment. Since the spastic type of patients have stiff pain, their data is estimated by the therapists with their past experience.

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 10 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 10 bit digital value.

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. Even though the theoretical range of muscle strain is 0-1023 ADC value, the practical obtained range is 0-750 ADC value.

Generally, there are different factors that affect the accuracy of the data. These includes the error on the adjustment of strain gauge sensor on the human body, the hand tremor of the patient, the temperature of the measuring environment, the sensitivity of the measuring device and other related problems. However, since we are using the range of values, these errors will not have a significant effect on the control system.

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6. Control Strategy

Control system design in practice requires cyclic effort of iterating between modeling, design, simulation, testing, and implementation [21]. The signals such reference signal, error signal, control signal, actuation signal, measurement signal and other signals are the major factors for the accuracy of the control system. This research paper proposes a control system by generating input (reference) signal which is the desired range of motion of a manipulator as shown in the Fig. 6.

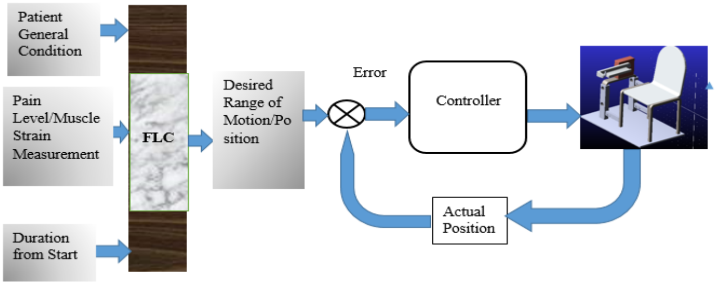


Fig. 6. The proposed control system

And also since the model is developed in ADAMS, the behavior of this ADAMS dynamic model is analyzed by using the PID control approach. The whole control system has two sections. The first section deals with generating an actual input signal (Reference signal) for the Position of a manipulator which is developed with a fuzzy logic system. The second section deals with the main controller which is PID control design as shown in the Fig. 6. The value of the output signal of the first fuzzy system becomes the input as a reference value of the motor's position.

A. General Description of the control System

The control system shown in the Fig. 6 has four main parts. These are the input (reference signal), the controller (PID controller), the actuator (rehabilitation robot) and the measurement system. First, the reference signal is generated by the fuzzy logic system. There are three inputs to determine the desired range of motion or position of the manipulator. These are the patient's general Condition, the muscle contraction (pain level) and the time duration at which the patient starts the rehabilitation.

By using these inputs the fuzzy system provide the desired range of motion of the manipulator. The actual range of motion is measured and compared with the desired one. By seeing the error signal, the PID controller maintains the manipulator to track this desired position by providing appropriate control signal to the plant. The details of the control mechanism is discussed below.

B. 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 [20]. However, we are considering the rehabilitation of the fractured/ broken hand after immobilization. Here we have proposed a mechanism to estimate the exercise 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 patient correlated from the strain gauge measurement, and (3) Duration of exercise from the starting day. The Patient's general condition is decided by the expert therapist. Therapists have a great experience in classifying patients as Flaccid, Intermediate and Spastic [20]. 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 gives the intelligence for the robot. After classifying the patient's status, the strain gauge assembly will be 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 exercise by providing the accurate input (reference) signal.

C. Designing the Fuzzy Logic Using Matlab

The designed fuzzy logic has three inputs and one output as shown in the Fig. 7. The Fuzzy Inference System (FIS) is used for determining the range of motion of the manipulator. In this design Membership 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 a range of 1-10 and three membership Function i.e Flaccid, Intermediate and Spastic.

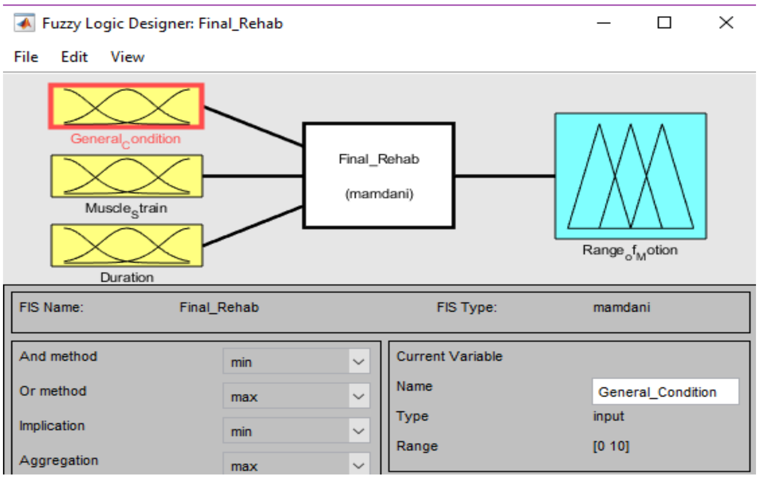


Fig. 7. Fuzzy Logic design

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 functions starts from very low to Very High. Here due to some measurement errors and sensor misplacing, the muscle strain ranges from 0-750. The third Input variable is the time elapsed from the first day of rehabilitation. As an 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. The range of the membership function is taken from 0-1.

So, by combining these three inputs, the fuzzy system will provide the desired range of motion. The plant (the dynamic model) of the manipulator is imported on Matlab Simulink. The PID controller also designed and the final control system is developed as shown in the Fig. 8.

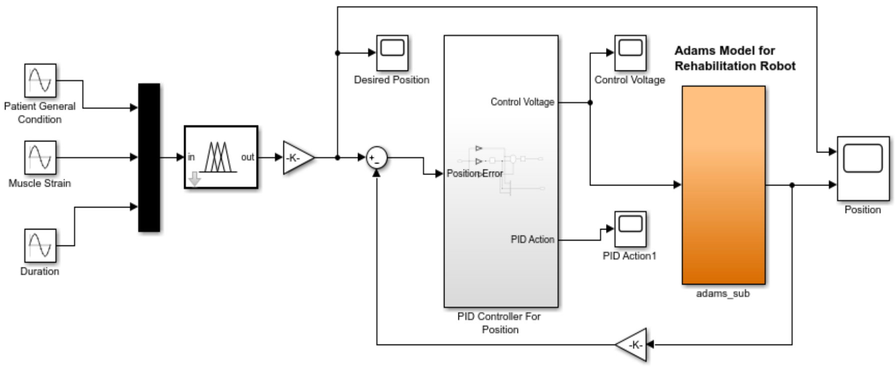


Fig. 8. Full control system design using PID

7. Simulation and Results

This work deals with the co-simulation of Elbow-Forearm rehabilitation robot using ADAMS software and the Matlab/Simulink toolbox to verify the virtual reality of the system. ADAMS allowed us to import the model of mechanical systems, modify systems parameters and testing virtual prototypes of the projects and researches without building them. It also helped us to perform control objectives through the PID controller. However, to implement more sophisticated controllers, alternative procedures must be taking into account [22]. The proposed co-simulation integrate the qualities of the software, the modeling and simulation features of the ADAMS with the computational facilities of the Matlab environment [22]. Here, we are going to perform the simulation in two ways:

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

A. 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 MATLAM and Easy5. To verify correctness and effectiveness of the system, here we exerts sine moment function at elbow joint:

$$Motion1 = 30d * \sin(0.1 * time) \quad (7)$$

With this function driving, we set simulation time as 100s and simulation step as 0.1 and then center of mass of robot arm in postprocessor in ADAMS see Fig. 9. From the position curve, the simulation demonstrates that the motion achieves the desired angle with an error of ±1.23 degrees. 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 using the designed the control block on the target software, in our case MATLAB/Simulink, we can control the system as desired.

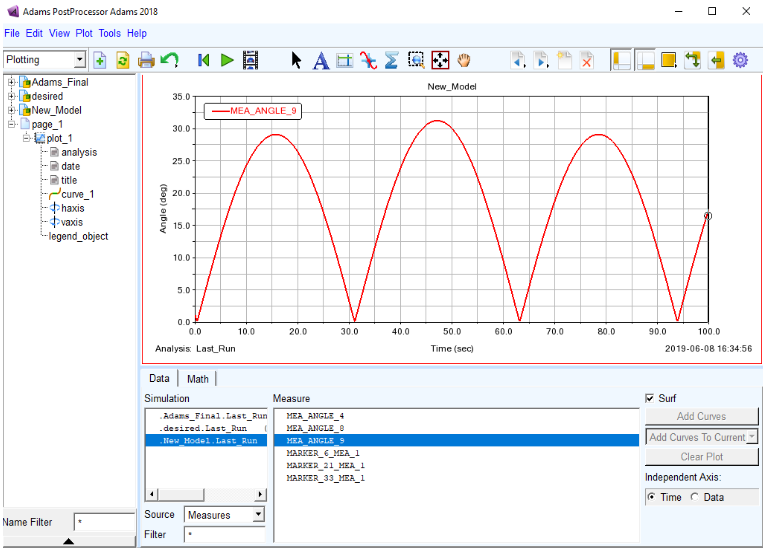


Fig. 9. Position curve of ADAMS PostProcessing

B. 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. In this section, we have observed the behavior of the system using three reference signals. These are:

- Step Input
- Sinusoidal input
- Fuzzy Input Signal

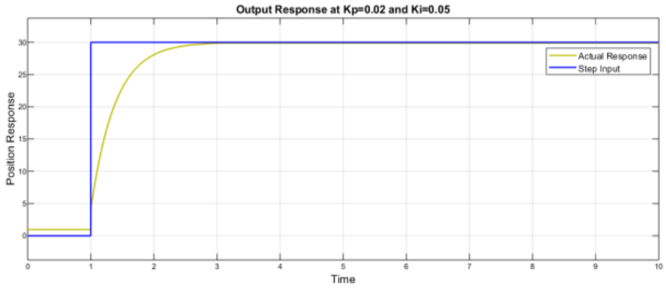
C. Step Response of the System in Co-Simulation

Here, we were dealing the step response of the system by giving the step of 1sec and final value of 30 deg. When we gave the step input to the Adams plant, No oscillating motion is experienced in ADAMS-MATLAB Co-simulation rather it just track 30 degree step. 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.

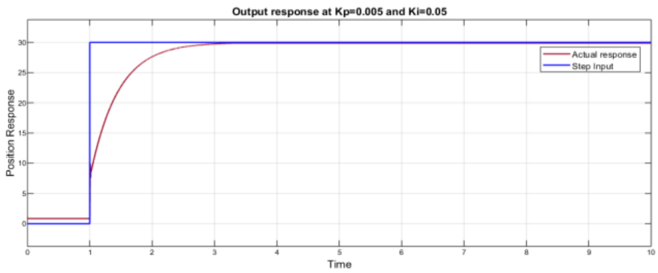
We choose PID controller due to the reason that since we were applying an approach of using fuzzy system for reference signal of the control system. Using fuzzy as a reference input is difficult with advanced control algorithms. So we have started from the conventional PID controller. The behavior of the system is critically investigated 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 was selected. First we start by increasing the proportional gain of the PID controller. The simulation is done with four different Kp values and the corresponding parameters are recorded on the Table 1. Figure 10 also shows the effect of the proportional gain parameter on a step input. Any change in the control signal, u (t) is directly proportional to change in the error signal for a given proportional gain Kp. From the simulation results shown in the Fig. 10 and the corresponding characteristics parameters shown in the Table 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, the oscillating characteristics of the system will also increases as clearly shown in the Fig. 8 (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. 8 (c) and (d).

Table 1. The effect of Proportional gain

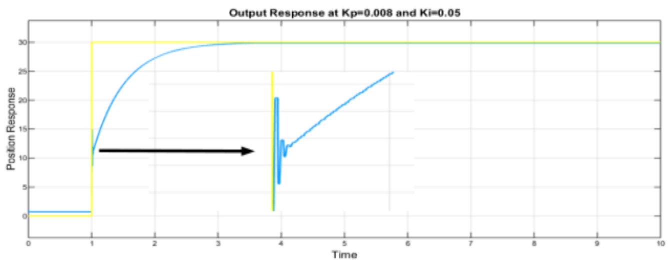
The effect of Proportional Gain				
Kp	Ki	Rise Time (ms)	Overshoot/Undershoot	Settling Time
0.002	0.05	809.817	0.505/1.974	-
0.005	0.05	872.068	0.505/1.979	-
0.008	0.05	923.485	0.505/1.98	-
0.01	0.05	953.538	0.505/1.998	-



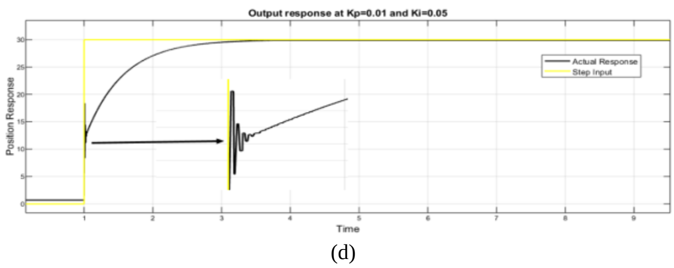
(a)



(b)



(c)



(d)

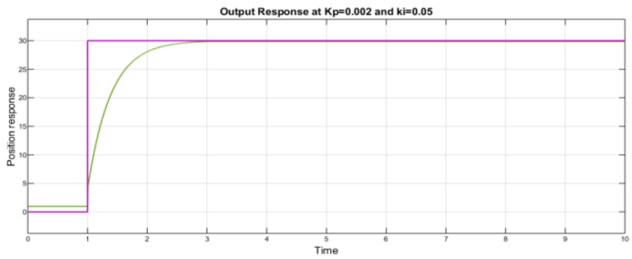
Fig. 10. The effect of Proportional gain (Kp)

Since this system is critically damped type, So that settling time and the overshoot will not characterize the system. As shown in the Table 1, there is no change in overshoot and settling time. However, there is a very small increase in undershoot. Therefore, proportional action K_p is used to eliminate the steady state error, reduce the Rise time and eliminate the oscillating effect. Fig. 11 and Tab. 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. 9 (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.

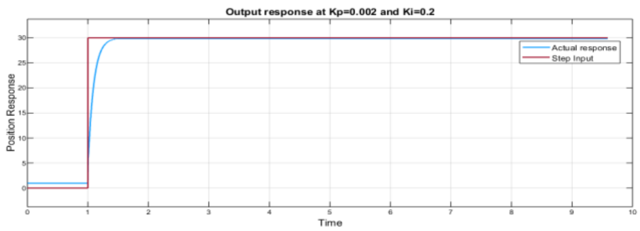
However, the real application of this system needs a slow motion to attain the desired position. Since we are dealing with elbow-forearm fractures patients, their pain level should be considered critically. The step response indicates how fast the manipulator takes the immobilized forearm to the desired range of motion. Here, 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. 12. With these gain combination, slow enough motion is obtained with the rise time of 3.885 seconds. This result satisfy our objective in controlling the manipulator as per the pain level of the patient.

Table 2. The effect of Integral gain

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	-



(a)



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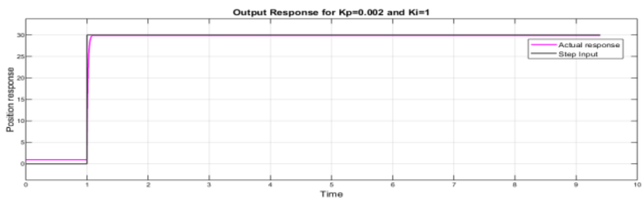

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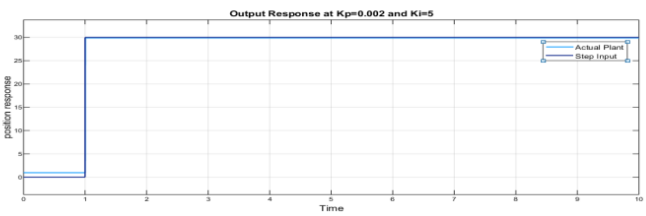


(d)

Fig. 11. The effect of Integral gain (Ki)

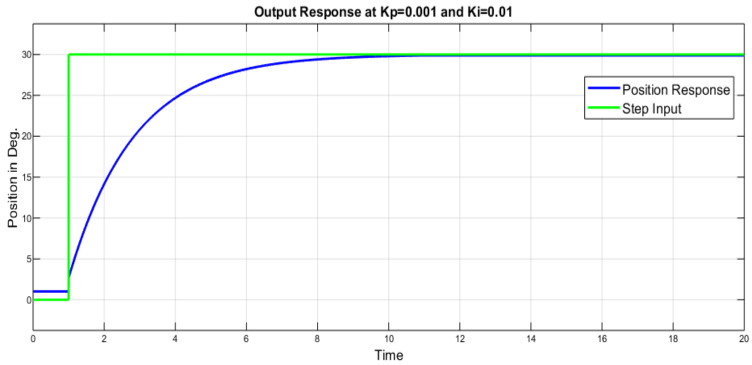


Fig. 12. Step Response of the System

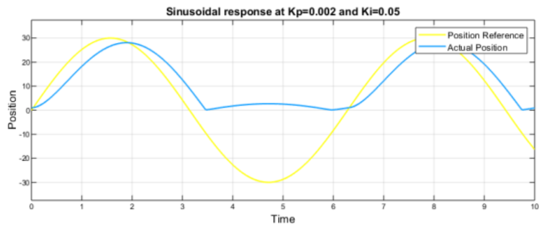
D. Co-Simulation Based on Sinusoidal Input

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 virtual ADAMS-MATLAB Co-simulation as shown in Fig. 15 is used to show the motion of the manipulator on ADAMS software. To observe the behavior of the system for sinusoidal input, we exerts sine input function as follows (see eq. 8).

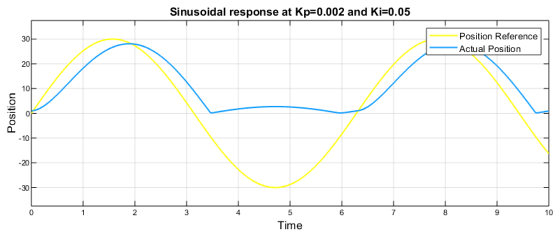
$$Motion = 30 * \sin(time) \tag{8}$$

Table 3. The effect of Proportional gain

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



(a)



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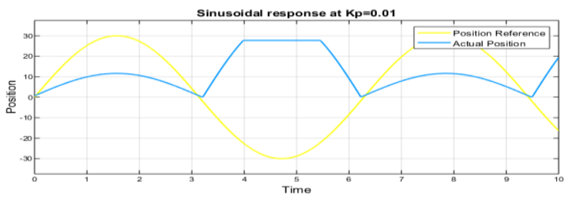

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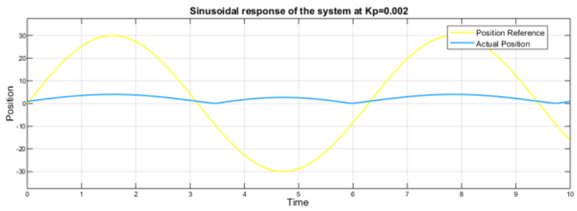
Fig. 13. The effect of Proportional gain (Kp)

Now we are going to see the effect of the proportional gain, K_p on the system. By setting K_i and K_d 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 can see 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. 13 and on the Table 3. From the table we have seen that the rate of change of position in the negative sinusoidal input is more than that of the positive input. This implies that the ROM of the manipulator in the negative sinusoidal input is 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.

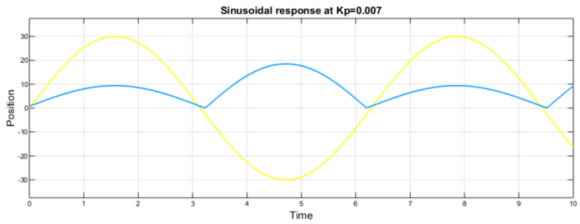
When we come to the integral gain, it will have an effect on the positive sinusoidal input. As seen from the Table 4 and Fig. 14, small increase in the integral gain will results the rapid rising of the plant output to track the reference signal. However, there is some error in degree which is eliminated by increasing the integral gain. This change is clearly observed in the Fig. 16. Now, by combining the two gains at the optimum gain values, we could 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 if the reference input as shown in the Fig. 9.

Table 4. The effect of Integral gain

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



(a)



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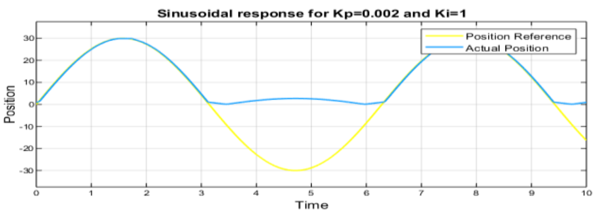

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Fig. 14 The effect of Integral gain (Ki)

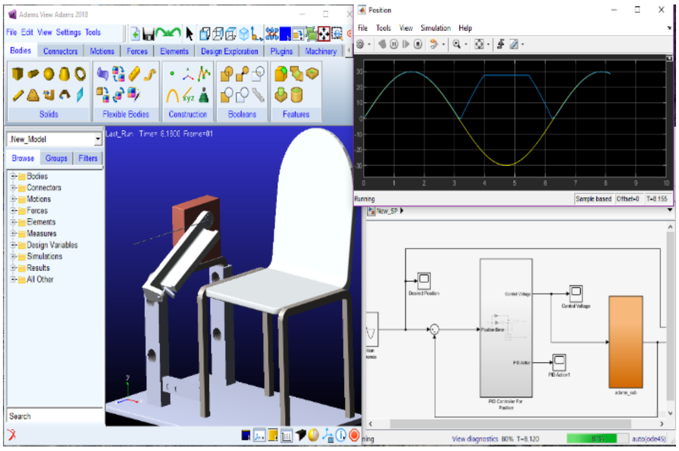


Fig. 15. ADAMS-MATLAB Co-Simulation

This shows that we are achieving 29.88-27.74=2.14 degrees of accuracy by the introducing PID controller. This in turn implies that the real system will response according to the desired range of motion.

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. 7 and Fig. 16 respectively. This shows that the PID controller is successfully applied on the Adams plant with the same sinusoidal input. In both simulations, we have seen that the position curve in the full cycle is positive unlike the sinusoidal input. This is due to the reason that the Adams simulation measures both side motions with a positive angle and it considers both side movements as positive.

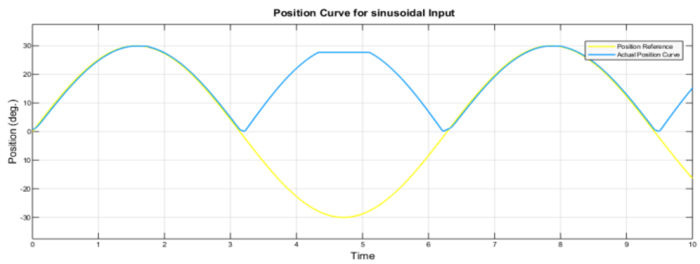
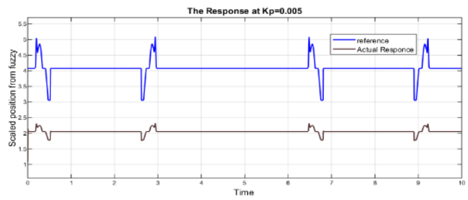
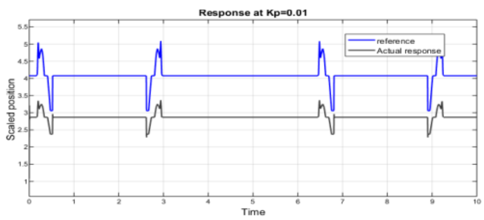


Fig. 16. Position curve of ADAMS PostProcessing



(a)



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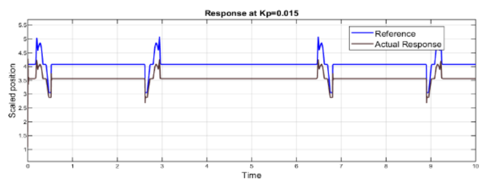

(c)

Fig.17. The response with the proportional gain

E. Co-Simulation Based on Fuzzy Reference Input

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 (see Fig. 6) takes the role for determination of the desired range of motion of the elbow as well as forearm twist see. We have seen in the previous section 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. 15, 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. So by manually tuning the gain, finally the exact tracking of the output to that of the reference signal at which the error will be zero as shown in Fig. 18.

Fig. 18. Simulation Results of the position curve

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. 18. From the simulation, we have seen that the output Position curve tracks 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 tuning of the proportional gain and we get satisfactory result at Kp=0.01925 as shown in Fig. 18. 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.

8. Conclusion and Future Work

A. Conclusion

The use of Rehabilitation robot for patients of accidental fracture after immobilization is not adequately addressed by researchers. However this paper develops the elbow-forearm rehabilitation robot. And also it controls the range of motion of the manipulator by considering the pain level of the patient. First, flexible and rugged mechanical design is developed by considering ergonomics of the patient. Then by collecting the relevant data from patients, we develop the fuzzy 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 step response demonstrated that the system attains its final range of motion with a minimum of 4 seconds. This shows that the rehabilitation system is slow enough and it will not create an extra pain to the patients. The Adams-Matlab co-simulation in sinusoidal signal gives us 29.88 degree of sinusoidal motion with the given 30 degree range of motion. This implies the system tracks the desired position with an accuracy of 99.6%. And then by applying the fuzzy output of the reference position, we can see that the system tracks the given reference fuzzy input at k_p=0.01925.

To summarize, this paper contributes a significant approach on the development of Upper limp rehabilitation robot by giving a great attention on patients suffer from fracture and elbow dislocation. By taking, the rehabilitation robotic systems for stroke patients as a reference, this paper realizes the virtual prototype of the system. And it also invites other researchers to focus and advance this fracture areas.

B. Future Work

This paper concentrates on the mechanical design, acquisition of relevant data from patients, 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 of this Rehabilitation robotic 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.

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